USDA

United States
Department
of Agriculture

Forest Service

Rocky Mountain Research Station

Proceedings
RMRS-P-46CD

September 2007

The Fire Environment—Innovations, Management, and Policy

26-30 March 2007
Destin, FL

Butler, Bret W.; Cook, Wayne, comps. 2007. **The fire environment—innovations, management, and policy; conference proceedings. 26-30 March 2007; Destin, FL.** Proceedings RMRS-P-46CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 662 p. CD-ROM.

The International Association of Wildland Fire sponsored the second Fire Behavior and Fuels conference in Destin, Florida. The conference theme was "Fire Environment—Innovations, Management, and Policy." Over 450 attendees participated in presentations on the latest innovations in wildland fire management, examples of successful and maybe not so successful management practices, current and potentially future wildland fire policy and recent advances in wildland fire science. Special sessions focused on smoke management, wildland urban interface, fire induced tree mortality, and live fuels. Integrated into this conference was the Joint Fire Science Program Annual Primary Investigator meeting where cutting edge JFSP sponsored research was presented.

Sponsors

- International Association of Wildland Fire
- U.S. Department of Agriculture, Forest Service Rocky Mountain Research Station
- National Wildfire Coordinating Group – Fire Environment Working Team
- National Center for Landscape Fire Analysis
- National Predictive Services Group
- National Interagency Fuels Coordinating Group
- Fire/Air Issues Coordinating Group
- Joint Fire Science Program
- National Fire Plan
- National Weather Service
- Florida Division of Forestry
- U.S. Air Force, Eglin Air Force Base
- The Nature Conservancy

Conference Coordinators

- Mr. Wayne Cook, National Technology Transfer Specialist, Missoula Fire Sciences Laboratory, Rocky Mountain Research Station, U.S. Department of Agriculture, Forest Service
- Dr. Bret Butler, Fire Behavior Research Engineer, Missoula Fire Sciences Laboratory, Rocky Mountain Research Station, U.S. Department of Agriculture, Forest Service

Editors' Note

Peer technical reviews of manuscripts were obtained by the authors before submission. The views expressed are those of the presenters.

Cover Photo by Wayne A. Cook, August 19, 2002. Flat Tops Wilderness Area, White River National Forest.

You may order additional copies by sending your mailing information in label form through one of the following media. Please specify the publication title and number.

Telephone	(970) 498-1392
FAX	(970) 498-1122
E-mail	rschneider@fs.fed.us
Web site	http://www.fs.fed.us/rmrs
Mailing Address	Publications Distribution Rocky Mountain Research Station 240 West Prospect Road Fort Collins, CO 80526

Rocky Mountain Research Station
Natural Resources Research Center
2150 Centre Avenue, Building A
Fort Collins, CO 80526

The Fire Environment—Innovations, Management, and Policy

26-30 March 2007
Destin, FL

Contents

Introduction

Fire Behavior

Fuels Management

Smoke Management

Erosion Control and Land Treatments

Innovations

Communication and Collaboration

Appendix

The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service

Pesticide Precautionary Statement

This publication reports research involving pesticides. It does no contain recommendations for their use, nor does it imply that the uses discussed here have been registered. All uses of pesticides must be registered by appropriate State and/or Federal agencies before they can be recommended.

CAUTION: Pesticides can be injurious to humans, domestic animals, desirable plants, and fish or other wildlife—if they are not handled or applied properly. Use all pesticides selectively and carefully. Follow recommended practices for the disposal of surplus pesticides and pesticide containers.

This
page is
blank
on purpose

This page is blank on purpose

Introduction

This page is blank on purpose

Introduction
2nd Fire Behavior and Fuels Conference: The Fire Environment—Innovations, Management, and Policy

Wayne Cook and Bret W. Butler, Conference Co-Chairs and Proceedings Compilers

The 2nd Fire Behavior and Fuels Conference: Fire Environment – Innovations, Management and Policy was held in Destin, FL, March 26-30, 2007. Following on the success of the 1st Fire Behavior and Fuels Conference, this conference was initiated in response to the needs of the National Wildfire Coordinating Group – Fire Environment Working Team.

Fire management programs are designed to reduce risks to communities and to improve and maintain ecosystem health. The conference addressed recent innovations in technology, management and policy. The scope included not only the how to, but also the what and why of the fire environment. The more than 450 conference participants represented a wide range of organizations, disciplines, and countries. The conference program included workshops, invited speakers, oral and poster presentations, panels, and vendor displays. Each day began with invited speakers who presented a range of viewpoints. Topics included the psychology of wildland fire management, smoke and public policy, fire as an ecological process in wilderness areas, and fuels management policy and direction of U.S. Federal agencies. Panels addressed two key topics: "Extreme Fire Behavior – What is it?" and "The Human Element in Forest Fire Operations: Thinking Deciding, Acting, Learning." About 100 people took advantage of the optional preconference workshops that described and demonstrated computer systems, models, and methods that can be used in support of fire and fuels management. In addition to the six invited speakers, there were 159 oral and 73 poster presentations. Presenters described their experiences, findings, and ideas on topics including:

- modeling, risk assessment, and decision support systems
- fuel characterization and mapping
- fuel treatment and prescribed fire
- fire ecology and fire effects
- economics and biomass utilization
- communication and collaboration
- case studies

Forty-eight of the presenters elected to submit a paper for the published proceedings.Titles and authors of presentations without papers are listed in the appendix to give an indication of the scope of the conference.

The published proceedings is a partial record of the conference content. An important element was the interaction and sharing of information that occurred outside of the formal presentations. Many of those who responded to the after-conference survey listed "networking" as one of the most valuable aspects of the conference. They noted the mix of managers, researchers,

In: Butler, Bret W.; Cook, Wayne, comps. 2007. The fire environment—innovations, management, and policy; conference proceedings. 26-30 March 2007; Destin, FL. Proceedings RMRS-P-46CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 662 p. CD-ROM.

academia, practitioners, and policymakers. The field of fuels management will undoubtedly benefit from the many personal contacts made at the conference. Special thanks are owed to the organizing committee, who formulated the structure of the conference, and planned and implemented details of the conference. The conference was a success due to the contributions of many dedicated individuals.

Conference Co-Chairs:

- Wayne Cook, U.S. Department of Agriculture (USDA), Forest Service, Rocky Mountain Research Station (RMRS), Fire Sciences Lab, Fire Behavior Research, Missoula, MT
- Bret Butler, USDA, Forest Service, RMRS, Fire Sciences Lab, Fire Behavior Research, Missoula, MT

Invited Speakers:

- Susan Conard, National Program Leader for Fire Ecology Research, USDA Forest Service
- Joe Ferguson, National Incident Management Organization, Fire and Aviation, USDA Forest Service
- Michael Long, State Forester, Florida Division of Forestry
- William Paleck, Superintendent-Retired, Lake Chelan National Recreation Area, Ross Lake National Recreation Area, North Cascades National Park, U.S. Department of the Interior (USDI) Park Service
- Sally Shaver, Director Air Quality Standards Division, U.S. Environmental Protection Agency
- Karl Weick, Professor of Organizational Behavior and Psychology, University of Michigan

Conference Organizing Committee:

- Detlef Decker, Washington State University
- Bill Gabbert, International Association of Wildland Fire Executive Director
- Marc Titus Washington Department of Natural Resources
- Dan Jimenez, Fire Behavior Research, RMRS Missoula Fire Sciences Lab
- Robert Ziel, Michigan Department of Natural Resources
- Paul Sopko, Fire Behavior Research, RMRS Missoula Fire Sciences Lab
- Matt Jolly, Fire Behavior Research, RMRS Missoula Fire Sciences Lab
- Tim Swedberg, Joint Fire Science Program
- Louise Kingsbury, USDA Forest Service Research (retired)
- Kyle Shannon, Fire Behavior Research, RMRS Missoula Fire Sciences Lab
- Jason Forthofer, Fire Behavior Research, RMRS Missoula Fire Sciences Lab
- Jim Brenner, Florida Division of Forestry
- Colleen Finneman, USDA Forest Service, Region 1 Fire and Aviation Management
- James Furman, Eglin Air Force Base
- Dave Thomas, USDA Forest Service (retired), Renoveling consultant
- Mike Spaits, Eglin Air Force Base
- Paul Schlobohm, USDI Bureau of Land Management
- Zachary Prusak, The Nature Conservancy
- Pete Lahm, USDA Forest Service

Fire Behavior

This page is blank on purpose

Wildfires, Weather, and Productivity

Michel Louis Bernard[1] and Noureddine Nimour[1]

Abstract—*The object of this paper is to show the intercorrelations existing between statistics of wildfires (occurrences: N; areas burned: A), climatic parameters (precipitation: P; temperature: T) and net primary productivity: NPP. To this purpose, statistics of wildfires have been studied in several regions of the world, focusing on temperature and precipitation. The present analysis has been performed on French Mediterranean Departments (Bouches-du-Rhône, Hérault, and Var), Northern Ontario (Canada), Alicante Region (Spain), Yellowstone National Park –YNP-(USA), San Diego (California, USA). Concerning the temperature, the monthly analysis of fire occurrence shows two distinct periods with different fire production laws, both being of the Arrhenius type: the first one corresponding to the vegetation during the rest period, the second one during the vegetative production period. Concerning the precipitation, the monthly analysis of fire occurrence led to two distinct laws depending on the region climatic type (or eventually the seasonal characteristics). Thus, the monthly variation of fire occurrence (in log scale) is a linear increasing or decreasing function according to precipitation. In French Mediterranean Regions these expressions are bound to the rate of soil water extraction by the plant roots (a limiting step of plant production?). Out of the intrinsic importance of the presented results, in the field of primary productivity (dependence on Kelvin temperature) it brings a confirmation of the reality of our hypothesis on the role of the limiting steps of plant production in the rate of wildfire production.*

Introduction

Wildland fire studies on a statistical point of view are more fructuous in information than the individual determinist studies. They are the only ones allowing correlating wildland fires with intrinsic factors (nature and composition of vegetation, water content…) or extrinsic factors (precipitation, air temperature, wind, lightning…) given an area and period of time. In the first part of this document, we will discuss our studies of the dependence of fires occurrence and burnt area on meteorological data (precipitation and temperature).We will then show how correlations obtained can be representative of climate of some regions. That will finally lead us to show you how they are bound to vegetation productivity on an annual scale.

Wildfire and Climatic Parameters

Statistics of wildfires have been studied in several regions of the world, focusing on temperature and precipitation. The present analysis has been performed on French Mediterranean Departments (Bouches-du-Rhône, Hérault, and Var), Northern Ontario (Canada), Alicante Region (Spain), Yellowstone National Park –YNP-(USA), San Diego (California, USA).

In: Butler, Bret W.; Cook, Wayne, comps. 2007. The fire environment—innovations, management, and policy; conference proceedings. 26-30 March 2007; Destin, FL. Proceedings RMRS-P-46CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 662 p. CD-ROM.

[1] Research Scientist and Research Technician, respectively, Laboratoire de Chimie Macromoleculaire, Université de Provence. Lead author ml-bernard@numericable.fr

Wildfires and Precipitation

Past works—Many works have been done on the influence of water content of plants on their flammability and the propagation of wildland fires. On the contrary, only a few thorough studies have been published on the role of precipitation on wildland fires.

Trabaud (1980) has studied occurrence of fires of *Brachypodium Ramosum* in the Montpelier garrigue. According to him, rainfall is the more important climatic factor that influences occurrence of fire. It is not really the total quantity of rainfall that is a stopping event, but rather its distribution mode. According to him, the number of fires is an exponentially decreasing function of precipitation. However, the statistical curve he showed expresses a 1/X function, not an e^{-x} function.

Trabaud has looked for predictions of fire occurrence taking account of rainfall regime, and particularly of the number of days without rain that increases risk of fires. He proposed a model that has shown that the risks of fire increase linearly as dry periods are longer.

Douguedroit (1992) pointed out the close relation between precipitation and wildland fires in the Mediterranean region. Precipitation in summer controls actual evapo-transpiration (AET) but no correlation analysis between these factors is proposed.

Latham and Rothermel (1993) have investigated the possibility that a useful probability of fire stopping precipitation could be developed from historical weather records. Persons familiar with weather and fire behavior suggested a fire stopping precipitation criterion of "at least 0.5 inches of precipitation in 5 days or less." Using data from weather stations in the Northern Rocky Mountains, USA (daily precipitation data for the period between 1970 and 1985) they found that the Weibull probability distribution was an excellent fit for the problem. The method can be applied to other "*fire stopping criteria*" using the same techniques.

Viegas and Viegas (1994) have related the total area burned yearly in Portugal (from 1975 to 1992) to rainfall during particular periods of the year. The best correlation: annual burned area – precipitation, concerns the modified precipitation observed in Coïmbra from June to September of each year, showing that it is possible to use data from a single weather station to represent rainfall in a wider area.

Forgeard (1994) has related the monthly number of fires in the Lande Bretonne (west of France) to precipitations for the years 1976 to 1993. Their number (Y) is correlated to monthly precipitation (X) according to the equation:

$$Y = 98.968 + 1.7885\ X\ (R^2 = 0{,}781)$$

Daily correlations: lightning fires in Northwestern Ontario—Wildland fires may have different possible causes, most of them being human causes. To avoid any influences coming from various causes we have taken account in a preliminary study only a natural cause: lightning ignited fires.

A number of Canadian fires are lightning ignited fires: according to Boulard (1993) they represent a proportion of 30 to 50 percent of fires.

Flannigan and Wotton (1990) have investigated the relationship between lightning activity and the occurrence of lightning-ignited forest fires in the Northwestern region of Ontario. They found that Duff Moisture Code and the multiplicity of the negative lightning discharges were the most important variables for estimating the number of lightning ignited fires. Fires have been counted with corresponding values of local precipitation and temperature. From data files provided by the authors and completed by the Ontario Ministry of Natural Resources (Ward 1994), we have analyzed the data relating to UTM:15 zone, to be 1,152 fires accounted in 1988.

In this region, in a log scale (fig. 1), the variation of fire occurrence is a linear increasing or decreasing function of precipitation. The distinction between the two regimes has been done comparing temperature periods:

$\text{Log N} = 1.019 + 0.0622\text{P}$ *For humid and warm period*

$\rightarrow \quad N = 10.44\ e^{+0.143P}$

$\text{Log N} = 2.739 + 0.2517\text{P}$ *For dry and cold period*

$\rightarrow \quad N = 548\ e^{-0.579P}$

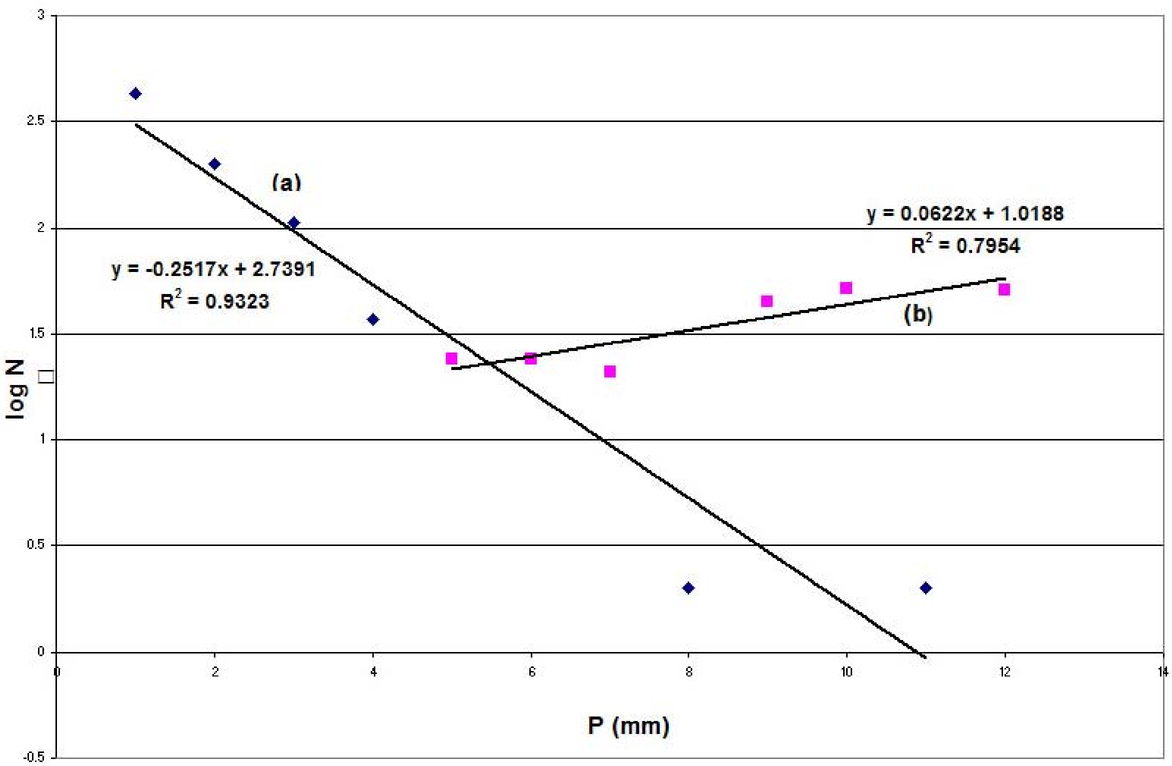


Figure 1—Log N = g(P). Ontario, UTM15, 1988.

Humid period for precipitation must be associated to warm period for temperature. So precipitation highly contributes the evapo-transpiration during this period (positive exponent). Dry period for precipitation must be associated to cold period for temperature. So precipitation contributes to evapo-transpiration at a low rate.

The humid and warm periods approximately correspond to the periods of vegetation production in this region (sub artic region).

Daily correlations: wildfires in West Var (1973)—Olivier (1975) has studied the role of vegetation and ecological factors on the "Basse Provence" region wildfires. Individual wildfires were registered from area as low as 0.01 ha over the whole year 1973.

Occurrence of fires and precipitations were summarized by half a month values (fig. 2). Again we observe the same type of behavior:

(1) $\text{Log } N = 0.6306 + 0.0107P$ *For humid and cold period*
(2) $\text{Log } N = 1.1716 + 0.0125P$ *For dry and warm period*

The warm and dry period approximately corresponds to the period of vegetation production in this region (Mediterranean region).

Such typical relations have been found in other Mediterranean regions such as:

- Languedoc-Roussillon region (data from Rambal 1984):

(3) $\text{Log } N = 2.8961 – 0.0047P$

- Alicante region (data from Terol 1987):

(4) $\text{Log } N = 1.537 – 0.029P$

So the monthly occurrence of fires in Mediterranean regions in the warm period is a function of the exponential form:

$$N = \text{Constant} * e^{-\alpha P}$$

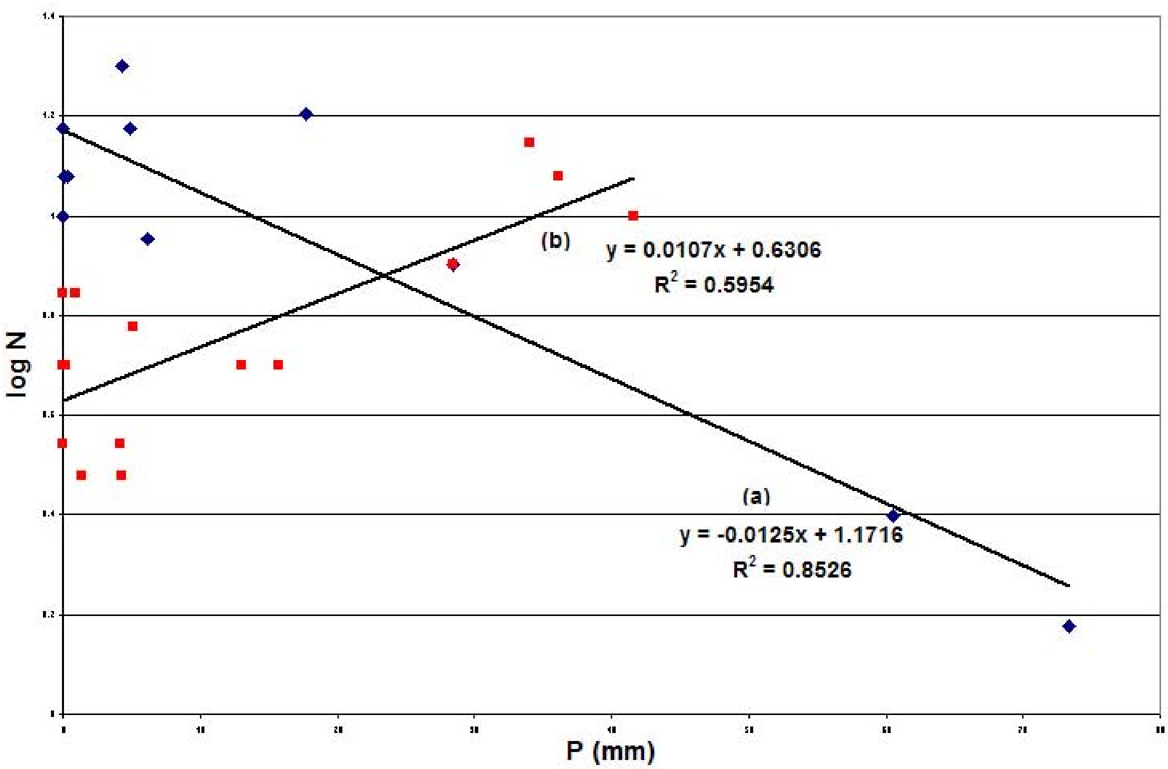


Figure 2—Log N = g(P). West Var, 1973.

In order to interpret these equations, it is necessary to examine the dynamics of water in the ecosystem, that is to say, soil water balance and the relative importance of its different terms with season (particularly during the summer season, in the Mediterranean regions; Humbert and Najjar 1992).

Rambal (1984) has studied soil water balance and water uptake characteristics by *Quercus Coccifera L*, which cover in the garrigue more than 100,000 ha in the French Mediterranean region.

Water balance equation: $\Delta S = P * R * AET * D$

Where ΔS is the daily change in stored water, P is the precipitation, R is the surface runoff, AET is the actual evapo-transpiration and D is the flow of water at the bottom of the root zone measured in mm/day.

The study of water balance during every year shows that when yearly precipitations are less than 578 mm, deep drainage loss is negligible and almost all the precipitations infiltrating the soil are lost by evapo-transpiration. Studying the water uptake at different deepness in the summer, Rambal proposed a relation between the relative deep uptake and the precipitation. According to Rambal, precipitation modifies relative water uptake Y (%) according to an exponential law:

$$Y = 25.7 * e^{-0.006 * x} \qquad r^2 = 0.963$$

X being precipitation in June and July.

This relative water uptake is also the expression of relative actual evapo-transpiration, which is the equivalent of photosynthetic fixation of carbon within the same period (Frontier and Viale 1991; Ramade 1994). Photosynthetic activity on plants leads to formation of new twigs and chemical modifications of old ones, then to production of fire sensible biomass.

Interannual occurrence of fires in Var area—Yearly occurrences of fires have been correlated to precipitation with the data of Var area, for the period 1974 to 1986 (Promethee Databank). Several 1-year periods have been tested, and the best result was found taking a period starting in July. The correlation equation is:

$$\text{Log } N_{annual} = 2.90 - 0.000365P_{annual} \qquad \text{with } r^2 = 0.98$$

Thus, we can conclude that in Mediterranean regions, during the vegetation production period, occurrences of wildfires (monthly or yearly) are regulated by the deep water uptake rate of plant roots.

Wildfires and Temperatures

Quantitative effects of temperature on wildfire statistics have not been developed as for precipitation. In order to approach the problem we appealed to chemical kinetics laws.

Considering the parameters of fire occurrence N or area burnt A, during a defined time interval and in a given region as reaction rates in chemical kinetics, we studied their possible dependences to Arrhenius factor E/RT, E being the activation energy of the reaction, R the gas constant, and T Kelvin temperature (compare: lightning fires dependence on precipitation and temperature, Bernard 2004c).

Lightning fires in Northwestern Ontario—Coming again to Northwestern fire data (fig. 3), we observe two Arrhenius plots, the first being the warmest period and the second the coldest one. During the vegetation production period (warmest period) the activation energy corresponds to photosynthesis. During the vegetation rest period (coldest) the activation energy corresponds to U.V.B. energy.

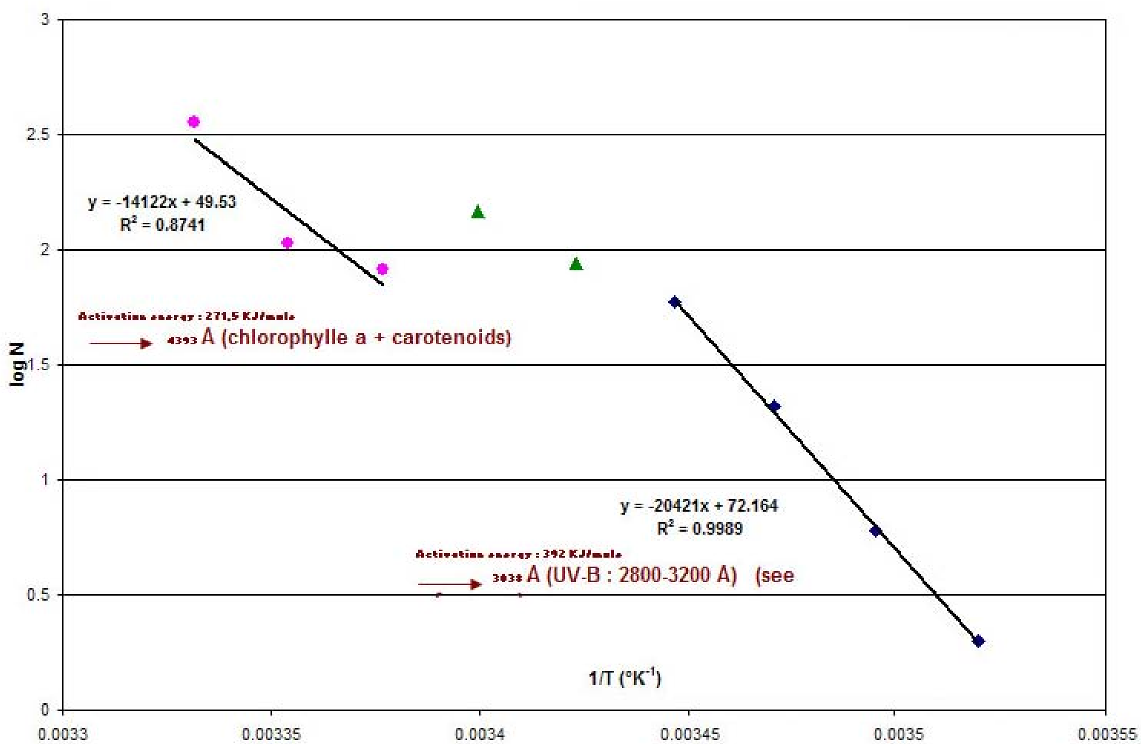


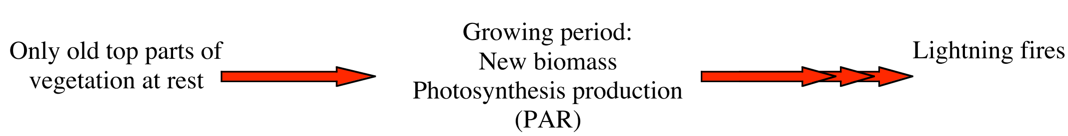
Figure 3—Log N = f(T). Ontario, UMT 15, 1988.

Log N = 49.52 – 14,122 / T → **Warmest period**
E_{act} = 271.5 KJ/mol. → 439.3 nm (Chlorophyll A)

Log N = 72.164 – 20421 / T → **Coldest period**
E_{act} = 392 KJ/mol. → 303.8 nm (U.V.B)

In analogy with the chemical kinetics laws, to interpret those results, we need to use the law of the bottleneck (the rate of the global reaction is determined by the slowest rate among the different successive reactions that compose it).

Warmest period



Rate of global processes (N) controlled by rate of the biomass production

Coldest period

Vegetation at rest (before or after growing period) → Lightning fires

Rate of global processes (N) controlled by U.V. flux

Wildfires in Bouches-du-Rhône area 1986—Two Arrhenius linear plots are observed for monthly wildfire in Bouches-du-Rhône area (fig. 4) with a good square correlation coefficient (**R^2 = 0.93**), one for the summer period and another for the winter period. These results must be interpreted using the same argument as for the wildfires in Northwestern Ontario.

Other equations of Arrhenius type have been observed for Mediterranean type regions:

- Languedoc-Roussillon area (temperature in Montpellier)

Log N = –5797 * 1 / T + 22.034 (R^2 = 0.461)

- Southern California, USA, 2005 (temperature in San Diego)

Log N = –28674 * 1 / T + 99.04 (R^2 = 0.497)

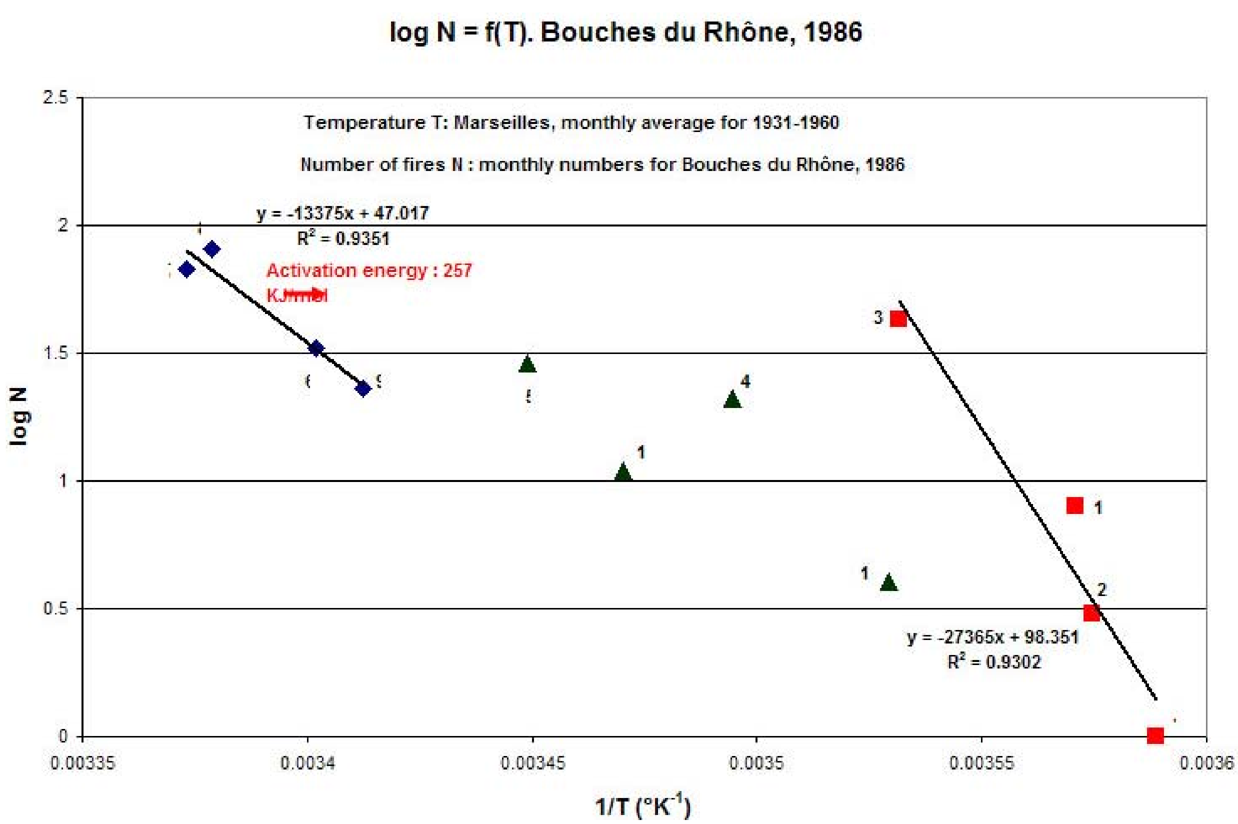


Figure 4—Log N = f(T). Bouches-du-Rhône, 1986.

Annual Wildfires in Yellowstone National Park—They have been extensively analysed as much on area burnt as on wildfire occurrences, and as much on lightning caused fire as on human ones (Douglas 1975; Romme 1989; Despain 1998). See Bernard (1998a): interpretation of fire intensity in Yellowstone National Park for the 1700-1990 period.

Most of the wildfires in YNP are class 3 fires (fig. 5). We observe the same Arrhenius law with the lightning fires (fig. 6) on the annual occurrence criterion.

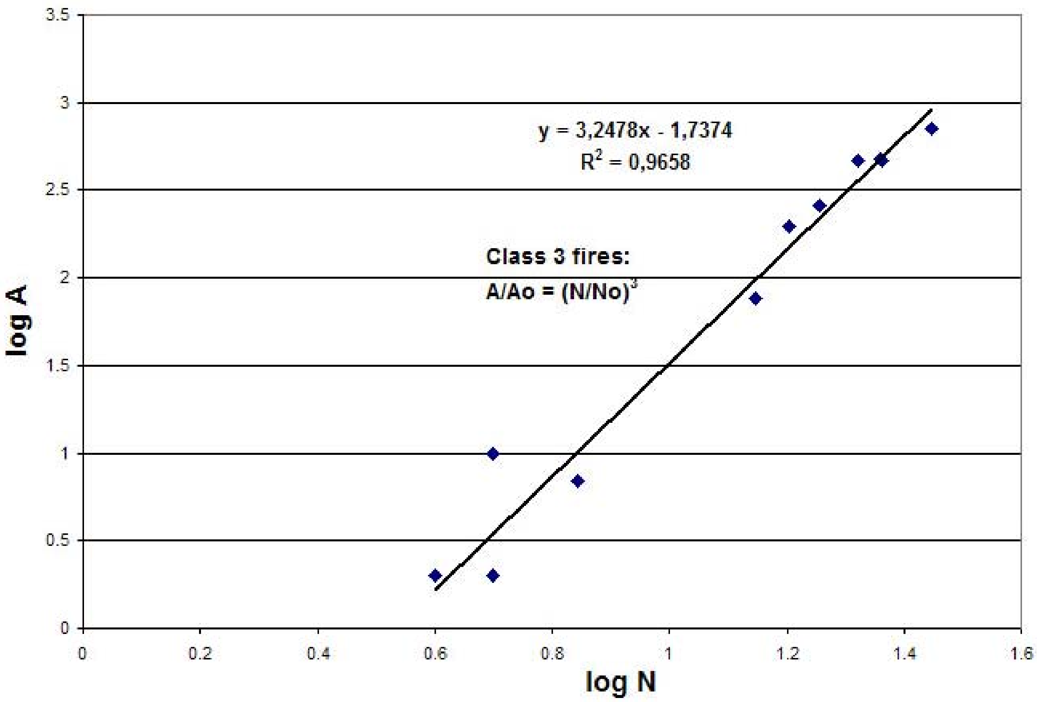


Figure 5—Yellowstone National Park: log A =f(log N). Human caused fires. Years: 1933, 1934, 1940, 1947, 1948, 1949, 1953, 1954, 1955, 1960, 1967, 1968.

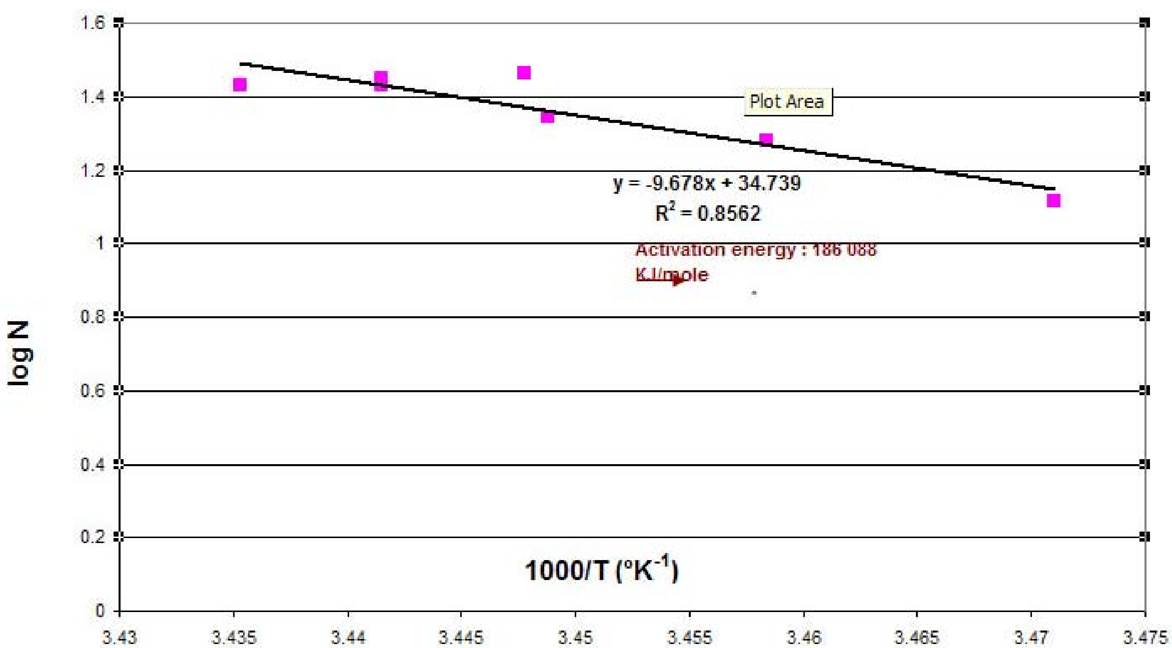


Figure 6—Yellowstone National Park: logN= f(T) Lightning fires. Years: 1933, 1948, 1949, 1952, 1960, 1961, 1963.

For the human caused fires, the Arrhenius law is verified for both annual occurrences and area burnt criterion (fig. 7).

Thus, we can conclude that the rate of photosynthetic radiations regulates the monthly occurrence of fires during the vegetation production period and yearly occurrences of fires and area burnt at the interannual scale.

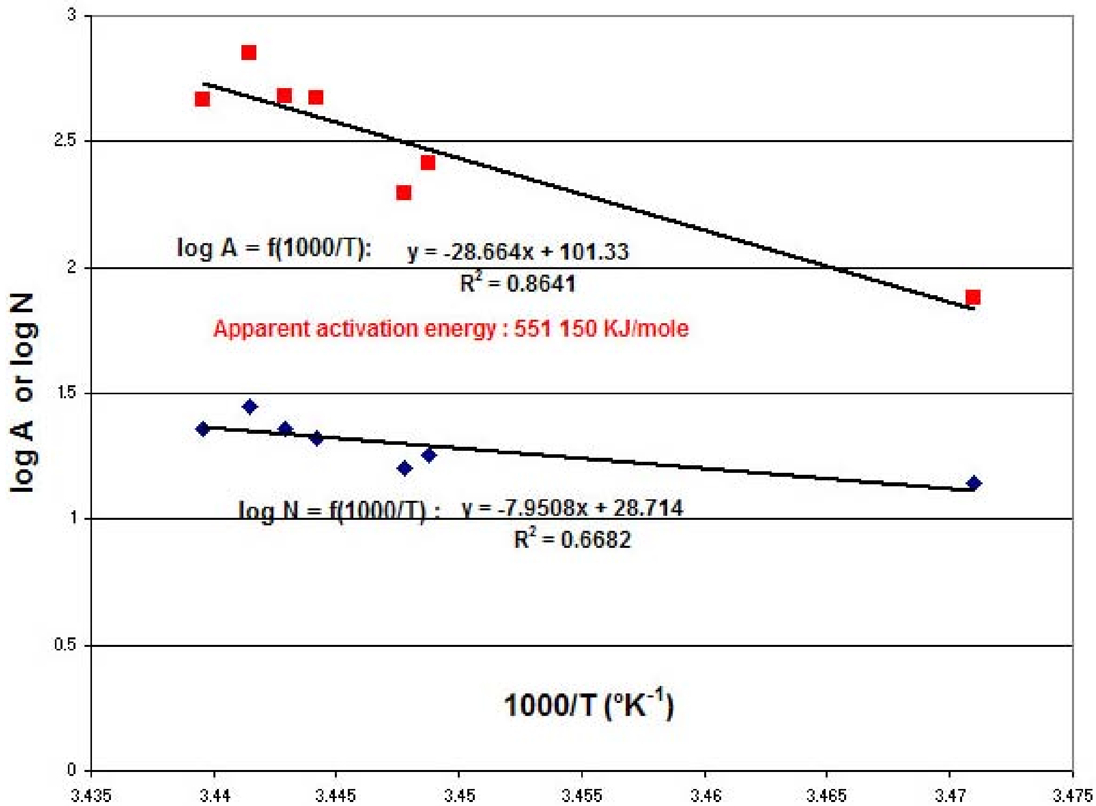


Figure 7—Yellowstone National Park: log A = f(T) and log N = f(T). Human caused fires. Years : 1933, 1934, 1940, 1948, 1949, 1953, 1960.

Wildfire and Climate

During the vegetation period we define the occurrence of fires as function of variable P and T.

(1) Log N = a + b * P
(2) Log N = c – d / T

We observe the following conditions on the constants:

- c : c > 0,
- d : d > 0,
- a : a > 0,
- b : b > 0 (NW Ontario Climate)
  b < 0 (Mediterranean type Climate)

In the equation 1, N is univocal of P, in equation 2, N is univocal of T. P and T are measured data or data taken from meteorological stations and are interdependant in the vegetation production period.

Identifying the two equations, we get:

(3) P = (c–a) / b + d / (b *T)

We now need to compare this relation (3) to real temperature and precipitation data of different regions.

Wildfires in Northwestern Ontario

Referring to the figure 1 for precipitation and figure 3 for the temperature, here are the equations expressed with the real data from Northwestern Ontario:

(1') Log N = 1.019 + 0.0622P
(2') Log N = 49.5 – 14,122 / T

By identification, we get:

(3') $P = 780 + 0.227 * 10^6 / T$

To compare those data, we choose the 1988 meteorological data from Sioux Lookout station in Ontario, and try to demonstrate this relation monthly from May to August 1988. Figure 8 shows what we found for each studied month. We found an equation that even has a **correlation coefficient equal to 1**:

$P = 3,607 – 1.044 * 10^6 / T$ **(R^2 = 1)**

We observe:

- Climate data from Sioux Lookout verify the linear correlation P, 1/T.
- Precipitation from Sioux Lookout is found 4.6 times larger than from the N.W. Ontario region.

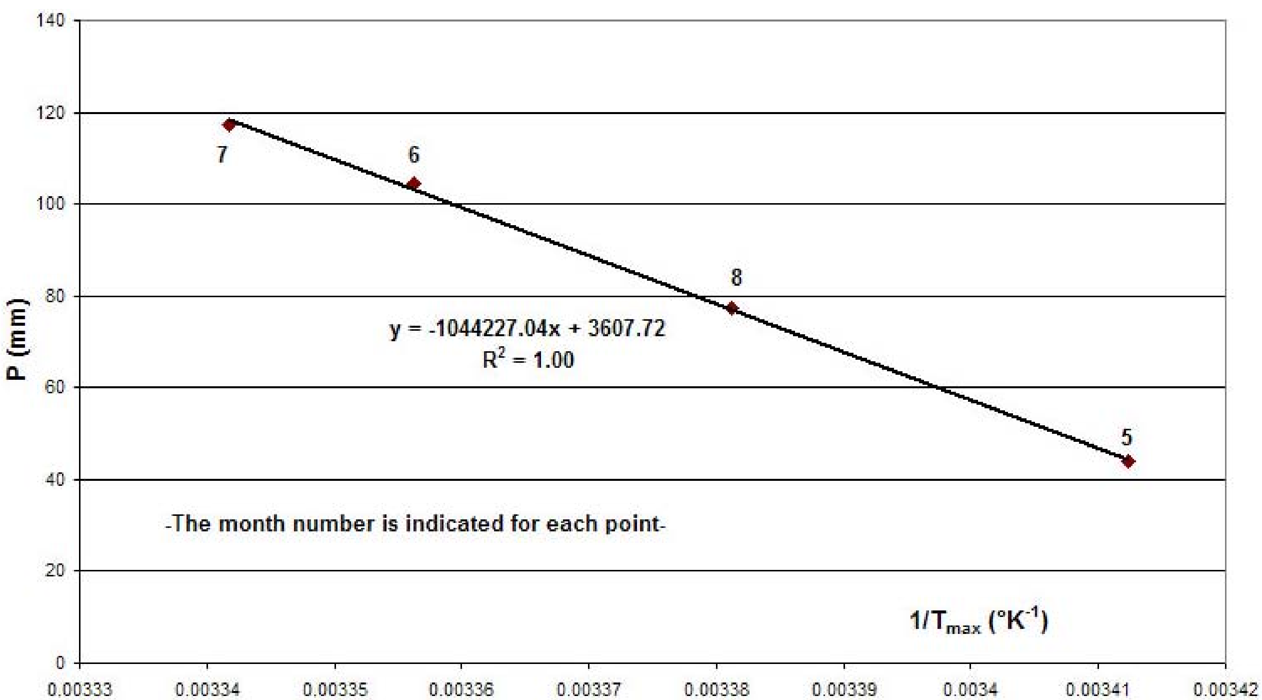


Figure 8—Climatologic chart of Ontario, UTM 15, Canada at Sioux Lookout meteorological station. P = f(Tmax). May-August 1988.

Wildfires in the Languedoc-Roussillon Area

The next equations (1'') and (2'') are explained in a deeper way in a former publication (compare "Application of the concept of climatologic chart to Mediterranean climate variability," Bernard and Nimour 2005a).

Here are the equations expressed with the real data from Promethee database and from Rambal (1984). For Montpellier, we found:

(1'') $\text{Log } N = 2.896 - 0.0047\, P$
(2'') $\text{Log } N = 22.034 + 5{,}797 / T$

By identification, we get:

(3') $P = -4{,}071.91 + 1.234 * 10^6 / T$

To compare those data, we choose the average values of meteorological data from Montpellier station in Languedoc-Roussillon (the average values of each month are calculated over the 1964 to 1982 period for precipitation, and the 1980 to 1982 period for temperatures). We try to demonstrate this relation monthly from July to October. Figure 9 shows what we found for each studied month. We found an equation that even has a **correlation coefficient equal to 0.9995**:

$$P = -3{,}932.7 + 1.00 * 10^6 / T \qquad \mathbf{(R^2 = 0.9995)}$$

The agreement is very satisfactory: Climate data from Montpellier verify the linear correlation P, 1/T

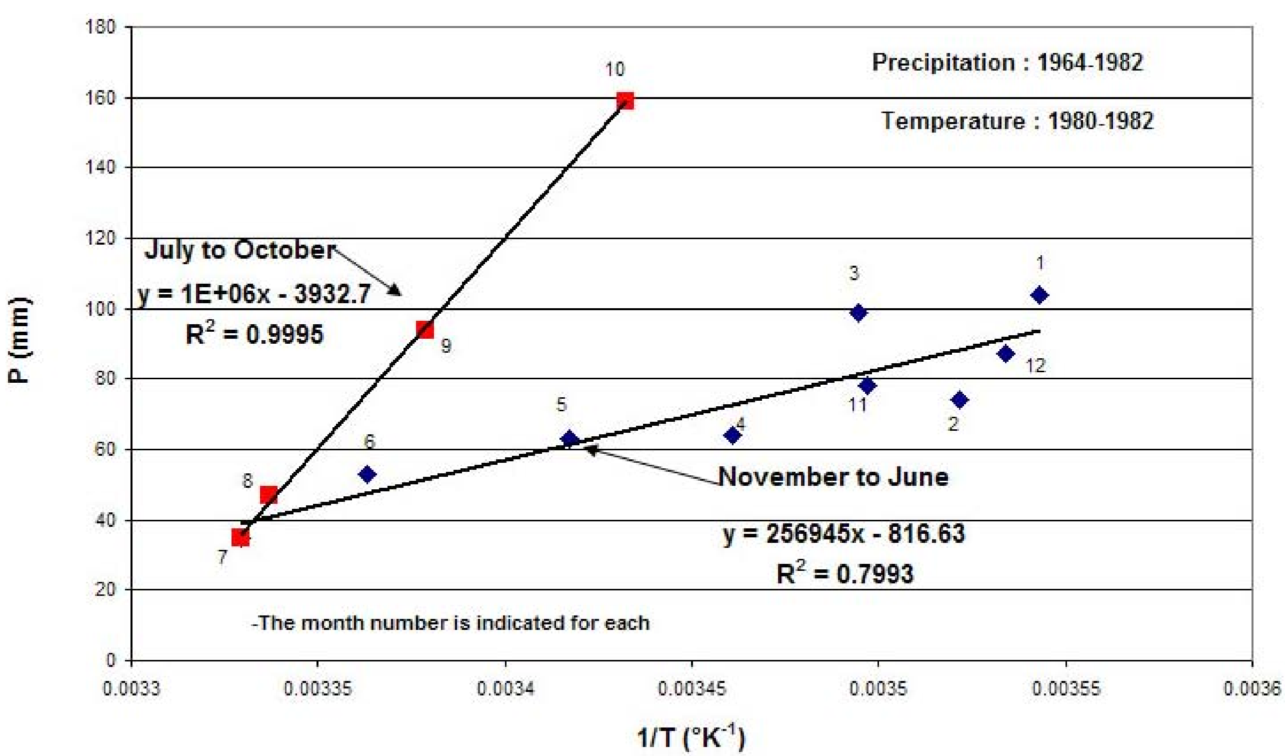


Figure 9—Climatologic chart of Montpellier.

A Concept of Climatologic Chart

Other reconstructions of climate from wildfire occurrence have been stated. That confirms the generality of the method. So we introduced the concept of climatologic chart ("A concept of climatologic chart," Bernard and Nimour 2004a), which is based on the law of interaction between the vegetation, the soil, the water, the atmosphere, and the solar radiations.

Climatologic charts could be more useful than historic representations of climate characteristics (climatogram, Emberger or Gaussen ombrothermal diagrams) to build a new classification of climate in order to perceive any possible climate changes (compare "Application of the concept of climatologic chart to Mediterranean climate variability," Bernard and Nimour 2005a).

To illustrate the prior statement, we can refer to figure 10 as an example of semiarid climate.

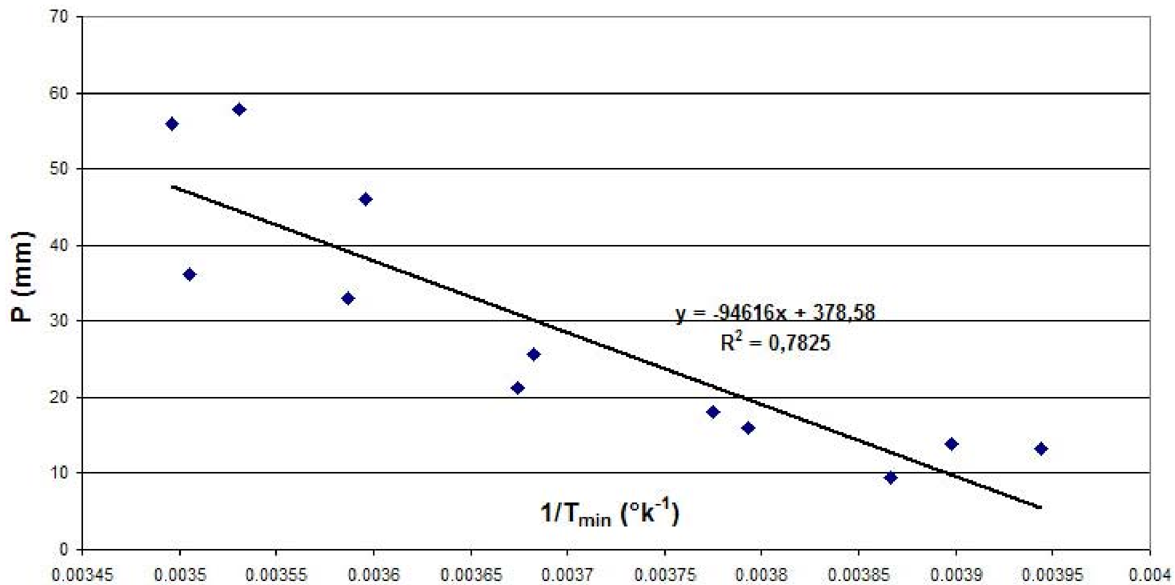


Figure 10—Climatologic chart of Willistone (North Dakota) January-December 1971 to 2000.

Hyper-Mediterranean Climate in San Diego (CA, USA)

The San Diego climate belongs to west-facing continents climate, a particular case of Mediterranean climate that we'll called "Hyper-Mediterranean." Among this type of climate we also find Mexico, Chile, South Africa (Le Cap), West Australia (Brisbane).

They are characterized by an attenuation of precipitation along the year compared to precipitation we observe in Mediterranean climate. The expression of this attenuation is of an exponential form and leads to a new expression of the climatologic charts:

$$(4) \quad \text{Log } P = A / T - B$$

A and B being characteristic constant of the meteorological station.

In order to study the interaction between wildfire and climate data of San Diego, we chose the year 2005 because its summer was abnormally warm. Monthly occurrence of fires in southern California was taken from N.I.C.C. 2005 data. As shown in figure 11, the equations are:

$$\text{Log } N_{2005} = -1.4202 \text{ Log } P + 3.34$$

$$\text{Log } N_{2005} = -28{,}674 / T + 99.04$$

The identification gives us:

$$(4') \quad \text{Log } P = 20{,}190 / T - 67.38$$

Compared to climatologic chart of San Diego 2005, the agreement is satisfactory:

$$\text{Log } P = 16{,}835 / T - 56.012 \qquad (R^2 = 0.46)$$

In order to study a possible climate change in San Diego, we established its climatologic chart for two annual periods 1927 to 1932 (a) and 1995 to 2004 (b):

$$\text{(a)} \quad \text{Log } P = 30{,}823 / T - 104.33 \qquad (R^2 = 0.87)$$

$$\text{(b)} \quad \text{Log } P = 12{,}028 / T - 40.23 \qquad (R^2 = 0.73)$$

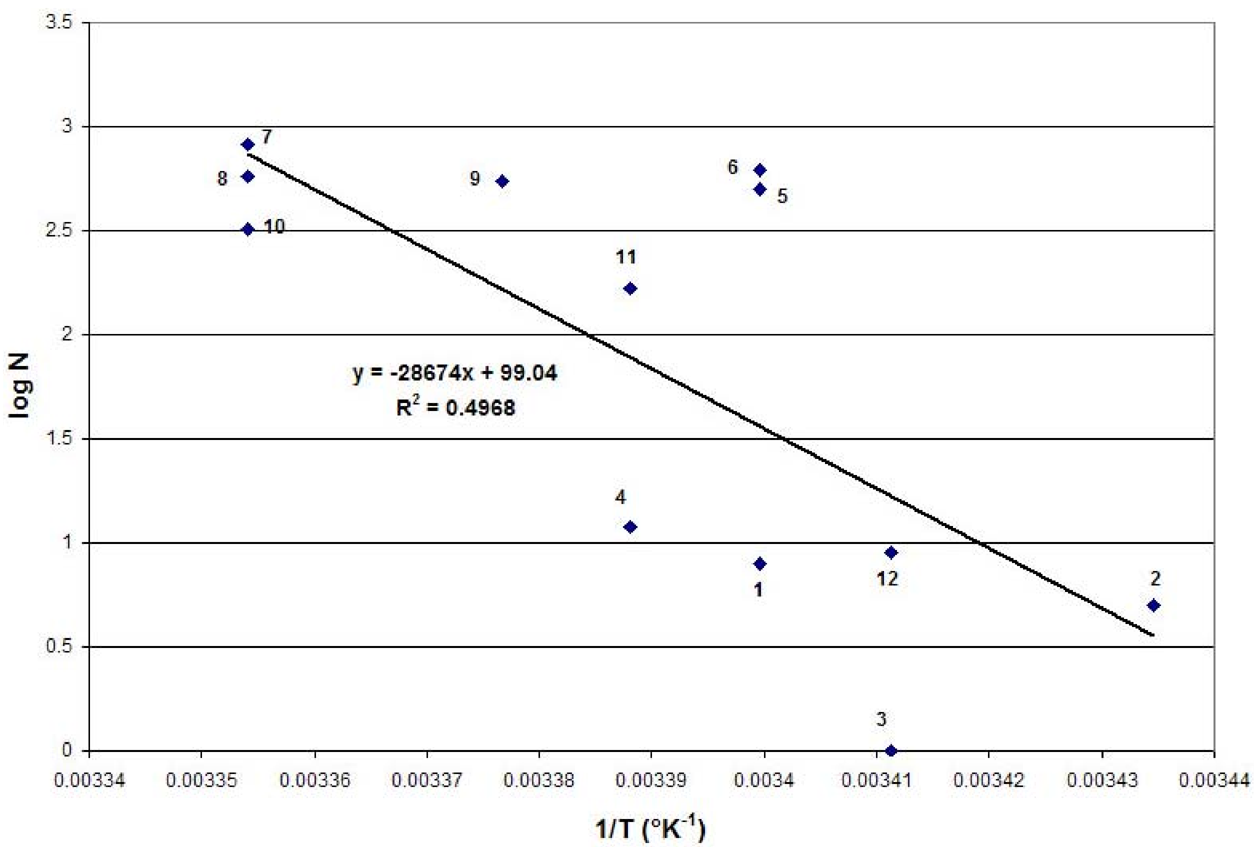


Figure 11—San Diego, 2005. Log N = f(T).

In analogy with the equations found for the Mediterranean climate, we will use for the Hyper-Mediterranean one, the next method of reconstruction:

$$(1) \quad \text{Log N} = a + b * \text{Log P}$$

$$(2) \quad \text{Log N} = c - d / T$$

Identifying the two equations, we get:

$$(3) \quad \text{Log P} = (c-a) / b + d / (b * T)$$

Comparing the coefficient of the 1927 to 1932 period to the 1995 to 2004 period, we observe:

- The only variation of the “b” term. A 61 percent reduction of term “b” expresses the increasing value of aridity in the San Diego climate.
- A stability of the “d” term (containing the activation energy).

Wildfires and Global Warming

A particular interest for the effect of temperature on wildfire comes from global warming. Recent well documented publications of Westerling (2006) and Running (2006) analyze the different causes of increasing wildfire activities with global change, particularly in the Western United States of America.

In our own analyses of large wildfires in southern California in October 2003 (Bernard and Nimour 2004b), we pointed out an abnormal temperature rise in the region some days before the start of large landfires (Bernard and Nimour 2004d).

Conversely, the statistics of annual fires in Yellowstone National Park (1700 to 1990) show no fire during the little ice age (compare “Interpretation of fire intensity in Yellowstone National Park for the 1700-1990 period,” Bernard 1998a).

Using the Arrhenius models of occurrence of fire and burnt areas:

$$\text{Log N}_2 - \text{Log N}_1 = - E^n_{act} / (2.3\ R)\ (1 / T_2 - 1 / T_1)$$
$$\text{Log A}_2 - \text{Log A}_1 = - E^n_{act} / (2.3\ R)\ (1 / T_2 - 1 / T_1)$$

A “theoretical” evaluation of the effect of global warming on natural forest fire was performed in 2004 (table 1). Different cases have been considered according to the two different fire classes (class 1 and class 3) and the two natures of control (UV lightning and PAR)

Table 1—Implication of global warming on natural forest fires.

Remarks	ΔT (°C) (t_0 = 21°C)	Control by UVB E_{act} = 392 KJ/mole		Control by PAR E_{act} = 271.5 KJ/mole	
		Coefficient for N or A [a]	Coefficient for A [b]	Coefficient for N or A [a]	Coefficient for A [b]
	0	1	1	1	1
	+0.5	1.3	2.23	1.20	1.44
Reference : 1900-2000 (Papadopol 2000)	+0.77	1.5	3.50	1.33	2.35
ESTIMATIONS 21st century	+2	2.9	25.3	2.10	9.26
	+5	13.72		6.12	
Extreme thermal event	+10	192	(Re-evaluation of basic hypothesis)		
Little ice age (no sunspot)	–2	0.33	0.04	0.48	0.1

[a] Class 1 fires : Δ log A = Δ log N
[b] Class 3 fires : Δ log A = 3 Δ log N

Productivity and Climate Parameters

Net primary productivity, biomass, and associated environmental variables are now publicly available for 53 detailed study sites, of which more than half have data for belowground biomass or biomass dynamics. Aboveground NPP ranges from 35 to 2320 $g.m^{-2}.year^{-1}$ (dry matter) and total NPP from 182 to 3538 $g.m^{-2}.year^{-1}$. These data are available from the Oak Ridge National Laboratory Distributed Active Archive Center (Scurlock and Olson 2002).

According to Lieth and Whittaker (1975), the range of NPP in $g.m^{-2}.year^{-1}$ is: for tropical rain forest 1000 to 3000, warm temperature mixed forest 600 to 2500, Tundra 60 to 1300, Mediterranean sclerophyll forest (chaparral) 250 to 1500.

According to Gray (1982), when he studied productivity in southern California, the annual aboveground primary production in *Ceanothus Chaparral* was 1056 $g.m^{-2}.year^{-1}$ and in Costal Sage scrubs 355 $g.m^{-2}.year^{-1}$.

We will refer for our studies to the original works made by Lieth and Whittaker (1975) on modeling of the primary productivity of the world.

Lieth and Whittaker Data

Lieth and Whittaker (1975) have summarized the net primary productivity of four large zones in the world, each of them containing from 12 to 20 ecoregions with their climatic data of precipitation in millimeters and temperatures in Celsius degrees.

For each zone, we analyzed the correlation between net primary productivity with precipitation and with Kelvin temperature according to the Arrhenius term (table 2). Identifying the two correlations, we obtain an expression of precipitation as function of 1 / T (table 3). For the three first regions, the agreement is satisfactory in spite of their low square regression coefficients.

We have particularly examined the fourth region results, which has the best square regression coefficient. In this zone, the net primary productivity is among the highest of the world, up to 4,000 gr per square meters by year (Lieth 1962).

Table 2—Net primary productivity (NPP) as functions of precipitation (P) and temperature (T).

Zone	NPP = f(P) NPP in $g/m^2.year$; P in mm	NPP = ϕ(T) T in Kelvin
1	NPP = 0.528 P + 727.3 R^2 = 0.24	NPP = –2.10^6 (1/T) + 7 881 R^2 = 0.23
2	NPP = 0.4651 P + 858.8 R^2 = 0.11	NPP = –2.10^6 (1/T) + 8 403 R^2 = 0.11
3	NPP = 0.849 P + 356.7 R^2 = 0.19	NPP = –2.10^6 (1/T) + 6 603 R^2 = 0.20
4	NPP = 0.710 P + 911 R^2 = 0.46	NPP = –6.10^6 (1/T) + 22 074 R^2 = 0.65

Table 3—Climatologic charts from productivity and from climate data.

Zone	Chart from productivity $f(P) = \phi(T)$	Chart from climate data
1[a]	$P = -3.79\ 10^6\ (1/T) + 13\ 554$	$P = -3\ 10^6\ (1/T) + 12\ 832$ $R^2 = 0.79$
2	$P = -4.3\ 10^6\ (1/T) + 16\ 229$	$P = -4\ 10^6\ (1/T) + 15\ 098$ $R^2 = 0.79$
3	$P = -2.35\ 10^6\ (1/T) + 7\ 348$	$P = -2.10^6\ (1/T) + 6\ 603$ $R^2 = 0.20$
4	$P = -8.44\ 10^6\ (1/T) + 29\ 782$	$P = -5.10^6\ (1/T) + 19\ 454$ $R^2 = 0.57$

[a]Excepted October data.

So the net primary productivity of region 4 as function of temperature is:

$$P_2 - P_1 = 6 * 10^6 (1 / T_2 - 1 / T_1)$$

P expressed in g/ m^2/year and T in Kelvin degrees.

In the same publication, Lieth and Whittaker (1975) proposed an empirical equation of productivity Y as a function of Celsius degrees X:

$$Y = 3{,}000 / (1 + e^{1.315 - 0.119X})$$

Converting temperature data from Celsius to Kelvin degrees, we obtain an expression of productivity containing an Arrhenius term:

$$P_2 - P_1 = \text{Constant}\ (1 / T_2 - 1 / T_1)$$

Taking 10 values of temperature between –13 °C and +28 °C, we obtain an Arrhenius law of net primary productivity with a **square correlation coefficient very close to 1** (fig. 12).

$$P = 5*10^6 / T + 19{,}320 \qquad \mathbf{(R^2 = 0.979)}$$

Wildfire Net Primary Productivity and NDVI

The values of the normalized difference vegetation index (NDVI) extracted from satellite sensor data acquired by the National Oceanic and Atmospheric Administration's Advance Very High Resolution Radiometer (NOAA – AVHRR) have often been used for estimating forest fire risks.

According to Fang and others (2001), to examine the relationship between variability of NPP and precipitation at a broad scale, a long-term NDVI data set coupled with a historic climate data set constitute a useful and powerful data source, because NDVI data are strongly correlated with terrestrial NPP.

The relative greenness (R.G.) was described by Burgan and Hartford (1993) as expressing how green each cell is relative to the range of greenness. Relative greenness, which has been used by Burgan and others (1998) for the evaluation of fire potential index (F.P.I.), indicates that it is a potentially valuable fire management tool for land management agencies.

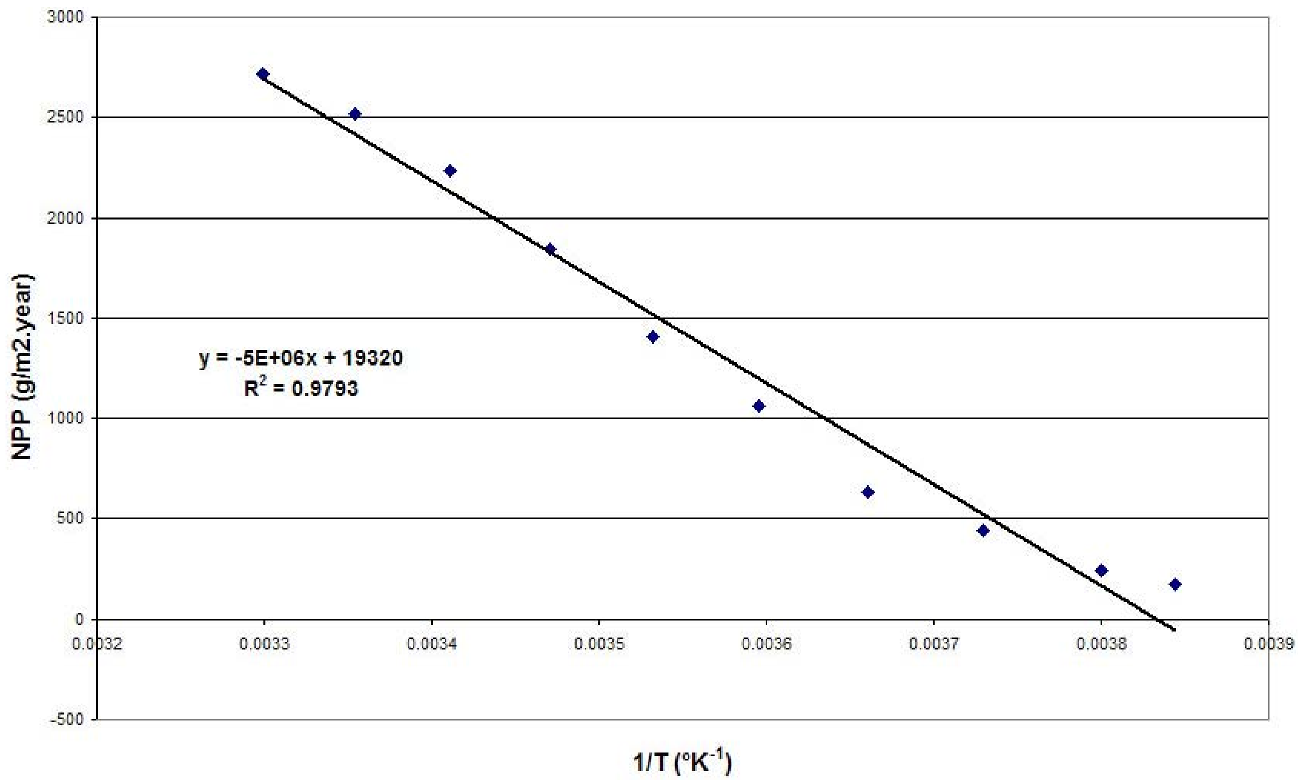


Figure 12—NPP = f(1/T). Data from Lieth and Whitaker (1975).

Gabban and others (2006) proposed a use of a new index referring to the dynamic relative greenness index (DRGI), to consider the interannual variability of NDVI at each precise location within the studied region. It was computed over the European Union countries and tested in Spain, France, and Italy. DRGI values and the number of fires were fitted using an exponential model. The testing of the DRGI over the 13 years showed a high correlation (R^2 = 0.94) between the number of fire outbreaks and the level of risk determined by the index.

So, this statement introduces the number of fires on a logarithmic form as a linear increasing function of DRGI.

Conclusions

It was established that the fire monthly frequencies are linearly correlated with precipitation. With regard to the temperature, the fires frequencies are narrowly correlated with the Arrhenius factor (1/T, T in Kelvin degrees) translating the existence of a regulating photochemical activation phenomenon (PAR or UVB according to the season). All these correlations can be found on a multiannual scale.

The reconstruction of the studied area climate can be carried out by identifying the expressions of the frequency of fires in function of precipitation and temperature. We proposed the concept of "climatologic chart" (Bernard and Nimour 2004) starting from such reconstruction process. This graphical representation method of the “climatologic chart” that we introduced starting from the climate data, P= F (1/T) is fully justified by the highlighted vegetation production laws.

Indeed, the net primary productivity is expressed in function of precipitation or temperature, through laws similar to those found on the fires frequency in log scale on an interannual scale. That brings an answer to the questions that we had on the role of the biomass production in the fires frequency laws. Moreover, the NDVI and its interannual variability, which are closely linked to the vegetation production and the fires statistics, still reinforce this similarity.

The proposed model set will constitute valuable tools for the study of the climatic changes and their repercussions on the fires regimes, aridity, and stability of vegetation communities and may contribute to developing new fire management strategies as expressed in the San Diego declaration on climate changes and fire management.

References

Bernard, M.L. 1998a. Interpretation of fire intensity in Yellowstone National Park (1700-1990). Lecture at Y.N.P., May 29 1998; USA.

Bernard, M.L. 1998b. Wildland fires, sunspot and solar flux: a tentative of correlation. 3rd International Conference on Forest Fire Research, 14th Conference of fire and Methodology, 16-20 November 1998; Coimbra, Portugal.

Bernard, M.L.; Carbonel, M.; Nimour, N. 2000. Are large wildland fires –as anomalous ecological processes- natural hazards. Phys. Chem. Earth (A). 25 (12): 763-768.

Bernard, M.L.; Lleras, J.; Nimour, N. 1999. Wildland fires, solar flux and total ozone content of the atmosphere: mutual correlations. European Geophysical Society 24th General Assembly; The Hague, Netherlands.

Bernard, M.L.; Nimour N. 2004a. A concept of climatologic chart. EMS Annual Meeting Abstracts. 1 (00286). European Meteorological Society.

Bernard, M.L.; Nimour N. 2004b. Large fires in South California, October 2003: climatologic analysis, theory and reality. Geophysical Research Abstracts. 6 (00339). European Geosciences Union.

Bernard, M.L.; Nimour, N. 2004c. Lightning fires dependence on precipitation and temperature. Geophysical Research Abstracts. 6 (00354). European Geosciences Union.

Bernard, M.L.; Nimour, N. 2004d. Short-range forecasting of large wildland fires. EMS Annual Meeting Abstracts; 1 (00285). European Meteorological Society.

Bernard, M.L.; Nimour, N. 2005a. Application of the concept of climatologic chart to Mediterranean climate variability. Geophysical Research Abstracts. 7 (01839). European Geosciences Union.

Bernard, M.L.; Nimour N. 2005b. Reality of the climatologic theory of wildland fires based on UV-B efficiency. Geophysical Research Abstract. 7 (2906). European Geosciences Union.

Boullard, B. 1993. De la poudre aux incendies de forêts…une approche canadienne. La Forêt Privée. 212: 84-87.

Burgan, Robert E.; Hartford, Roberta. 1993. Monitoring vegetation greenness with satellite data. Gen. Tech. Rep. INT-297. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station.

Despain, D.G. 1998. Personnal communication.

Douglas, Arthur V.; Stockton, Charles W. 1975. Long-term reconstruction of seasonal temperature and precipitation in the Yellowstone National Park region using dendroclimatic techniques. The University of Arizona. Prepared for United States Department of the Interior, National Park Service, Yellowstone, WY.

Douguedroit, A. 1992. Sécheresse et incendies de forêts en region mediterranéenne. Revue d'Analyse Spatiale Quantitative et Appliquée. 22. Colloque International «Le feu; avant-après». Nice, France.

Fang, J.; and others. 2001. Interannual variability in net primary production and precipitation. Science. 7 September 2001. 293 (5536): 1723.

Flannigan, M.D.; Wotton, B.M. 1991. Lightning ignited forest fires in Northwestern Ontario. Canadian Journal of Forestry research. 21: 227-287.

Forgeard, F. 1994. Importance and characteristics of heathland fires in Brittany (France). 2nd Int. Conf. Forest Fire Research. 1 (B 28): 447-458.

Frontier, S.; Pichod, Viale. 1991. Ecosystèmes, structure, evolution. Collection d'écologie. Masson.

Gabban, A.; San-Miguel-Ayanz, J.; Barbosa, P.; Liberta, G. 2006. Analysis of NOAA-AVHRR interannual variability for forest fire risk estimation. International Journal of Remote Sensing. 27 (8), 20 April 2006: 1725-1732.

Gray, J.T. 1982. Community structure and productivity in Ceanotus Chaparral and Coast Sage Scrubs of South California. Ecologic Monographs. 52 (4), December 1985: 415-435.

Humbert, J.; Najjar, G. 1992. Influence de la forêt sur le cycle de l'eau en domaine tempéré. Une analyse de la littérature francophone. CEREG, Université de Strasbourg I, France.

Latham, D.J.; Rothermel, R. 1993. Probability of fire stopping precipitation events. Res. Note INT 410. Ogden, UT: United States Department of Agriculture, Forest Service, Intermountain Research Station.

Lieth, Helmuth; Whittaker, M., eds. 1975. Productivity of the biosphere. Springer-Verlag.

NICC. 2005. Incident Management Report 2005. South California National Interagency Fire Center.

Nimour, N. 1997. Flammability of the Mediterranean vegetation. Thesis. Laboratoire de Chimie et Environnement, Université de Provence. Marseilles, France.

Olivier, L. 1975. Première contribution à l'étude de l'intervention de la végétation et de certains facteurs écologiques dans les incendies de forêts en Basse Provence. Doctorat de spécialité. 28 february 1975. Université d'Aix-Marseille III (Saint-Jérôme). Marseilles, France.

PROMETHEE. 1985-1997. Forest fires database. Conseil General des Bouches-du-Rhône, France.

Ramade, F. 1994. Eléments d'écologie. Ecologie fondamentale. Ediscience International.

Rambal, S. 1984. Water balance and pattern of root water uptake by Quercus coccifera L. evergreen scrub. Oecologia (Berlin). 62: 18-25.

Romme, W.H.; Despain, D.G. 1989. The long history of fires in the Greater Yellowstone ecosystem. Western Wildlands. 15: 10-17.

Running, Steven W. 2006. Climate change: is global warming causing more, larger wildfires? Science. 313 (5789). 927.

Scurlock, J.M.; Olson, R.J. 2002. Terrestrial net primary productivity—A brief history and a new worldwide database. Environ. Rev. 10 (2): 91-109.

Terol, C.M.M. 1987. Incendios forestales en Alicante; Publicaciones de la Caja de Ahorros Provincial. 143. Alicante, Spain.

Trabaud, L. 1980. Impact biologique et écologique des feux de la végétation des zones de garrigues du bas-Languedoc. Thesis. Université des Sciences et Techniques du Languedoc. France.

Viegas, D.X.; Viegas, M.T. 1994. A relationship between rainfall and burned area in Portugal. International Journal of Wildland Fires. 4 (1): 11-16.

Ward, P.; Wotton, M. 1994. Personnal communication.

Westerling, A.L.; Hidalgo, H.G.; Cayan, D.R.; Swetnam, T.W. 2006. Warming and earlier spring increase Western US forest wildfire activity. Research articles. Science. 313 (5789): 940-943.

Technical Background of the FireLine Assessment MEthod (FLAME)

Jim Bishop[1]

Abstract—*The FireLine Assessment MEthod (FLAME) provides a fireline-practical tool for predicting significant changes in fire rate-of-spread (ROS). FLAME addresses the dominant drivers of large, short-term change: effective windspeed, fuel type, and fine-fuel moisture. Primary output is the ROS-ratio, expressing the degree of change in ROS. The application process guides and instills a systematic methodology, utilizing a simple worksheet. The information developed provides a basis for safety judgments and for applying Lookouts, Communications, Escape routes, Safe zones (LCES). The ROS-ratio can be applied to observed fire spread to provide a timeline of future fire spread. Compared to four BehavePlus examples FLAME is accurate to within an average error of 14 percent. In four fireline-fatality cases FLAME predictions match reconstructed ROS-ratios with an average error of 9 percent, and in every case could have foretold the rapid changes that impacted the crews. Adjustment factors are developed to account for variations of windspeed across terrain, and for flame height and sheltering by vegetation. Field application of FLAME is explained and demonstrated with examples.*

Part 1: The FLAME System

Essentially the FireLine Assessment MEthod (FLAME) applies fire behavior prediction science to the implementation of the fire order 'Base all actions on current and expected fire behavior.' With fireline-based observations firefighters apply it using only simple paper-and-pencil pocket tools. FLAME takes account of the 'current' fire behavior as a baseline, directs attention to the 'next big change' in fire behavior, and evaluates the magnitude of that change. The magnitude of the anticipated change in fire behavior is based on the relationships embodied in the Fire Behavior Prediction System (FBPS) as computed by BehavePlus, on grass fire behavior expressed in the Australian CSIRO model, and on observed rates of spread in grass, brush, and timber. The measure of the 'change in fire behavior' is expressed in FLAME as the factor by which fire rate-of-spread (ROS) will increase/decrease, the 'ROS-ratio'. (For example, an increase in ROS from 4 ch/hr to 24 ch/hr has an ROS-ratio = 24/4 = 6X.) Application of that ROS-ratio to the observation of current fire behavior provides an extrapolation of the fire spread-time, expressed most practically in terms of the fire's position on the landscape through time (using 'natural yardsticks,' things you can see on the land) rather than as a rate-of-spread in distance/time.

The two basic things that we must do: provide a systematic, practical, and effective tool to firefighters for evaluating fire behavior on the fireline, and effectively communicate and instill the important points of basic fire behavior training (as in S-290 Intermediate Fire Behavior). Application of FLAME in training and on the fireline supports both needs.

In: Butler, Bret W.; Cook, Wayne, comps. 2007. The fire environment—innovations, management, and policy; conference proceedings. 26-30 March 2007; Destin, FL. Proceedings RMRS-P-46CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 662 p. CD-ROM.

[1] Physicist, mathematician, geologist, formerly with the California Department of Forestry and Fire. cjbishop1991@sbcglobal.net

In assessing potential fire behavior firefighters need to be proactive, to consider all of the key factors, and not to simply be passively waiting to notice, or to be made aware of, a significant development in the fire's behavior. And they need to have a realistic sense of the impact such a change could have on them, the magnitude of the change. **Seat-of-the-pants assessments are not adequate.** A common tendency is for firefighters to rely too much on current fire behavior as a basis for their actions, with the expectation that they will simply notice any developing changes in time to react. **That failure to foresee dangerous (yet predictable) changes is evident in perceptions revealed again and again in fireline fatality cases.** Without an organized approach to that fire behavior assessment, it is too easy to miss something while being unaware of what information is missing, and too easy to be unaware of the magnitude of an impending change. Separate short papers (Bishop 2005, 2006) describe more fully the place for FLAME in training and on the fireline.

FLAME offers a systematic methodology that prompts and guides the user to explicitly consider the key factors that drive significant, sudden changes in fire behavior—based on a minimum number of inputs, usually only two: effective windspeed and fuel type. It is important that the process be usable, or it won't get used, so the emphasis in FLAME is on simple tools and the information that is available to the firefighter on the fireline, remembering that computers don't make it to the fireline. FLAME fills a need that is not addressed by the other applications of the fire model (nomograms, and so forth). It is far simpler to use, requires minimal materials, builds on observed fire behavior, directly addresses the important question of 'change' in fire behavior, and expresses outputs in terms that are easily applied (what's next, how much change, when will the fire be here).

FLAME application proceeds from basic to more refined steps and yields these three important results:

1. The identity and timing of the 'next big change'—Knowing the nature and timing of the pending change allows firefighters first of all to be aware of that potential, and also to better monitor the environment and maximize the value of fireline lookouts.
2. The magnitude of that change (expressed as the 'ROS-ratio', the degree of relative increase or decrease in ROS)—Knowing the magnitude of the pending change alerts the firefighter to the level of possible danger. In fact, large ROS-ratio might well be viewed as a universal common denominator in fireline accidents.
3. An estimate of the timeline of the fire's advance—Knowing the fire spread-time allows rational planning of escape routes and timing, as well as informing well-chosen tactics.

All in all, the FLAME information provides a solid basis for the implementation of LCES (Lookouts, Communications, Escape routes, Safe zones). It is, first and foremost, a tool for making sound safety decisions on the fireline, but also provides relevant information for tactical decisions.

Figure 1 illustrates the basic idea of combining a change in fuel type with a change in effective windspeed (EWS) to produce a measure of the resultant change in fire behavior (the ROS-ratio). Fuel type and EWS changes are the dominant changemakers. All of the details of how the FLAME 'standard curves' were derived and are used, and the relative sizes of fire behavior factors, are contained in sections below. This graphic simply portrays the basic FLAME inputs and output so that subsequent discussion makes more sense. The arrow depicts an example of change from 'current' (low windspeed, fire

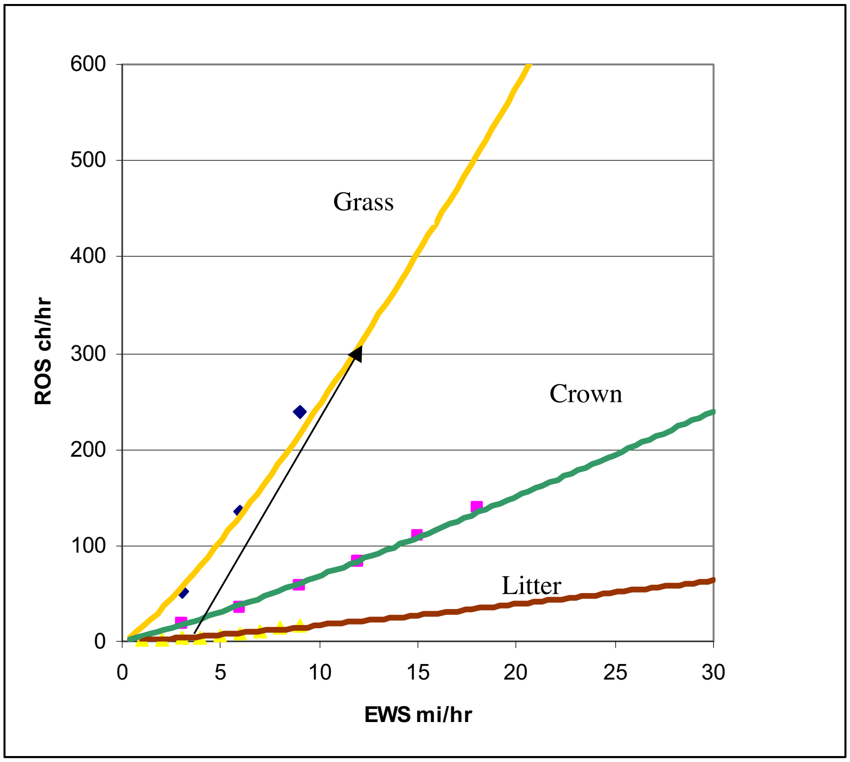


Figure 1—EWS vs. ROS for each of the major fuel types (litter, crown and grass). The arrow depicts an example in which fire in litter with an EWS of 3 or 4 mi/hr changes to fire in grass with EWS about 12 mi/hr. The initial and final ROS would be on the vertical axis, and the larger divided by the smaller would be the ROS-ratio for this change in fire behavior (approx. 70X).

in litter) to 'expected' (grass, moderate windspeed) fire behavior. The ROS-ratio would be the higher ROS on the vertical axis divided by the lower ROS on that axis. In this example the ROS would increase by a factor of about 70X as the fire moved from litter into grass and the EWS increased by between 3X and 4X. These curves form the basis for the FLAME predictions and illustrate the idea, but they are not the user-application tool (which is described in part 3).

The FLAME user observes the fuel type and current EWS affecting the fire, and looks ahead to the fuel type and EWS that will prevail after the anticipated change in conditions. The ratio of the larger EWS to the smaller EWS is obtained either by simple division or table look-up. With the fuel-type change and the EWS-ratio, use the FLAME table (table 2, later in this paper) to look up the ROS-ratio: join the EWS-ratio row with the column describing the fuel change, and read the ROS-ratio. For example, a 6X increase in EWS together with a transition from fire in the litter to crown fire would result in an increase in ROS of about 35X (or in the opposite case, a decrease of 35X). Associated diagrams and a field guide and worksheet help the user obtain inputs, move through the process, and determine the needed outputs.

The application of FLAME affords a range of information levels (corresponding to the aforementioned three important outputs), each with its own inherent degree of completeness and precision, and determined by the user and the circumstances on the fireline. In practice a firefighter can proceed from one level to the next, making use of the output at each stage, as time and information allow.

1. 'Initial application' level: user depicts/describes the current fire behavior, the expected fire behavior, and identifies the next big change; this stage involves only a qualitative assessment.

2. 'Standard application' level: user inputs current and expected conditions and predicts the ROS-ratio.
3. 'Complete application' level: user combines an observation of the current fire-spread timeline with the ROS-ratio to yield a predicted fire-spread timeline (or spread time). The spread-time line lays out at what time the fire will reach a given point. If the fire moved this far in a certain time under current conditions, how long will it take to go that far under expected conditions? It is related to ROS but is a projection of the fire's progress in terms of features visible on the landscape (natural yardsticks), rather than an explicit rate in units of distance/time.

The following examples illustrate the idea of the FLAME process, the application stages, and the kinds of outputs a firefighter can obtain, with suggestions on how the information relates to LCES. They are not intended to explain how FLAME is applied (inputs are simply given), and they are not to be 'over interpreted' in terms of tactical/operational considerations. Both examples are of dangerous changes in fire behavior, but the FLAME idea applies to any change in behavior, dangerous or benign.

Example 1—an upslope run:

- **Fireline observations**: Fire spreads over the course of 4 hours up the lower half of a forested 20 percent slope as a litter fire with midflame windspeed 2 mi/hr. By late morning, conditions will allow the midslope fire to transition to a crown fire and to be exposed to higher windspeeds on the upper slope.
- **Initial application**: The next big change expected is a transition to crown fire and the effects of the higher windspeeds on the upper half of the slope.
- **Standard application**: The litter-to-crown change in fuel will combine with a total 8X increase in effective windspeed (wind on the upper slope being 16 mi/hr at the crown-fire flame level) to produce an increase in ROS of 50X, ROS-ratio = 50X.
- **Complete application**: The fire took 4 hours spread up the lower half of the slope. The crown fire could run the upper half of the slope in about $1/50^{th}$ of 4 hours, or about 5 minutes.
- **LCES**: Lookouts—be especially vigilant for signs of the transition to crown fire, such as torching or short crown runs, and also to wind direction as revealed in the smoke column to anticipate which side of the upslope run might be most threatening to crews in the area. Communications—regular reporting of crown-fire precursors, RH, and wind direction. Escape—must take much less than 5 minutes and be located out of the line of the crown fire run.

Example 2—a major wind increase and direction change:

- **Fireline observations**: Fire is burning on a flank in litter under conifers; the head of the fire made a short crown-fire run earlier. The wind is predicted to blow across that flank at 20 mi/hr when a cold front arrives in the next 2 to 4 hours. The flanking fire has moved ¼ of the way to a road in the last 2 hours (a rate that puts it at the road in 6 more hours).
- **Initial application**: The next big change is a large increase in wind pushing the flank outward toward the road, and the fire is expected to transition to crown fire with the increase in wind. The change is expected in as little as 2 hours.

- **Standard application**: The litter-to-crown change in fuel will combine with a 20X increase in effective windspeed to produce an increase in ROS of 140X. (Effective wind on the flank is taken as 1 mi/hr, as will be explained in part 2.)
- **Complete application**: The fire could be halfway to the road in 2 more hours when the wind hits, and the wind-driven crown fire will complete the remaining half of the distance to the road in about 1/140th of 4 hours, or about 2 minutes (less time if the fire is more than halfway to the road when the wind comes).
- **LCES**: Lookouts—besides having local lookouts, a remote lookout should be established 'upstream' of the fire to provide early warning of the approach of the cold front. Communications must be arranged with the remote lookout. Escape via the road would allow only about 2 minutes after the wind hits, so escape should be initiated earlier based on the reports of the remote lookout.

Why not stop at the 'initial application' stage? That is certainly a good start, and in some cases will be all one needs to know…to have identified the next big change. But going further, to the standard application, requires the firefighter to explicitly look at the big changemakers: effective windspeed (EWS), current and expected; fuel type; fine-fuel moisture (FFM) or RH, and therefore to either obtain those critical parameters or to become aware that important information is missing. Seeking the explicit ROS-ratio prediction directs a method that prompts and leads specific appraisal of the key fire behavior factors. The ROS-ratio gauges the magnitude of coming changes. The complete application provides a timeline that can provide a realistic sense of fire movement and can guide good choices about the timing of safety actions and effective control actions.

Focusing on the Dominant Changemakers

Many factors in the fire environment contribute to fire behavior: fuel physical/chemical characteristics, fuel arrangement, fuel moisture, slope, and wind. Fire behavior (as measured by ROS in FLAME) is less sensitive to some of these factors than to others, and some factors change less rapidly than others. In a given situation current fire behavior demonstrates the integrated effects of the prevailing fire environment factors…firefighters can observe that. If nothing much changes in the fire environment, prediction requires only extrapolation of observed fire behavior. But things eventually do change, often quickly, and the degree of change from that 'baseline' fire behavior can be predicted.

We focus on the major changemakers that will cause large changes in 'current' fire behavior on short timescales (those factors will be quantitatively identified below). In eliminating some detail in fire behavior inputs, a little accuracy is traded for practical applicability, but without compromising the basic capacity to predict significant change. Also, in order to focus on potentially dangerous fire behavior FLAME emphasizes the range of fuel conditions that accompany active fire behavior (meaning the lower FM ranges, typical of a late-season afternoon). The relative response of ROS to a change in effective wind or fuel type is similar over a range of fuel moistures, and here we use model guidance assuming fairly dry fuels (usually 1-hr FM 6 percent and live FM 80 percent). In other words, the ROS change due to a doubling of windspeed is essentially the same at 4 percent as at 8 percent FM.

We want to anticipate change that can be 'sudden', those changes that can develop in minutes ('minutes' is the timescale of escape) or tens of minutes.

Changes that evolve gradually over many hours, or days, present less of an imminent threat to fireline personnel, and one can remain current on such gradually changing fire behavior. So in seeking the dominant drivers of short-term change we look at fire behavior factors that *can* change significantly in roughly an hour or less. Whether such changes actually take place over several hours, or in just minutes, the FLAME application is still relevant. And while change can occur quickly, it may not get under way for hours. To extend a FLAME prediction, a firefighter simply updates the observation of ongoing fire behavior and looks ahead to further change.

Live, 10-hour, 100-hour, and 1000-hour fuel moisture are not drivers of large, short-term changes. Live fuel moisture (LFM) varies over the season. When LFM levels are low enough, fire can propagate through the crowns of shrubs or trees. The LFM usually continues to decline throughout the fire season, but for a given species of live fuel it usually doesn't drop more than another 20 percentage points or so after crowns become flammable. In extreme and prolonged drought it may drop by 40 percentage points in timber fuels after the time when crowns become flammable, typically less than that (about 20 percentage points) in chaparral.

However, the change in LFM in a given plant over an hour is much less than the seasonal changes. Consider a change in LFM of 5 percentage points (which is greater than would be typical in an hour), from 80 to 75 percent. As indicated by BehavePlus for Model 5, such a variation in LFM would result in a change in ROS of only about 5 percent.

Changes in 10-hour FM over the course of an hour are not likely to be more than about 2 percentage points. Consider the effect of a 2 percentage point 10-hr FM change on ROS in grass and in litter. For fuel model 1, and for fuel model 9, BehavePlus shows no change in ROS for a 2 percentage point variation in 10-hour FM. Hundred-hour and 1000-hour fuels will undergo even smaller changes in FM over an hour than do 10-hour fuels. Short-term moisture changes in larger-diameter fuels are not a significant moderator of large, sudden changes in ROS (though moisture in larger fuels certainly does affect the overall fire intensity).

Variations in fuel conditions on the fire can result from the fire's movement, as well as through overall change with time. For example, a fire can move from one slope-aspect to another, and fuels on those different slopes can have different fuel moistures. Such differences might be as high as a few percentage points of dead FM and 10 or 20 percentage points of live FM (in the same species of plant). Those variations certainly contribute to changes in ROS, of order approximately 20 percent, sometimes less. However, there are almost certainly other significant changes associated with such a slope-aspect change—in plant community, fuel architecture, and the wind-slope influence driving the fire. In the face of these significant changes in more dominant factors, the variations in live and larger-diameter dead fuel moistures on different slope aspects are a relatively minor influence on the changes in ROS.

For purposes of predicting significant changes in ROS that result from 1-hour-timescale changes in fuel conditions, live FM, 10-hour FM, 100-hour FM, and 1000-hour FM are considered essentially constant and a minor influence on ROS change. The effects of those factors on fire behavior will be manifested in, and observable in, current fire behavior, the baseline fire behavior.

1-hour fuel moisture plays a significant role—Changes in 1-hour FM (FFM, fine-fuel moisture) can be significant over 1-hour timescales. The combined effects of relative humidity, temperature, and time-of-day typical of 'summer day' changes, might lead to a change in FFM on the order of 2 percentage points in an hour. As indicated by BehavePlus for fuel models 1 and 9 such a variation in FFM would lead to ROS changes of about 12 percent in grass or 17 percent in needle litter. If fire moves from an open south slope to a canopy-shaded north slope (or vice versa) it can experience a change in FFM of about 3 percentage points—corresponding to ROS changes of about 21 percent in grass or 32 percent in needle litter. The FLAME system handles changes in FFM with the following guideline (in two versions):

For a change of FFM of 'n' percentage points, the ROS (in a given fuel) will change by about 1.nX. For example, FFM dropping by 2 percentage points would yield roughly a 1.2X increase (a 20 percent increase) in ROS (compared to an average of 1.15X, or 15 percent, as per the BehavePlus example cited above).

An alternative way of doing essentially the same thing is based on the change in relative humidity (RH). Given that a change in RH of 5 percentage points leads to a change of about 1 percentage point in FFM, the change in ROS in fine dead fuels is about 2X(RH-change). For example, a drop in RH from 40 to 25 percent (= 15 percent) would increase ROS in fine dead fuels about 2X15 percent = 30 percent, or by a factor of 1.3X. Such adjustments can fine-tune the ROS-ratio that is based initially on just changes in fuel type and EWS, though such refinements are usually not necessary.

There can be more dramatic changes in FFM. A good example is the onset of foehn winds, where in a few 10s of minutes FFM might drop by about 6 percentage points. The direct effect of that FFM change would suggest roughly a 60 percent increase in ROS. But the other changes, likely a transition from surface fire to crown fire and the onset of high winds, would dwarf the direct effect of changes in FFM on ROS.

Probably the most important effect of changes in FFM on changes in fire behavior is the influence it has on transition to crown fire (an important change in fuel type) and on spotting. In the FLAME system FFM can be used to fine-tune predicted changes in ROS (for changes between largely fine-dead fuels grass and litter) as noted above, but more importantly FFM (and relative humidity) is explicitly considered in FLAME applications as a factor in the onset of crown fire (detailed in part 2).

Fuel type is a major changemaker—FLAME classifies fuels as litter, grass, or crown foliage (of shrubs and trees), a classification based on the ROS characteristics of those fuels, their similarity within a group. The reasons for treating fuels in that way are:

1. Those fuel types are quickly and easily recognized by firefighters, without the need for extensive training on determining fuel models.
2. ROS within each group of fuels is sufficiently characteristic of that fuel and distinct from the others to allow meaningful predictions of ROS-change as a function of fuel type.
3. Changes in fuel type contribute to major changes in ROS.

As a generalization, with other fire behavior factors constant, ROS in crown fuels is about 4X faster than in litter, and in grass fuels about 3X to 4X faster than in crown foliage. The total range in variation in ROS across the three fuel-type averages is on the order of 15X (for comparison, recall that changes in ROS due to short-term changes in fuel moisture are no more than about 1.2X for live FM and the heavier dead fuels, and about 1.6X for changes in FFM).

Effective windspeed is the greatest changemaker— Effective windspeed (EWS) is taken to be the midflame windspeed (MFWS) plus a component that accounts for the effect of slope on ROS. In these discussions in part 1 EWS is considered to be 'a given' and an appropriate measure of the combined effects of wind and slope on ROS. Guidelines for obtaining wind-adjustment/reduction factors used to determine EWS, and for obtaining the wind-equivalent of slope, are in part 2.

EWS has a great influence on ROS, and varies rapidly in time and place. It is by far the most dominant changemaker for short-term changes in fire behavior, capable of driving ROS changes of >200X. The influence of EWS on ROS is derived from the curves of ROS vs. EWS inherent in FBPS models, the CSIRO grass fire model, and observations of ROS in crown fuels.

In summary, the magnitudes of the short-term changes (~1 hour) in ROS produced by the various factors are listed below. It is clear that the dominant changemakers are EWS and fuel type, with FFM relevant but less influential as a direct factor (remaining useful for fine-tuning and for helping to reveal potential for crown fire).

- Fuel moisture in live and larger dead fuels ~ 1.2X (~20 percent)
- Fine-fuel moisture (and therefore RH) ~ 1.6X (~60 percent)
- Fuel type (litter, crowns, and grass) ~ 15X (~1400 percent)
- Effective windspeed (including slope) ~200X (~20,000 percent)

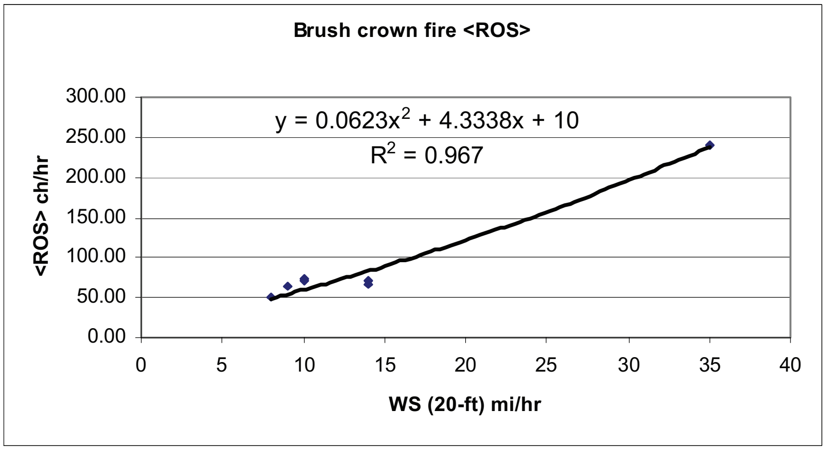
The Basic Data Used in FLAME

The dependence of ROS on fuel and EWS was derived from a combination of model outputs and observations. The model outputs were obtained from BehavePlus (1-hr FM 6 percent, 10-hr FM 7 percent, 100-hr FM 8 percent, live FM 80 percent) and from the CSIRO grass fire nomograms (Cheney 1997). The curve of ROS vs. EWS for each fuel type is derived from the averages of inputs summarized below.

1. Grass fuels are represented by FBPS fuel models 1 and 3, the CSIRO grassfire model, and at high windspeeds by observed spread of Australian grass fires (Cheney 1997).
2. Crown fuels are represented by FBPS fuel models 5, 6, and 7, and observations of crown fire in brush and in timber (including Range and others 1982, Rothermel 1991).
3. Litter fuels are represented by FBPS fuel models 8, 9, and 10.

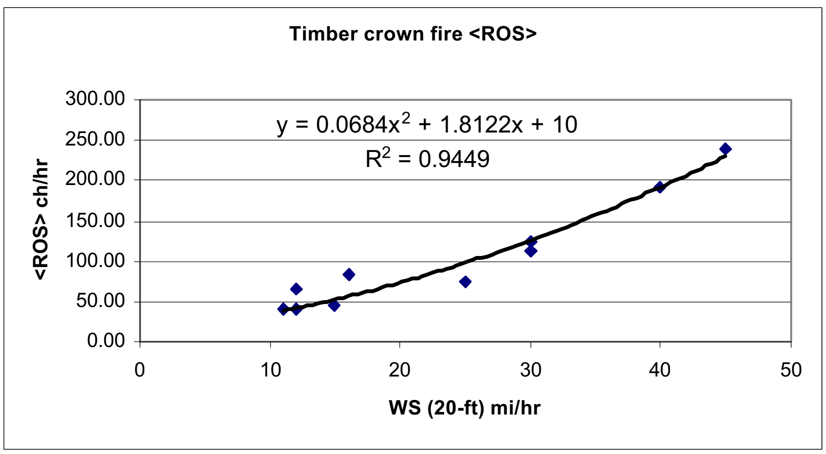
Slash fuels are not explicitly considered in FLAME, as they are uncommon in wildfire environments, but they can be considered via adjustment of standard ROS-ratios. The number of permutations between fuels rises rapidly as the number of fuels considered increases, and to keep the system simple unnecessary variations in fuel type are not included. However, it is possible to address a lot of variation from the standard by making adjustments to the standard FLAME outputs. Specific adjustments to FLAME outputs are described later in this paper.

Crown fuel ROS observations—Summarized in figures 2 and 3 are observations of crown fire ROS as a function of 20-ft windspeed (which in FLAME is taken to be the midflame windspeed for crown fire). Best-fit 2^{nd}-order polynomials are displayed on the graphs, together with the regression coefficients (here R represents regression coefficient, but later R represents ROS). Observed crown fire data used in the graphs are shown in the accompanying table. The data used to represent the crown-fuel group ROS values for the FLAME standard curves were derived from the regression plots.



Brush fire cases	20-ft WS mi/hr	<ROS> ch/hr
Ely 1	10	70.40
Carson B	14	65.60
Carson C	14	70.40
Carson A	9	64.00
South Canyon	35	240.00
Pilot	8	49.60
Fort Ord	10	73.60

Figure 2—Observed crown fire ROS in brush fuels are plotted against 20-ft windspeed (for cases shown). Overall topographic slope in these cases was slight. Best-fit 2nd-order polynomial curve and regression coefficient are shown. <ROS> denotes the spread rates as averages.



Timber fire cases	20-ft WS mi/hr	<ROS> ch/hr
Sundance	45	240.00
Sundance	30	112.00
Red Bench	12	41.60
Lily Lake	25	73.60
Sandpoint	16	83.20
Pattee Canyon	30	124.80
Mink Creek	15	44.00
Black Tiger	11	40.80
Scott Able	40	192.00
Butte Fire (Wallace Crk.)	12	65.60

Figure 3—Observed crown fire ROS in timber fuels are plotted against 20-ft windspeed (for cases shown). Overall slope was not a major direct influence on ROS. Best-fit 2nd-order polynomial curve and regression coefficient are shown. <ROS> denotes the spread rates as averages.

The data shown encompass considerable variation in species and structure, and in fuel moistures. The brush fires were in Great Basin shrubs (such as sagebrush and antelope brush), chaparral (both interior and maritime), and Gambel oak. The timber fuels (mostly from the Northern Rockies but also New Mexico, included pines, firs, and spruce). Each had its own live fuel moisture, and dead FMs varied as well. In spite of that variation there is strong and consistent correlation of ROS with windspeed in brush crowns and in timber crowns. Changes in ROS can be related to changes in EWS with good accuracy, over a broad range of crown fuel types. And crown fuels can be treated as a group with adequate results.

Overall, the ROS data for timber fuels tend to represent long-term spread, including periods of discontinuous crown fire. The brush fire data tend to represent shorter, more continuous crown-fire spread. An upward adjustment of crown ROS by 1.7X (Rothermel 1991) to better reflect the faster continuous portions of the spread shows it to match the brush ROS data almost exactly (see fig. 4, later in this paper). The similarity in brush versus timber ROS, together with the well grouped FBPS model outputs, allow a treatment of crown fuels as a single fuel type with good results, as will be developed below.

Crown fuel-model representatives—FBPS fuel models 5 and 6 are good representatives for crown-foliage fire spread in shrub/brush fuels. Model 7 represents fire spread in crown fuels typical of the Southeastern United States. FBPS fuel model 4 tends to predict ROS that are too high. Calibrations of fuel model 4 suggest that its outputs be reduced by at least half. Given the other, more accurate models for fire spread in brush, and the crown fire observations, fuel model 4 was not used. Fuel models 5, 6, and 7 have very similar ROS outputs and, together with the above crown fire observations, are used to represent fire spread in crown foliage in constructing the FLAME standard curves.

Litter fuel representatives—FBPS fuel models 8, 9, and 10 are all used. ROS outputs for models 9 and 10 are similar. ROS outputs for fuel model 8 tend to be only about one-third of the litter-fuel average, and when such compact short-needle litter fuels dominate fire spread, the FLAME outputs can be adjusted (the ROS-ratio is increased) to reflect the slower spread in the litter.

Compiling the data—The following data were averaged to produce the points that define the FLAME 'standard curves' (fig. 4), the curves that characterize ROS for each fuel type as a function of EWS.

- Grass: The average of models 1 and 3, CSIRO grassfire model, and grass fire ROS observation on the Australian Narraweena Fire of 1983 (which helps to define the curve at high windspeeds); data points at EWS 1 through 10 mi/hr and 30 mi/hr (30 is an observation; model 1 hits wind limit at < 9 mi/hr)
- Crowns: The average of models 5, 6, & 7, and best-fit curves for observed ROS in brush and in timber (which also reflect higher windspeeds); data points at EWS (mi/hr) of 3, 6, 9, 12, 15, & 18.
- Litter: The average of models 8, 9, & 10; data points at EWS 1 through 9 mi/hr.

Deriving the Dependence of ROS on Fuel Type and EWS

The FLAME standard curves (fig. 4)—The data for each fuel type (grass, crown, litter) have some scatter within the group, but do not overlap; each fuel type is uniquely and separately characterized (especially when the faster components of average timber ROS are considered). The resulting degree of variation in predictions will be defined in discussions of accuracy below. You can visualize the 'sector' of fuels represented by each standard curve in figure 4:

- The grass group is at about '1 o'clock.'
- The crown group is at about '2 o'clock' and extends from the points above the curve to the first set below the curve (the brush and 'continuous timber' points, but not the 'average timber' points, as will be explained below).
- The litter group is at about '3 o'clock.'

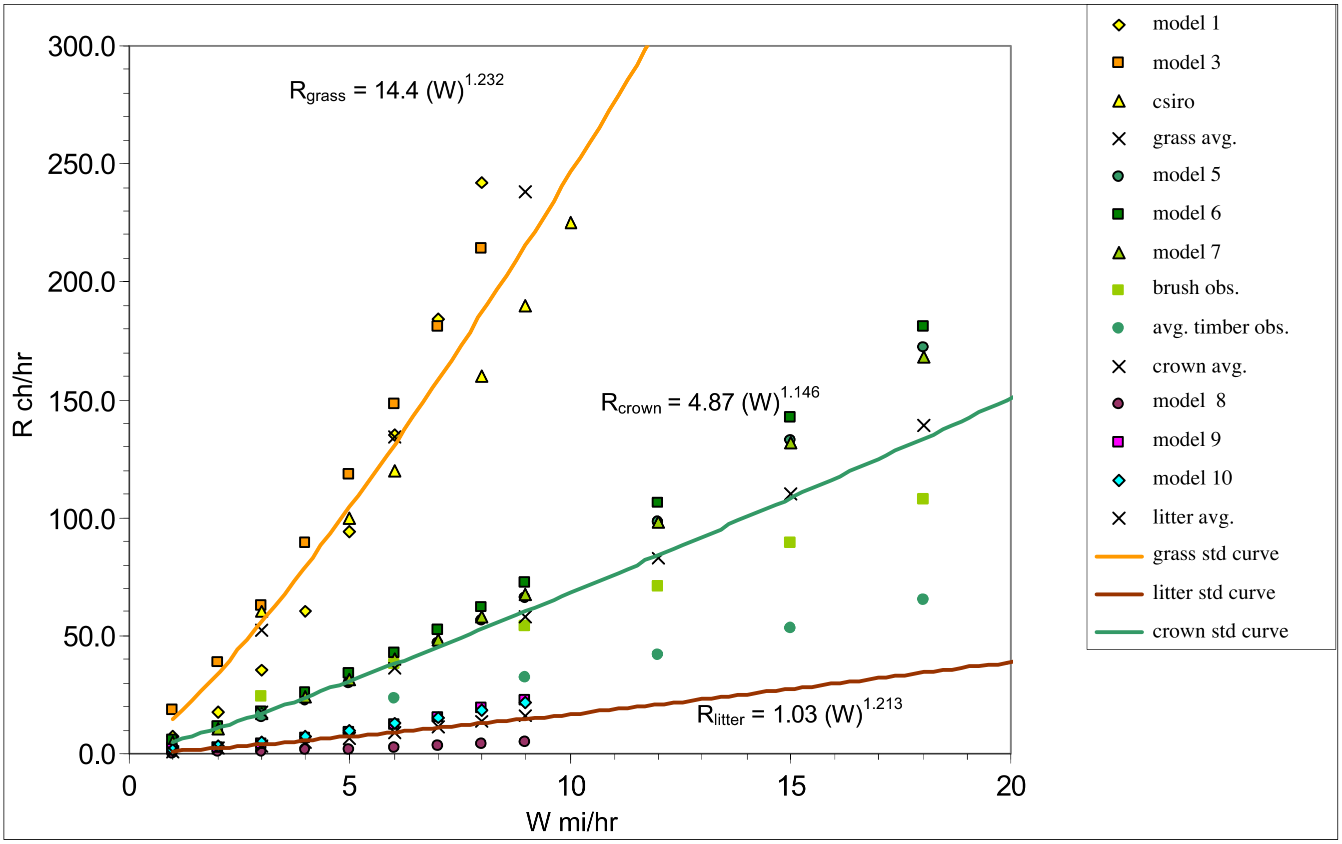


Figure 4—Standard FLAME curves. ROS (ch/hr) on the vertical axis as a function of EWS (mi/hr), for each model or observation set used to generate the standard curves (grass fuels in yellows, crown fuels in greens, litter fuels in purple, blue, and brown). Standard curves are the best-fit power curves for each fuel type, with the defining equation shown. As will be explained below the curves are effectively truncated at EWS = 0.5 mi/hr.

Best-fit FLAME curves could be defined by polynomials and would offer good approximation to the data. However, it is necessary to compare values (as a ratio) between standard curves, and quotients of polynomials are not easily handled analytically. Therefore the standard curves are defined by best-fit power curves, which are amenable to analytic solutions when combined as ratios. The fit of the power curves to the average ROS values within each fuel types is quite good, with regression coefficients of at least r^2 = 0.99. R, the ROS (not to be confused with earlier use of R as the regression coefficient), is in ch/hr; W, the EWS, in mi/hr.

The equations of the FLAME standard curves for each fuel type are (in the form expressed in equation 1 below):

- Grass: $R_{grass} = 14.4\ (W)^{1.232}$
- Crown: $R_{crown} = 4.87\ (W)^{1.146}$
- Litter: $R_{litter} = 1.03\ (W)^{1.213}$

ROS-ratio for cases involving no change in fuel—Each fuel type has a unique ROS dependence on EWS, a unique wind response, as reflected in the exponent in the power equation (this paper would be a lot shorter if that were not so). To characterize changes in EWS in cases where there is no change in fuel the exponents are averaged, to give the 'no-fuel-change' dependence of

ROS-ratio on EWS-ratio (for all fuels), as derived below. The accuracy consequences of using an average wind-response coefficient are evaluated in treating the wind response of all fuels the same in the 'no-fuel-change' case.

The general ROS equation (from regression curves) for a given fuel type is:

$$R = \alpha (W)^{\beta} \qquad \text{Eq. 1}$$

Where R is ROS; α is the fuel coefficient; W is the EWS; β is the wind-response coefficient.

For change in EWS (in a given fuel), where $R_R = R_{larger} / R_{smaller}$ is the ROS-ratio, $W_R = W_{larger} / W_{smaller}$ is the EWS-ratio, the FLAME ROS-ratio will be

$$R_R = R_{larger} / R_{smaller} = [\alpha (W_{larger})^{\beta}] / [\alpha (W_{smaller})^{\beta}] = (W_R)^{\beta} \qquad \text{Eq. 2}$$

The average of $\beta_{grass} = 1.232$, $\beta_{crown} = 1.146$, and $\beta_{litter} = 1.213$ is: $\beta_{average} = 1.20$

Therefore for EWS changes only (no fuel change), the ROS-ratio is given by

$$R_R = (W_R)^{1.20} \qquad \text{Eq. 2a}$$

ROS-ratio for cases involving both a change in fuel type and in EWS—ROS-ratios are formed for change between litter and crown fuels, between crown and grass fuels, and between litter and grass fuels. Note that the equations express an ROS-ratio that can describe a fuel change in either direction (for example litter to crown, or crown to litter), and either a reduction or an increase in EWS. The conventions regarding whole-number (versus fractional) ROS-ratio are detailed below in the section on *The net effect on ROS*.

Consider a change from an initial fuel-type and initial EWS to a final fuel type and final EWS, as expressed by the ROS-ratio R_R. Here are the quantities involved (where R_R and W_R apply to a more general case than the ratios used in equation 2).

R_I = initial ROS; R_F = final ROS; W_I = initial EWS; W_F = final EWS; $W_R = W_F/W_I$

Using equation 1, where here parameters α_I and β_I correspond to the curve for the initial fuel, α_F and β_F to the curve for the final fuel (as shown on fig. 4):

Initial ROS $R_I = \alpha_I(W_I)^{\beta I}$; and final ROS $R_F = \alpha_F(W_F)^{\beta F}$

$R_R = R_F / R_I = [\alpha_F(W_F)^{\beta F}] / [\alpha_I(W_I)^{\beta I}]$; and since $W_F = (W_I)(W_R)$, then

$$R_R = (\alpha_F / \alpha_I)(W_I)^{(\beta F - \beta I)} (W_R)^{\beta F} \text{, the basic ROS-ratio equation} \qquad \text{Eq. 3}$$

What do the terms in equation 3 mean?—Consider first the case in which $W_R = 1$, and the equation represents a case in which there is no change in EWS, strictly a change in fuel, then:

$R_R = (\alpha_F / \alpha_I)(W_I)^{(\beta F - \beta I)}$ (for no change in EWS)

For a given W_I, R_R above represents the ratio of ROS typical of fuels α_F& α_I at that EWS. The fraction (α_F / α_I) itself represents the ratio of ROS in the different fuels at an EWS of W_I = 1 mi/hr.

The term $(W_I)^{(\beta F - \beta I)}$ incorporates the fact that as W_I varies, the relative ROS between different fuel types changes, reflecting the difference in the wind-response coefficients between fuel types. In other words, the relative ROS in the different fuels changes slightly as actual EWS changes…the relative ROS is slightly different at EWS of 3 mi/hr versus that at 6 mi/hr. One way to visualize it is that the relative spacing of the FLAME standard curves in figure 4 changes slightly as EWS varies, because each curve bends upward at slightly different rate (due to their different wind-response coefficients). If β_F and β_I were equal, the dependence of relative ROS for different fuels on EWS would vanish. As will be shown later in the sections on evaluating the accuracy of FLAME, the ROS-ratio is only weakly dependent on the term $(W_I)^{(\beta F - \beta I)}$, and that effect introduces only a small error (usually less than 10 percent).

We can consider $(W_I)^{(\beta F - \beta I)}$ to be a constant, C, once we've chosen a standard W_I. For changes from litter to/from either crown or grass fuels W_I will be set at 2 mi/hr, and for changes from crown to/from grass fuels W_I will be set at 15 mi/hr (as explained below in the section on *The specific equations for combining fuel and wind changes*). The consequences of those values of WI will be evaluated quantitatively in the section on *The dependence of ROS-ratio on actual EWS (in addition to the EWS-ratio)*.

The third term in equation 3, $(W_R)^{\beta F}$, represents the influence on ROS-ratio of a change in EWS (via the EWS-ratio). The wind-response coefficients, β, are a bit greater than 1 (ranging from 1.146 to 1.232), which indicates that a given increase in EWS produces a little greater increase in ROS.

Rewriting Equation 3 with the constant C gives

$$R_R = C\ (\boldsymbol{\alpha_F} / \boldsymbol{\alpha_I})\ (\mathbf{W_R})^{\beta F} \qquad \text{Eq. 3a}$$

Equation 3a embodies the essential point of the FLAME process, with the fireline input shown in bold. A huge range of significant fire-behavior change, expressed by the ROS-ratio, R_R, can be described by just two things: the knowledge of the change in fuel types (represented by α_F / α_I), and the degree of change in windspeed (via the EWS-ratio, W_R). You can visualize the standardized fuel coefficients as representing the relative change in ROS between two different fuel-type curves at a standard EWS (either 2 mi/hr or 15 mi/hr), with the further effect of changes in EWS represented by movement along the appropriate standard curve an amount specified by the EWS-ratio.

The net change in ROS, slower or faster?—The expression in equation 3 is analytically complete and covers all possible cases of speeding up or slowing down. Initial fuels can be slower or faster than final fuels; initial EWS can be slower or faster than final EWS. An ROS-ratio <1 will indicate that the fire is expected to slow down as fuel and EWS change. But applying fractional EWS-ratios and interpreting fractional ROS-ratios can be awkward for the FLAME user, so equation 3 is used to generate a user-friendly lookup table containing only whole-number ROS-ratios and EWS-ratios.

For most real-world cases (especially those changes that threaten firefighter safety), the 'slower' fuel experiences the lesser wind, and the 'faster' fuel experiences the greater wind. For example, litter (the slowest fuel) under a stand will feel less wind than will overlying crowns (a faster fuel). So in practice ROS-ratio = (larger ROS)/(smaller ROS), and EWS-ratio = (larger EWS)/(smaller EWS). The user avoids working with fractional ratios, and simply keeps track of whether the change will be an increase or a decrease in ROS.

Table 1 shows the four possible combinations of 'faster' and 'slower' for fuels and EWS. The most common 'big change' combinations by far are those that fall into the upper left or the lower right quadrants of the table. Those are combinations where the change in fuel type and the change in EWS reinforce each other in increasing or in decreasing the fire ROS—they effectively multiply together to produce the final ROS-ratio that is shown in the main section of table 2, the basic FLAME table. The lower left and upper right quadrants show combinations where the change in fuel type and the change in EWS oppose each other, with the dominant change determining whether the net effect is to reduce or to increase the ROS. Direct changes between grass and crown fuels are the most likely possibility for such cases. For example, a fire backing in grass (a fast fuel) could then move up a slope with increased wind in crown fuels (a slower fuel). Such situations are covered in the rightmost two columns of the FLAME table (table 2), or by a technique described below in the section *When changes have opposing effects.*

Table 1—The several possible combinations of change in fuel type and change in **EWS** and the net change in ROS that could result.

		Change in EWS	
		Faster	**Slower**
Change in fuel type	**Faster**	ROS always increases	increase or decrease
	Slower	increase or decrease	ROS always decreases

Table 2—Rate-of-spread ratios (R_R in the equations) as a function of changes in fuel and changes in effective windspeed. The table is generated by application of equation 3a. The left-hand column shows the EWS-ratio (W_R in the equations), the factor by which EWS changes. Each column corresponds to a change between particular fuel types (or to no change). Table values express the ROS-ratio that results from the combined change in EWS and fuel. The left side applies to cases in which fuel and wind changes reinforce. Cases in which changes in wind and fuel have opposing effects are handled with the rightmost two columns. Highlighted ROS values define a range that includes situations associated with fireline fatalities.

FLAME Table (source of ROS-ratios)

		EWS biggest in faster fuel			EWS less in grass	
EWS-ratio	No fuel change	Litter to/from crown	Litter to/from grass	Crown to/from grass	Crown to/from grass	Litter to/from grass
No chg 1	**1**	**4**	**14**	**4**	*4*	*14*
2	**2**	**10**	**30**	**8**	***2***	*5*
3	**4**	**15**	**60**	**13**	**1**	*3*
4	**5**	**20**	**80**	**20**	**2**	*3*
5	**7**	**30**	**100**	**27**	**2**	*2*
6	**9**	**35**	**130**	**35**	**3**	*2*
8	**12**	**50**	**180**		**4**	**1**
10	**16**	**60**	**240**		**5**	**1**
12	**20**	**80**	**300**		**6**	**2**
16	**30**	**100**	**440**		**8**	**2**
20	**40**	**140**	**600**		**10**	**3**
24	**50**	**180**	**700**		**13**	**3**
30	**60**	**220**	**1000**		**17**	**4**
40	**80**	**300**	**1300**		**23**	**6**
50	**110**	**400**	**1800**		**30**	**8**
60	**140**	**500**	**2200**		**40**	**10**
80	**200**	**700**	**3100**		**60**	**16**

The specific equations for combining fuel and wind changes—The specific parameters (analogous to α and β in equation 1) for each fuel type are (see the FLAME standard curves in fig. 4):

- For grass fuels: $\alpha_G = 14.4$; $\beta_G = 1.232$
- For crown fuels: $\alpha_C = 4.87$; $\beta_C = 1.146$
- For litter fuels: $\alpha_L = 1.03$; $\beta_L = 1.213$

The 'α' coefficients measure the effects of fuel type on ROS (for the above values, at EWS= 1 mi/hr)—indicating that litter is the slowest fuel, crowns faster, and grass the fastest fuel. The 'β' coefficients measure the response of ROS to changes in EWS. β-coefficient comparisons reflect the fact that grass is a little more wind-responsive than litter fuels, and that litter fuels are a little more wind-responsive than crown fuels (as characterized by the FLAME standard curves).

The final equations 4, 5, and 6 (below) are obtained from equation 3 by inputting the above specific values of α and β to represent the initial and final fuels. For changes from litter to/from either crown or grass fuels the standard initial EWS is set at $W_I = 2$ mi/hr, and for changes between crown and grass fuels the standard EWS is set at $W_I = 15$ mi/hr. Those 'standard values' of EWS are chosen because each falls at the 'geometric' midpoint of a reasonable range of actual EWS (+/– 4X or +/– 3X). For cases in which there is no change in EWS, $W_R = 1$, and the approximate relative change in ROS between fuel types can be gauged from the fuel-change coefficients (4.51, 3.73, and 14.2)—that relationship varies slightly at W away from the standard W_I. ROS in crown fuels is roughly 4½ X faster than in litter (less difference with increasing EWS), ROS in grass fuels is roughly 3½ X faster than in crowns (more difference with increasing EWS). Those figures do not multiply to give exactly the relationship between litter and grass fuels because they represent different 'standard EWS' values (otherwise they would).

Litter to/from crown fuels:

$$R_C / R_L = (4.87/1.03)\,(2)^{(1.146\text{-}1.213)}\,(W_R)^{1.146} = 4.51(W_R)^{1.146} \qquad \text{Eq. 4}$$

Crown fuels to/from grass:

$$R_G / R_C = (14.4/4.87)\,(15)^{(1.232\text{-}1.146)}\,(W_R)^{1.232} = 3.73\,(W_R)^{1.232} \qquad \text{Eq. 5}$$

Litter to/from grass:

$$R_G/R_L = (14.4/1.03)\,(2)^{(1.232\text{-}1.213)}\,(W_R)^{1.232} = 14.2\,(W_R)^{1.232} \qquad \text{Eq. 6}$$

The above equations are used to generate the table of ROS-ratios used in FLAME (table 2 and appendix B table B2), as a function of the two fuels involved and of the EWS-ratio. In the main part of the table (center three columns) a change in fuel and the change in EWS are assumed to reinforce (which is usually the case) to cause a net decrease or net increase in ROS. The less common cases where the change in fuel opposes the change in EWS (such as fire backing down a slope in grass, then running up the next slope as a wind-driven crown fire) are handled in the rightmost two columns. Those exceptional cases can also be handled by a technique described briefly in the section below on *Adaptation to nonstandard cases*. The same ROS-ratio can describe either a net increase or a net decrease in ROS (in other words, a fire could go 6X faster or 6X slower). Tabled numbers have been rounded off (within about 10 percent accuracy) to make for easier application and interpolation, and physically unrealistic combinations are left blank.

To use the table join the EWS-ratio row with the column describing the fuel change, and read the ROS-ratio. For example, a 6X increase in EWS together with a transition from fire in the litter into the crowns would result in an increase in ROS of about 35X (or in the opposite case, a decrease of 35X).

Adaptation to nonstandard fuels—There are cases where fire is burning in a mix of fuel types. In those cases FLAME can be applied assuming each of the fuel components separately, and then averaging the two predictions. For example, a litter fire moves into a fuelbed of grass and shrubs. The change can be separately treated as 'litter to grass' and as 'litter to crown', and the two ROS-ratios averaged.

Also, there are real-world fuels that are not a good match for one of the standard fuel types, and those can be treated as described above. For example, fuel model 2 'grass' is a mixed fuel that has typical ROS values that lie between crown and grass values (at a given windspeed), and averaging FLAME predictions for a change-to-crown with a change-to-grass gives workable results. For example, with a fuel change from litter (avg of models 8, 9, 10) at EWS = 4 mi/hr to 'model 2' at EWS = 12 mi/hr BehavePlus predicts ROS-ratio = 51X. The average of the separate FLAME ROS-ratios = 60X.

Slash fuels have average ROS values that are approximately 1.5X the average litter ROS. ROS-ratios for slash fuels can be estimated by adjustment of the ROS-ratio obtained using the litter fuel type. The ROS-ratio for litter-to-slash would be 1.5X the no-fuel-change ROS-ratio. The ROS-ratio for changes between slash and crowns (or slash and grass) would be two-thirds of the litter-to-crown (or litter-to-grass) ROS-ratio.

When changes have opposing effects—Consider the case of a change in fuel type and an opposing change in EWS, such as a backing fire in grass becoming a wind-driven upslope fire in crown fuels. There are two ways to do it.

1. Simply do the FLAME prediction in two parts. First, use the ROS-table to predict the effects of just a change in fuel type. Second, predict the ROS-ratio that would result from just the change in EWS. Then divide the bigger ROS-ratio by the smaller ROS-ratio (keeping track of whether the speed-up or the slow-down in ROS will dominate). For example, an EWS increase of 20X would alone produce an increase in ROS of 40X. A change from 'faster' grass to 'slower' crown fuels would alone produce a decrease in ROS of about 4X. So the net change in ROS would be about 40/4 = 10X. Note: this 'two-step' approach is applicable to any FLAME application.
2. The appropriate section of the FLAME table can also be used, 'EWS is less in grass'. For the above example an EWS-ratio of 20X combined with a change from grass to crown fuels yields an ROS-ratio of 10X. (Minor discrepancies between the methods can result from round-off errors, and because the wind response of each fuel differs slightly from the average used in the 'no-fuel-change' case.)

Evaluating the Accuracy Limits

The FLAME-prediction performance standard—FLAME should be simple and practical enough to be used, and accurate enough to be useful. Presently firefighters have no routine and systematic process for assessing fire behavior on the fireline, and for focusing on *changes*. The full application of the fire model requires more input information and more processing capability than is realistic or available on the fireline, and yields outputs that require a map or a way of gauging distance in units such a feet or chains. FLAME is designed to fill that gap between no system and the full system. The specific goals for FLAME accuracy are:

1. That at least three-fourths of the predictions of ROS-ratio will be accurate within a factor of +/– 2X compared to FBPS predictions or to real-world observations. '+/– factor of 2X' means that the real ROS-ratio falls between the half of and twice the FLAME-predicted ROS-ratio—for example, for a FLAME ROS-ratio of 80X that the actual ROS-ratio falls in the range 40X to 160X. 'Factor of 2X' is easy to remember and apply, and spans a fairly realistic range of variations in many real-world processes. (The uncalibrated application of the FBPS is characterized as having that same level of accuracy, +/– factor of 2X.)
2. That no FLAME predictions mislead firefighters in their safety judgments. This qualitative accuracy goal, that FLAME predictions inform but do not mislead safety judgments, is the most relevant and important. This indeed could probably have called the first goal.

How might the accuracy range of ROS-ratio affect safety judgments, at each application level?

Initial application (identifying the next big change): Following the FLAME process a firefighter will be able to identify the large potential changemakers in the situation. The dominant changemakers are well characterized in FLAME (EWS and fuel type). The relative order of fuel types by ROS characteristics is correct and nonoverlapping, and the wind-dependence of ROS is well represented. So the initial application can be relied on to highlight the dominant changemakers, identify the next big change, and give the correct sense of decrease or increase in ROS.

Standard application (using the ROS-ratio as a guide to dangerous situations): Given that fireline fatalities correlate strongly with large ROS-ratios (preliminary data suggest ROS-ratio > approx. 60X is a common denominator), it is valuable for the predicted ROS-ratio to alert a firefighter to a potentially life-threatening situation. When the firefighter applies FLAME and obtains an ROS-ratio, he or she will double that prediction and consider the larger ROS-ratio as a guide to potential danger. And if the larger ROS-ratio is getting near the 'danger zone' prudence demands that safety judgments will be based on that potential. For example, if the predicted ROS-ratio is, say, 40X then twice that is 80X, and a firefighter should carefully evaluate the risks and benefits before committing to an action. Therefore, a FLAME ROS-ratio of 30X (while the actual ROS-ratio is 60X) would still alert the firefighter that he/she faces a level of change known to be associated with fireline fatalities. Also, the FLAME system tends to overpredict ROS-ratios.

Complete application (predictions of the fire-spread timeline): Consider two extreme possibilities: first a case of large ROS-ratio, and second a case of small ROS-ratio.

Large ROS-ratio: Suppose the ROS-ratio is 200X, with ROS increasing, and that it suggests the fire will reach a given point in about 10 minutes. Applying the error range of 2X means the fire's travel-time should be considered to fall between about 5 and 20 minutes. The difference between the predicted and actual travel times is only –5 minutes or +10 minutes, and operationally that is not a huge difference....certainly one should not try to cut any safety-essential actions too close to save 10 minutes. Assume the worst case and act wisely (how better to spend the 'extra' 10 minutes?). The point is that the time scale is short in any case, and even the inaccuracies are only on the order of minutes. Suppose the ROS-ratio is 200X, but the fire will slow down, suggesting the fire might reach a certain point in 6 hours. Applying the factor of 2X means that fire travel-time should fall between 3 and 12 hours. The actual variation from predicted spread time, up to 6 hours, is a long time. But the important point is that the firefighter will have hours to continue to observe the fire and to reevaluate the FLAME prediction.

In a sense, the consequence (on predicted fire-spread times) of errors associated with large ROS-ratios is 'self limiting' in that for large increases in ROS the response time is short in any case, while for large decreases in ROS there is ample time to update and adjust the prediction.

Small ROS-ratio: A small ROS-ratio means that the fire behavior is not expected to change dramatically. In that case, changes from the current fire behavior will be gradual. Variations of 2X from that ROS could be noticed before creating the sudden and extreme changes that put lives in danger. With the expectation of modest changes in fire behavior the firefighter would have the chance to observe and update the FLAME prediction, all the while looking ahead to the next big change.

It is important to keep the accuracy of the FLAME system in perspective. It is not perfect, but it is much better to have a helpful prediction than to have none, to call attention to important factors and the potential for significant change than to be unaware. And any system, even the most accurate, is fundamentally limited by the accuracy of inputs on fire environment factors (an especially challenging one being the actual midflame windspeed). There will be cases where FLAME falls short of the '+/– factor-of-2X' standard. The same is true for any of the operational prediction systems. (For example, model-predicted ROS for a litter fuel that falls between fuel models 8 and 9, in a situation where the sheltering is between wind-reduction factors 0.1 and 0.2, could vary by a factor of 9X depending on the inputs a practitioner might reasonably choose.)

We can only provide the best tools we have and make users aware of their limits—much better to have a decent, if imperfect, tool than no tool.

The dependence of ROS-ratio on the chosen standard EWS—Even though the main cause of change in ROS (for a given fuel) is the change in EWS, there is a weak dependence of changes in ROS on the actual EWS involved. Recall the discussion above under *What do the terms in equation 3 mean?*. How much accuracy do we lose in using values of the fuel coefficients fixed at a 'standard' windspeed?

Consider two cases, otherwise identical, one in which the initial EWS is W_1 and the other in which it is W_2. Comparing the ROS-ratio in one case (R_{R1}) with that in the other case (R_{R2}), with the initial and final fuels being the same in both cases:

$$R_{R2}/R_{R1} = [(\alpha_F / \alpha_I)\, (W_2)^{(\beta_F - \beta_I)}\, (W_R)^{\beta_F}] / [(\alpha_F / \alpha_I)\, (W_1)^{(\beta_F - \beta_I)}(W_R)^{\beta_F}]$$

$$= (W_2 / W_1)^{(\beta_F - \beta_I)} \qquad \text{Eq. 7}$$

Note that W_2 / W_1 here represents the ratio of two possible initial EWS values, not an initial and final EWS. This can be viewed as a case where one of those EWS values is the chosen 'standard' EWS, and the other is the actual EWS for a particular fireline situation. The error in the ROS-ratio that results from an actual EWS that differs from 'standard' EWS is a function of the ratio of those EWS values, (W_2 / W_1).

For fires in litter a realistic range in EWS values might be from EWS = 0.5 mi/hr (a backing fire) to EWS = 8 mi/hr. Compared to the assumed standard EWS which was set at EWS = 2 mi/hr, the maximum value of (W_2 / W_1) in equation 7 would be 4. For the case of transition from litter to crown fire, the variation introduced into the ROS-ratio by using that standard EWS would then be (using equation 7).

$R_{R2}/ R_{R1} = (4)^{(1.146 - 1.213)} = 0.91$, implying an error range of about +/– 9 percent

For the same assumed range in the actual EWS, and a transition from litter to grass,

$R_{R2}/ R_{R1} = (4)^{(1.232-1.213)} = 1.026$, which implies an error range of about +/– 3 percent

Similarly, for transitions between crown and grass fuels a variation in actual EWS from 5 mi/hr to 45 mi/hr, a maximum 3X deviation from the 'standard' EWS of 15 mi/hr, would result in:

$R_{R2}/ R_{R1} = (3)^{(1.232-1.146)} = 1.1$, which implies an error range of about +/– 10 percent

We can see from the above examples that the error introduced by assuming a standard EWS, and using the EWS-ratio alone to judge wind-induced change, is small, generally less than +/– 10 percent. Furthermore, due to its dependence on a small exponent, that error grows slowly with ranges of initial EWS much wider than assumed above.

Treating the wind response of all fuels the same in the 'no-fuel-change' case—For simplicity in application, changes in EWS only (with no fuel change) are treated with an equation that averages the wind-response effects (the β-coefficients) of the different fuels. How large is the error introduced by that approximation? We use equation 2 to express the ROS-ratio for an actual β (β_{act}) and for the average β (β_{avg}), and compare the resulting ROS-ratios. $R_{R\,ACT}$ and $R_{R\,AVG}$ represent the ROS-ratios using actual β-coefficients versus the average β-coefficient (= 1.20) respectively.

$$(R_{R\,ACT})/(R_{R\,AVG}) = W_R^{\beta act} / W_R^{\beta avg} = (W_R)^{(\beta act - \beta avg)} \qquad \text{Eq. 8}$$

Considering a large EWS-ratio in grass or litter to be on the order of 20X, and in crown fuels to be about 4X (the 'low end' of EWS pushing crown fires is much greater than for litter or grass, and therefore the total range in EWS-ratio for crown fires is less), the error introduced by using the average wind response in the 'no fuel change' case is about:

- for grass: $(R_{R\,ACT})/(R_{R\,AVG}) = 1.1$, which implies an error of 10 percent (with the FLAME prediction too low)
- for crowns: $(R_{R\,ACT})/(R_{R\,AVG}) = 0.93$, which implies an error of 7 percent (with FLAME prediction too high)
- for litter: $(R_{R\,ACT})/(R_{R\,AVG}) = 1.04$, which implies an error of 4 percent (with the FLAME prediction too low)

Such deviations fall well within the goal of factor-of-2X accuracy, and therefore simplifications embodied in the average wind-response factor for the 'no-fuel-change' case are not problematic.

Summary of accuracies of the above analytical simplifications—The various simplifications that are required to deal with the exponential dependence of ROS on EWS and with the different β-coefficients for each fuel type introduce errors in ROS-ratio that typically range from a few percent to about 10 percent. In a further 'direct test' comparisons of ROS-ratios computed directly using the raw ROS equations (equation 1, with specific coefficients for each fuel) with ROS-ratios computed from equations 4, 5, or 6 also show variations of less than 10 percent. Those errors are within the accuracy goal, and are normally subordinate to the errors introduced by imperfect inputs (especially of uncertainties in windspeed).

The variation of ROS within a FLAME fuel type—The largest simplification embodied in FLAME is treating a variety of fuels as a single fuel type, with regard to ROS. For example, crown fires in brush and in timber are considered all as one type of 'crown fire'. To assess the deviations introduced by the simplification of treating all fuels within a group as one fuel type, the following measure is used. For a given EWS, the associated ROS for a specific fuel is compared with the ROS associated with the FLAME standard curve (fig. 4) for that fuel type. For example, at EWS = 6 mi/hr, the grass-fuel curve shows ROS = 134 ch/hr, while fuel model 3 predicts 148 ch/hr. The deviation of fuel model 3 from the FLAME curve in that case is +9 percent. Similarly derived deviations are shown for a range of EWS values in tables 3 through 5 using the formula: [(fuel-specific value)/(standard-curve value) –1] X 100. Positive values of the deviation indicate that the specific fuel type is faster than the standard curve.

The standard curve for crown fuels is constructed from FBPS fuel models 5, 6, and 7, observed ROS in brush fuels, and observed ROS in timber fuels. The timber fuels are the slowest of the lot. However, the timber observations are dominated by averages over considerable times and distances, encompassing sustained crown runs and discontinuous crown fire. The brush observations are dominated by data from shorter, continuous crown runs. We can consider the shorter, sustained crown spread in timber to be faster than the long-term average (Rothermel 1991 estimates that maximum ROS in timber is often approximately 1.7X the average ROS), and that corresponds closely to the ROS observations for brush. The larger data set of longer-term-average timber ROS observations was used in constructing the standard curves, and overall

Table 3—Deviations of ROS for individual grass fuel representatives from the grass-fuel standard curve, at a range of effective windspeeds. Positive deviation values indicate that the actual ROS for a representative fuel would be higher than the ROS suggested by the FLAME standard curve; negative deviations indicate the representative ROS is lower than the standard curve. The apparent jump in average deviation at EWS = 9 mi/hr is due in part to the loss of fuel model 1 data points above its wind limit.

	EWS in mi/hr			
	3	**6**	**9**	**30**
Model 1	-33%	+1%		
Model 3	+19%	+9%	+20%	
CSIRO	+15%	-10%	-20%	-6%
Average absolute deviation from standard	**22%**	**7%**	**20%**	**6%**

Table 4—Deviations of ROS for individual crown fuel components from the crown-fuel standard curve, at a range of effective windspeeds. Positive deviation values indicate that the actual ROS for a representative fuel would be higher than the ROS suggested by the standard curve, negative deviations indicate the representative ROS for that fuel is lower than the standard curve. The FLAME standard curve for crown fuels is weighted toward the relatively higher ROS expressed in fuel models 5, 6, 7, and lies above observed crown fire ROS (except in one low-wind case). It is intentional to err on the side of not underpredicting the increase in ROS associated with the transition from litter fire to crown fire, because that dangerous event has too often killed firefighters. The original data for ROS in timber are dominated by observation of long-term averages (which include sustained runs and discontinuous crown fire). FLAME is aimed at predicting the shorter term, sustained fire behavior, so a comparison is also made here to a timber ROS adjusted by 1.7X to more realistically represent that behavior. In that comparison, timber ROS closely matches brush ROS, and therefore supports the strategy of treating all 'crown fuels' the same with regard to ROS.

	EWS in mi/hr				
	6	**9**	**12**	**15**	**18**
Models 5, 6, 7 averaged	+12%	+18%	+22%	+24%	+25%
Brush observervation ROS	+6%	-7%	-14%	- 19%	-22%
Timber observation ROS	-36%	-45%	-49%	- 48%	-53%
Timber ROS adjusted by 1.7X to represent continuous runs	+9%	-6%	-14%	-18%	-21%
Average absolute deviation from standard using adjusted timber ROS	**9%**	**10%**	**17%**	**20%**	**23%**
Average absolute deviation from standard using long-term average timber ROS	16%	20%	26%	30%	30%

Table 5—Deviations of ROS for individual litter fuel representatives from the litter-fuel standard curve, at a range of effective windspeeds. Positive deviation values indicate that the actual ROS for a representative fuel would be higher than the ROS suggested by the standard curve, negative deviations indicate the representative ROS is lower than the standard curve. Fuel models 9 and 10 are similar in ROS, but fuel model 8 has much lower ROS (a factor of about 3X less than the standard curve). To more realistically treat a case involving 'slow' model 8 litter fuels, the user can apply a correction factor of 3X to the FLAME ROS-ratio. Deviations of 'model 8' litter fire ROS from a 'corrected' ROS are covered in the lower two rows of the table.

	EWS in mi/hr			
	1	**3**	**6**	**9**
Models 9 and10 averaged	+40%	+36%	+33%	+41%
Model 8	-70%	-70%	-67%	-72%
Average absolute deviation from standard	50%	47%	44%	51%
Model 8 deviation from 'adjusted' FLAME standard	-9%	-9%	0%	-15%
Average absolute deviation from standard curve with adjustment for 'compact' litter	**30%**	**27%**	**22%**	**32%**

the balance represented by the standard curve seems satisfactory. Even with the timber 'average' ROS values built into the standard FLAME curves, the standard curve is 'faster' than the observed-crown-fire representative points. Given the FLAME intent of predicting short-term changes, the comparison between the standard curve and the faster ROS in timber is a more appropriate measure of how a FLAME prediction might compare to actual continuous crown-fire runs in timber. Therefore, in evaluating the fit between 'timber' ROS and the standard crown-fuel curve the adjusted timber ROS is also considered.

The standard curve for litter is constructed from FBPS fuel models 8, 9, and 10. Fuel models 9 and 10 have similar ROS characteristics. Fuel model 8, representing compact, short-needle litter displays considerably slower ROS, about 3X slower than the litter fuel average. The effect of model 8 is to lower the standard curve, and the effect of lowering the standard curve is to overstate, if anything, the increase in ROS accompanying a transition to crown fire (FLAME intentionally leans toward not underpredicting such a dangerous change). Most litter fuels tend to be more like fuel model 9 or 10.

However, given that the ROS in litter is often the denominator in generating an ROS-ratio, a large error could arise in cases where the fire was in 'model 8' litter. Such cases can be readily handled by multiplying the FLAME ROS-ratio by about 3X (though for simplicity, and because most litter is not as 'slow' as model 8, the practical adjustment guideline is to multiply the ROS-ratio by 2X when 'compact litter' is involved).

Dealing with the imprecision in fuel types—The simplest way to handle the variations of ROS within a given fuel type is to accept them—most of them fall well within the +/– factor-of-2X (–50 percent or +100 percent) goal. The notable exception is the 'slowness' of model-8 litter fuels, where actual ROS-ratios could exceed by 3X the FLAME-predicted ROS-ratio. The main consequence of such underprediction of a large increase in ROS-ratio would be on the fire-spread timeline. In cases of large ROS-ratio the operational impacts of such inaccuracies are small because they affect timescales that are already short enough to suggest the need for timely actions (as noted in a previous section, *Complete application)*. As with the FBPS, a practitioner can improve its accuracy considerably by observing and calibrating.

A practical and straightforward way to improve the accuracy of FLAME predictions is to make an adjustment to the ROS-ratio, or to average two ROS-ratios, based on known characteristics of the given fuel. For example: when dealing with compact litter ('model 8' fuels), double the predicted ROS-ratio; for 'model 2' fuels average the change-to-crown and change-to-grass outputs. See the section on *Adaptation to nonstandard fuels.*

A more sophisticated FLAME application tool could significantly improve the accuracy of predictions involving changes in fuel type. The key improvement in relating fuel types is to use the actual fuel coefficients (α) for the specific fuels involved. Array the fuels on paired logarithmic scales by fuel coefficient (like a slide rule), and apply user-friendly descriptions within each fuel group, such as 'sparse grass' or 'tall grass,' 'fluffy litter' or 'compact litter' to the scale. Sliding the scales to align the two fuels in question would then produce the ratio of their specific α-coefficients (exactly as a slide rule portrays a quotient), and the scale index could act as a pointer to the appropriate column of ROS-ratios. The whole affair could easily be built in to a compact calculator. It could also be an application on a hand-held computer.

Comparing FLAME outputs to FBPS predictions—Following are several examples of fire behavior events in which the ROS-ratio based on BehavePlus output is compared to FLAME predictions (table 6). Where round-off errors in the FLAME table would complicate the comparisons the FLAME predictions are obtained directly from the FLAME equations (equations 4, 5, 6) rather than the tables. This is a clearer test of the basic system itself.

Table 6—Summary of the results of comparing FLAME ROS-ratio to the ROS-ratio generated by BehavePlus (and in example 4 also from Rothermel's 1991 crown fire nomograms). Absolute error averages 15 percent, standard deviation of the errors 8 percent, largest error 26 percent.

Summary of accuracy tests	BehavePlus ROS-ratio	FLAME ROS-ratio	Deviation from BehavePlus
Example 1	2.6X	2.3X	-12%
Example 2	500X	370X	-26%
Example 3	162X	174X	+7%
Example 4	56X	64X	+14%

Example 1: A fire in burns with 3 mi/hr midflame windspeed in litter on the lower portion of a 20 percent slope; as it moves onto the upper slope the midflame windspeed increases to 6 mi/hr.
BehavePlus (model 9): the initial ROS = 4.7 ch/hr; final ROS = 12.2 ch/hr; ROS-ratio = 2.6X
FLAME: ROS-ratio = 2.3X
Deviation of FLAME from BehavePlus = –12 percent

Example 2: A backing litter fire on a 30 percent slope crosses to the opposite slope and moves upslope in grass with an 6 mi/hr eye-level wind.
BehavePlus (models 9 and 1): initial ROS = 0.3 ch/hr; final ROS = 151 ch/hr; ROS-ratio = 500X
FLAME: ROS-ratio = 370X
Deviation of FLAME from BehavePlus = –26 percent

Example 3: A fire creeping in litter up a 30 percent slope (EWS = 1 mi/hr) transitions to crown fire in brush when the 20-ft wind increases to 24 mi/hr.
BehavePlus (models 8/9 combined, model 5): initial ROS = 1.6 ch/hr; final ROS = 263; ROS-ratio = 162X
FLAME: ROS-ratio = 174X
Deviation of FLAME from BehavePlus = +7 percent

Example 4: A fire in litter (EWS = 2 mi/hr) transitions to crown fire in timber with 20 mi/hr winds (at 20-ft level).
BehavePlus (model 9) and Rothermel formula for Rocky Mountain timber, adjusted by 1.7X to represent faster portions of the overall crown fire: initial ROS = 2.5 ch/hr; final ROS = 83 ch/hr X 1.7 = 141 ch/hr; ROS-ratio = 56X
FLAME: ROS-ratio = 64X
Deviation of FLAME from BehavePlus-Rothermel solution = +14 percent

All of above FLAME predictions fall within factor-of-2X accuracy compared to BehavePlus (which in this test is considered to represent the 'true' value of ROS-ratio). FLAME overpredicts the danger presented by a litter-to-crown fire transition (which errs on the side of safety). In the case of underpredicting the grass fire case, the high FLAME ROS-ratio would still alert the firefighter to the clear danger and would yield estimates of fire travel-time that were within minutes of the BehavePlus prediction. In the clearly 'dangerous' cases represented above (examples 2, 3, 4) the predicted FLAME ROS-ratios (370X, 174X and 64X) fall in the range associated with fireline accidents.

Comparing FLAME outputs to actual fireline incidents—The most relevant test of the accuracy of FLAME predictions is against real-world fireline situations. To provide a common basis for comparison of FLAME versus real-world observations the ROS-ratio derived from fireline accident investigations is compared to that predicted by FLAME (fig. 5). The details of the assumptions used for FLAME application to these cases are in appendix A. The FLAME prediction is based on the fireline information as it could have been available to a firefighter applying FLAME—the idea is to evaluate the FLAME process with good information, and not muddy the comparison with inaccurate input. The documentation of the incidents is derived from the official reports, also in the cases of the South Canyon and Dude fires from on-site examination, and in all four cases from discussion with people who were there or who have studied the incidents.

Incident	Documented ROS-ratio	FLAME ROS-ratio	Deviation from documentation
South Canyon Fire	500X	500X	0%
Dude Fire	480X	500X	+4%
30-mile Fire	96X	100X	+4%
Cramer Fire	124X	160X	+29%

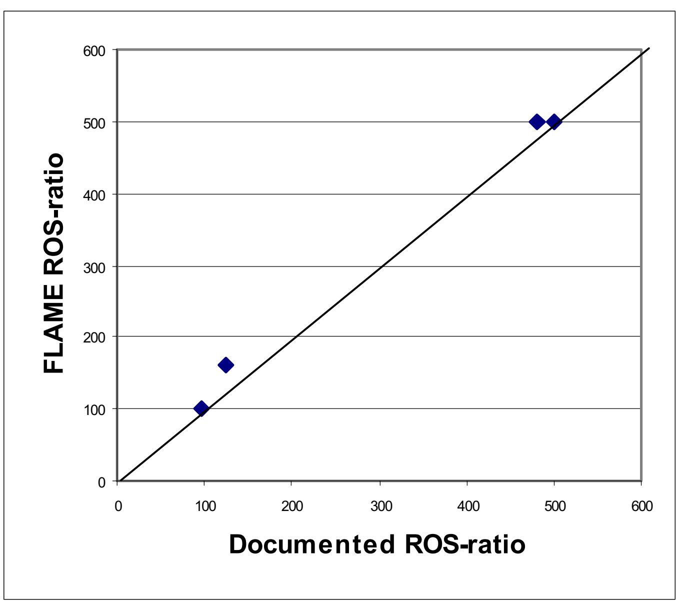


Figure 5—FLAME ROS-ratios versus documented ROS-ratios for fatality cases cited above. The diagonal represents perfect correlation between FLAME predictions and documented values. Average absolute error is 9 percent, standard deviation of errors 15 percent, and maximum error 29 percent.

In all of those cases, application of FLAME could have revealed the coming change, would have indicated clearly that it was of a magnitude that should be considered dangerous, and predicted with accuracies of order minutes the time it took for the fatal fire run.

Accuracy summary—By the most important accuracy standard—informing firefighter safety decisions and not providing misleading predictions that compromise safety—FLAME succeeds against BehavePlus calculations and in the four real-world cases above. Considering the three application levels, FLAME would be reliable in identifying the next big change, would provide good predictions of the magnitude of the ROS-ratio, and could suggest realistic timelines of the fire's advance.

The approximations inherent in the FLAME system—standardizing relative ROS between fuel types, using an average wind response for all fuels in cases of wind-change only, and treating similar fuels as a single fuel group—all fall within the 2X range, usually well within. The target quantitative accuracy standard (ROS-ratio within +/– factor-of-2X in at least 75 percent of the cases) is difficult to fully evaluate simply due to a lack of well-documented cases against which to test it. FLAME is within 2X of the four real-world cases (absolute error averaging 9 percent, standard deviation of the errors 15 percent, largest error 29 percent). And it is within 2X of the four BehavePlus examples (absolute error averaging 15 percent, standard deviation of the errors 8 percent, largest error 26 percent). But compared to other possible BehavePlus examples it might not meet the 'factor-of-2X' standard, and how do you choose a representative set of BehavePlus examples for which the 75 percent success rate is meaningful? As far as the incomplete set of comparisons above allows, FLAME meets the quantitative 'factor-of-2X' accuracy standard. Fuller evaluation awaits a larger set of real-world fire behavior cases.

A note on future improvements—No doubt, improvements in the basic fire behavior data, the models, and the application tools can make FLAME more accurate and more usable. Such improvements will not be difficult to incorporate and to disseminate to firefighters; they won't have to 'unlearn' anything. It might be as simple as issuing a new FLAME table with new ROS-ratio values, or it might involve an improved worksheet or a better 'field calculator'. The important thing is that firefighters will have already learned the process, a systematic process, of foreseeing the next big change, of evaluating the dominant changemakers, and of incorporating the expected fire behavior change into their fireline judgments. Assimilating a revised FLAME application tool will not be difficult.

Part 2: Obtaining Inputs

The main inputs to a FLAME prediction of ROS-ratio (table 2) are changes in fuel type and changes in EWS (effective windspeed). Changes in EWS are expressed as the ratio of the larger to the smaller EWS.

Changes in Fuel Type

New fuels ahead of the fire—The simplest change in fuel type occurs when the fire moves into new fuels ahead of the fire. Such changes are commonly encountered with changes in slope aspect, as fire crosses drainages or ridges.

A firefighter looks at what fuels lie out ahead of the fire, and can estimate the time of a potential fuel-type change by projecting the fire's current spread.

Transitions between surface and crown fire—An important change in fuel type, and a more challenging change to anticipate, is the transition of a fire in surface fuels into crown fuels. In essence, in a stand of trees or brush there are two fuel types juxtaposed, a surface fuel bed and crown-foliage fuel strata overlying it. The fire can transition between them rapidly, and undergo large changes in ROS and intensity.

The potential for fire to extend from surface fuels (usually a litter fuel type) into crown foliage depends on many factors. A major variable is the fuel moisture, both the live FM of the foliage and the FFM of the dead fuels.

The live FM 'sets the stage' when it drops below a threshold that permits sustained fire spread in the crown fuels. There is much variation of the threshold live FMs from one vegetation type to another, but some generalizations are possible and provide some guidance. At or below those live FM levels crown fuels are susceptible to sustained crown fire. The following represent such thresholds.

- California chaparral: live FM of 70 to 80 percent
- Great Basin shrubs: live FM of about 100 percent
- Rocky Mountain timber: live FM of about 120 percent
- Ponderosa pine: above 125 percent (maybe no practical upper limit)

The FFM plays a major role in the intensity of the surface fire, and the flammability of the dead attached component of the aerial fuels—essentially controlling the 'burner' under the foliage layer. FFM is strongly controlled by relative humidity (RH), and RH serves as a practical guide for firefighters. When live FM is in the range for potential crown fire, then RH (and FFM) dropping below a certain threshold-range greatly increases the potential for transition to crown fire. The threshold values of RH are surprisingly consistent over most vegetation types.

- Most fuels of the Western United States: RH below about 20 to 30 percent, especially below 20 percent
- Some fuels of the Southeastern United States: RH below about 35 percent

Firefighters can stay abreast of published trends in live FM and trends evidenced in the fire behavior, and they can monitor RH. The NFDRS is a valuable guide to crown fire potential. On the fireline the following accessible observations provide a practical guide/check-off list to suggest that transition to crown fire is a good possibility:

- Seasonal drought period prevails (meaning live FM is reaching the threshold of flammability).
- Overall drought makes matters worse (live FM will become critical sooner and go lower than normal).
- Recent crown fire, on other fires or your fire (crown fire possibility is demonstrated).
- Relative Humidity 35 to 20 percent, or less, especially RH below about 20 percent (FFM is low enough to trigger crown fire).
- Backing fire produces torchouts (a dead giveaway that headfire can crown).
- Fire moving up ladder fuels (early indicators of the transition to crown fire).
- Torchouts and short crown runs (with any worsening of burn conditions crown fire is imminent).

Determining the Effective Windspeed

EWS combines the influences of wind (at midflame level) and slope (as a bit of 'upslope wind') into one 'windspeed' that represents the driving force of wind and slope on the fire. Changes in EWS are the largest potential producers of changes in ROS. Making the determination of current and expected EWS is not easy, but it must be done as well as possible. Even though EWS is highly variable and subject to many influences firefighters can obtain worthwhile results from a few practical guidelines and observations. To not account for the variation in EWS, at least approximately, is to miss the largest potential source of change in fire behavior. In fact in some ways the firefighter on the fireline, making predictions of short-term significant changes in fire behavior, requires more detail about windspeed variation than is required for a typical longer term, average-fire-spread projection by an FBAN.

The following sections describe the adjustment methods for determining EWS as a function of topographic location, flame height, sheltering by vegetation, and slope. To predict changes in fire behavior the firefighter must estimate the windspeed currently affecting the fire and also the windspeed that will affect it in the future (to obtain the EWS-ratio).

Variations of EWS over the terrain—If even a steady, 'uniform' wind impinges on terrain it will vary greatly in speed and direction from one point to another across the landscape. It will be channeled by drainages, and its speed will be strongly influenced by the topographic obstacles it encounters. For unstable or neutrally stable unstratified airflows, typical of the well-mixed conditions of a sunny afternoon, the following patterns occur.

Windspeed will be topographically enhanced on upwind slopes, and diminished on downwind (lee) slopes; it will generally be higher on an upper slope than on a lower slope. A suitably accurate assessment of fire behavior depends on accounting for the variations in windspeed across the terrain. We want to gauge the windspeed on the upper slope (upper third or so) versus that on the lower slope (lower third or so), and on the downwind (lee) versus the upwind slope, and to relate them to the forecasted general or ridgetop windspeed. The guideline (illustrated in fig. 6) for estimating those variations is based on the several sources detailed below, all of which are compatible with such a guideline.

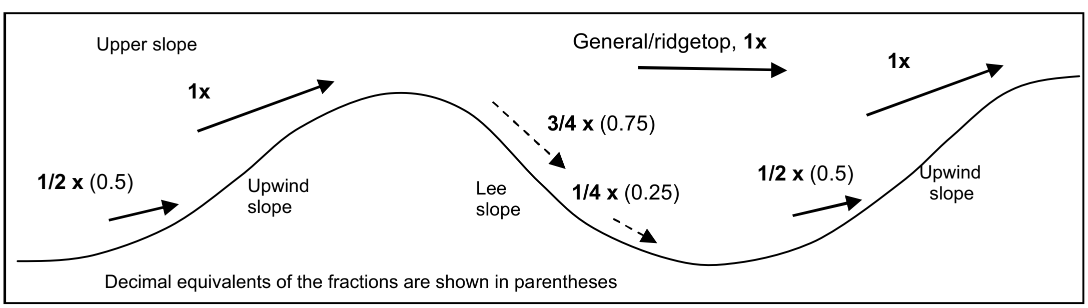


Figure 6—Schematic illustration of the FLAME guideline for estimating variations in windspeed over the terrain. Wind blows from left to right, values normalized to unity for general/ridgetop windspeeds. Lee-slope adjustments are valid only on slopes <30 percent and without sharp ridgetops. Winds described as 'winds of critical concern' by fire weather meteorologists and downslope winds are not subject to the above adjustments.

Equation 9 (below) can be used to estimate the 'speedup' of wind (ΔSmax, the excess of ridgetop windspeed above ambient over the plains) at the tops of hills or ridges (Barry 1992). The form below averages the coefficients for the 'isolated hill' case and the 'uniform ridge' case. Here 'h' is the height of the hill or ridge, and L* is the half width of the hill at its midelevation.

ΔS_{max} = 1.8 h/L* (note: units cancel in the ratio) Eq. 9

For a hill having symmetrically equivalent topographic profiles on its upper and lower halves, equation 9 can be expressed in terms of slope (slope being approximately [h/L*]/2)

ΔS_{max} = 3.6X (slope), where slope is expressed as a decimal figure Eq. 10

For a hill of moderate slope, say 30 or 40percent, that means the wind over the top will be about 2X the ambient wind that blows against the hill (remember that windspeed at the ridge = ambient + ΔS_{max}). For steeper slopes the ridgetop wind increases would be somewhat higher.

Detailed studies of windflow over hills and ridges are reported in Mason and Sykes (1979) and Taylor and others (1987). The pattern and magnitude of variations in windspeed as air flows around hills or over ridges are reasonably similar to each other, and are in accord with the 'speedup' described by equation 10. Figure 7 shows the results for two separate wind-speed profiles over an elongate ridge. The average values of windspeed at slope positions corresponding to figure 5, normalized to unity for the ridgetop are: 0.46X, 0.89X, 0.70X, and 0.26X (compared to 0.5X, 1X, 0.75X, and 0.25X for the FLAME guideline).

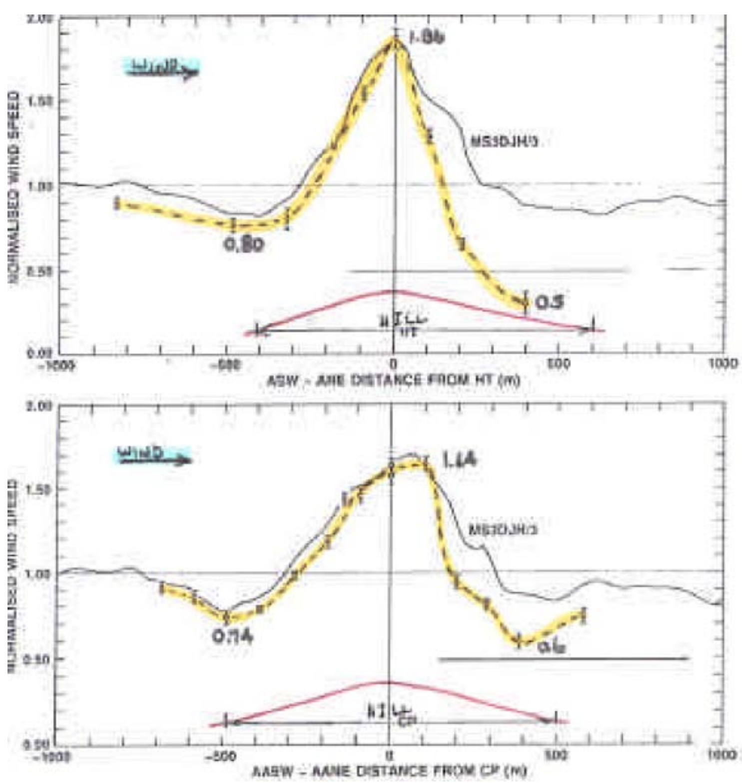


Figure 7—Profiles of windspeed over an elongate ridge at two locations (Taylor and others 1987). Wind blows more or less perpendicular to ridge axis; ridge topographic profiles shown in red. Windspeeds (yellow curve) are normalized to an ambient windspeed of one.

I have conducted several wind-speed surveys (often on S-290 field trips) over elongate ridges near Oroville and Susanville, California. Windspeeds were measured with handheld anemometers at eye-level, for either a 3-minute average, or by averaging 10 instantaneous observations taken over a couple of minutes. The normalized results are (moving with the wind from upwind to lee side): 0.5X (lower upwind slope), 1X (upper upwind slope), 0.8X (upper lee slope), and 0.2X (lower lee slope). This is close to figure 7 relative values and to the FLAME guidelines.

All of this pertains to neutrally stable or unstable airflows, but not to stable, stratified airflows such as sea breezes, outflow winds, night-time downslope winds, or foehn winds ('winds of critical concern')—these are often fastest on the downwind slope. I have not found data for a corresponding guideline in stable airflows, and one must simply use observed or forecasted windspeeds without extrapolation to other parts of the terrain. The scale of the topographic relief characterizing the observations is on the order of 100s of feet of elevation, and the observations were on slopes of 30 percent or less.

Table 7 compares the theoretical and observational data with the FLAME guidelines (which are arithmetically simplified to facilitate their application). Figure 8 illustrates a comparison between the FLAME guideline and an advanced airflow model.

Table 7—Summarizing the theoretical and empirical basis for the wind reduction factors (research studies and personal observations), and the FLAME guidelines, for approximating the variations in windspeeds as air flows over hills and ridges in neutrally stable or unstable conditions. Ridgetop windspeed is taken as the general windspeed, and the below values are normalized to ridgetop windspeed (as 1X).

	Equation 9	Taylor and others (1987)	Personal observation	FLAME guideline
Lower upwind slope	0.5X	0.46X	0.52X	**0.5X**
Upper upwind slope	1X	0.89X	0.88X	**1X**
Upper lee slope	NA	0.70X	0.64X	**0.75X**
Lower lee slope	NA	0.26X	0.24X	**0.25X**

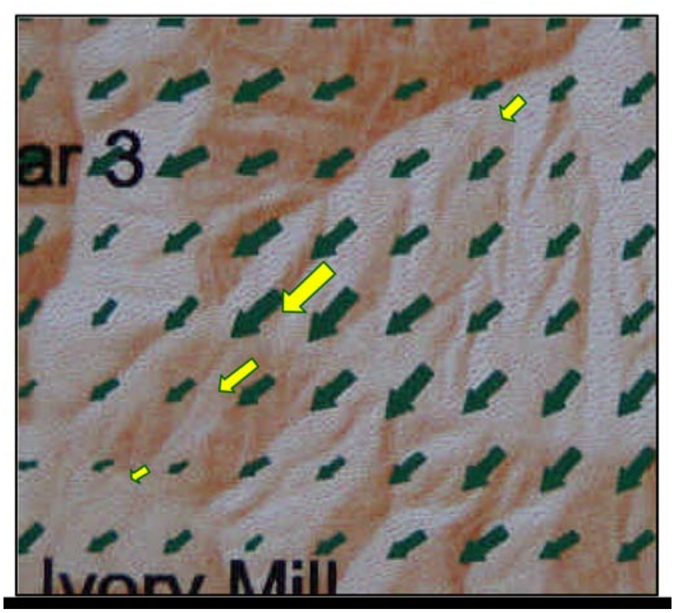


Figure 8—Comparison of FLAME guideline for windspeed variations over terrain with wind-field map generated by an advanced airflow-terrain model. Green arrows are model-generated. Yellow arrows along a line that crosses the ridge at the head of the basin are from the FLAME guideline, scaled to be (from upper right to lower left) 0.5X, 1X, 0.75X, and 0.25X. There is good overall agreement of the guideline with the model in predicting the magnitude of the variations in windspeed.

Variation of windspeed with flame height and sheltering by vegetation—What is needed for predicting fire ROS is the midflame windspeed (MFWS), or less formally the 'flame level' wind. For a given location on the terrain the MFWS depends upon the height of the flames and the wind obstruction by vegetation (for example, 1-ft flames under a stand of trees in litter versus 30-foot flames in an open brushfield).

The guidelines used in FLAME for adjusting wind for flame height and sheltering vegetation are equivalent to the 'wind reduction factors' of FBPS, and closely match that scale in relative terms. Using the adjustment factors to 'reduce' 20-ft winds conforms with the practice suggested by fire weather meteorologists and utilized in application of the FBPS.

The FLAME wind-reduction factors are keyed to each of the major fuel types, and are applied to the 20-ft windspeed. These values correspond closely to the FBPS reduction factors of 0.6X, 0.4X, and 0.15X (average for sheltered fuels), and bear nearly the same relative values. Reduction factors applied to 20-ft windspeeds for FLAME application are (expressed here as simple fractions for ease of use):

- crown fire MFWS (using the 20-ft wind directly) is 1X(20-ft WS)
- grass fire MFWS (and low/scattered brush) is (3/4)X(20-ft WS)
- litter fire MFWS (reflecting low flames and obstruction by the stand) is (1/4)X(20-ft WS)

Eye-level is the most practical wind observation level for people in the field. The following adjustments can be made to eye-level windspeeds for flame height and sheltering, based on the relative scale described above:

- crown fire MFWS is (1 1/3) X EL WS
- grass/low-shrub fire MFWS is 1X EL WS
- litter fire MFWS under a stand is (1/3) X EL WS

Where do the FLAME wind-reduction factors come from?—The basis for using the 20-ft windspeed at crown level, and the reduction factor for eye-level winds, lies in the following field observations and the logarithmic wind profile expressed in equation 11.

My observations of eye-level wind at two RAWS stations in open, scattered, low shrubs consistently yield eye-level values that are 0.8X of the corresponding 20-ft windspeed. The Australian CSIRO system (Cheney and Sullivan 1997) also applies a 0.8X reduction to obtain eye-level (2-m) windspeeds from 10-m windspeeds. In both cases the crown-fire MFWS, being several feet or more above eye-level, would be essentially those observed at 20 ft (or 10 m) or at least 0.9X of 20-ft windspeed.

The logarithmic expression for the boundary layer wind profile, applied with an average roughness coefficient characteristic of a mix of grass and low shrubs (0.09 m), is equation 11. Here u_Z is the windspeed at height z; u_{Z_o} is the windspeed at the reference height z_o. Heights are in meters.

$$u_Z / u_{Z_o} = [\ln (z/0.09 \text{ m})] / [\ln (z_o / 0.09 \text{ m})] \qquad \text{Eq. 11}$$

From equation 11 the reduction factor for eye-level (taken as 1.8 m) compared to 20-ft (6 m) windspeed is 0.71X. Combining the logarithmic data with the observations at RAWS stations (and to keep the rule simple) yields a (3/4)X reduction factor for eye-level windspeed (applicable to fires in grass and low/scattered brush).

The FLAME wind reduction factor for fires in litter is (1/4)X. That value comes mainly from the relative reduction in winds for fully sheltered litter fuels compared to ‘open fuels’ (grass fuel models) and to fuel model 4 brush as embodied in the FBPS guidelines: 0.15X for the average of sheltered fuels, 0.4X for open fuels, and 0.6X for crown fire in deep brush fields. 0.15X is about one-third of 0.4X and is one-fourth of 0.6X.

The slope contribution to EWS—BehavePlus incorporates the influence of wind and slope on ROS by adding a wind coefficient and a slope coefficient to the propagating flux ratio (Rothermel 1972). The combined coefficients can be thought of as accounting for the ‘effective windspeed’ (EWS). FLAME handles slope in the same way, by adding an increment of ‘upslope wind’ that has the same effect on the ROS as does the actual slope.

The slope-equivalent wind is similar for all fuel types. It is greatest at low MFWS and on steep slopes. And in many realistic situations it tends to be a small factor compared to the actual MFWS. The variation of the actual windspeed induced by topography is much more important to variations in ROS than is the ‘direct’ effect of slope. The following guidelines for handling slope (with upslope wind and upslope fire spread, as is also assumed in the FBPS nomograms) are utilized to yield the EWS used in FLAME.

- Slope less than 20 percent, no correction to the actual MFWS
- Slope 20 to 40 percent, add 1 mi/hr to the MFWS
- Slope 40 to 60 percent, add 2 mi/hr to the MFWS
- Slope 60 to 80 percent, add 3 mi/hr to the MFWS
- Slope greater than 80 percent, add 5 mi/hr to the MFWS

Defining the EWS for a backing or flanking fire—At low EWS, and for backing (negative EWS) or flanking fires the ROS curve flattens and represents a slowly changing ROS. One cannot use a zero or negative EWS in determining the EWS-ratio. A ‘backing-fire EWS’ to use in representing backing fires on the standard curve must be determined.

Basically, the problem is that ROS does not go to zero when EWS goes to zero (even though the standard FLAME curve, a power function, would go through the origin). The physical reason is that fire propagates by processes other than wind alone, and does not stop spreading in the absence of wind. For fires backing into the wind and/or down a slope intra-fuelbed radiation and convective dominate heat transfer, and ROS is relatively insensitive to variations in windspeed or slope.

In the original work on which BehavePlus is based the ‘backing’ ROS was taken as simply the flat-table, zero-wind ROS (Rothermel, personal communication). The Australian work on grass fires defines a similar relationship in that backing-fire ROS is found to remain essentially constant up to windspeeds of 20 km/hr (Cheney and Sullivan 1997). Other reports show backing ROS to decline slowly with increasing slope.

An important fireline-safety situation involving backing fires is fire in litter backing down a slope under largely wind-sheltered conditions. Such instances are common, and the change between backing litter fire and running crown fire is an extremely important FLAME application. So the backing EWS used in FLAME is based largely on the litter fuel type. The backing-fire EWS (not the backing ROS) for grass is similar to that for litter. Because backing fires do not propagate directly through crown foliage, there is no crown-fuel backing-fire EWS in FLAME.

It is assumed that over a reasonable range of slopes and windspeeds that the backing ROS falls between the zero-EWS value and half of that value (for example between 0.6 and 0.3 ch/hr). So the representative backing ROS is taken as the average of those values, or 0.75X(ROS at EWS=0).

The question of what EWS to use to represent backing litter fires is then: 'What EWS on the litter standard curve corresponds to the representative backing ROS?' The representative backing ROS (not EWS) is 0.47 ch/hr, which is 75 percent of the average zero-EWS spread (which is 0.63 ch/hr) for fuel models 8, 9, and 10. The corresponding EWS is 0.5 mi/hr (fig. 9).

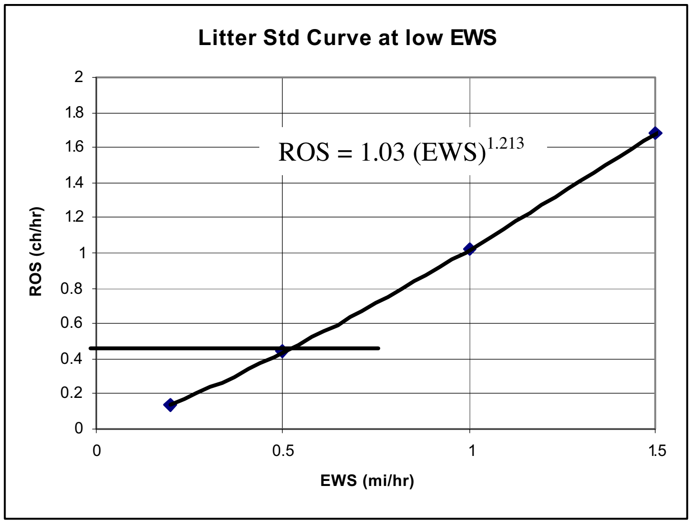


Figure 9—Standard curve for litter fuel type, with characteristic backing fire ROS at 0.47 ch/hr (which is 75 percent of the zero-EWS ROS of 0.63 ch/hr). The curves intersect at EWS = 0.5 mi/hr, and that is taken to be the EWS characteristic of backing fires. An EWS of 0.5 mi/hr is the lowest value of EWS used in FLAME. Comparisons (ROS-ratio) to other EWS and ROS values on the curve are mutually consistent. Vertical axis is ROS in ch/hr.

So, in FLAME the backing-fire EWS = 0.5 mi/hr. For flanking fires the EWS is taken to be 1.0 mi/hr (being slightly less retarded by the opposing influence of wind and slope, and given that even slight variations in wind on flanking flames can momentarily act to advance them).

A similar analysis to that above for grass yields a backing-fire EWS of 0.4 mi/hr. An adjustment can be made for cases involving grass, but most of the time it is not necessary to a useful FLAME result.

Basically, the use of a backing-fire EWS of 0.5 mi/hr states that a backing fire moves as if it were driven by a wind of 0.5 mi/hr in the absence of other heat-transfer processes, within the context of the ROS relationships expressed in the FLAME standard curves. That use of an 'equivalent wind' allows the comparison of ROS under backing conditions with ROS where effective wind is the dominant fire-spread influence. The standard curves are effectively truncated at EWS = 0.5 mi/hr, and that represents the slowest possible ROS.

Computing the EWS-ratio—Given the EWS associated with 'current' fire behavior, and an estimate of the EWS that is expected, the EWS-ratio is computed. Because it is easier to work with whole numbers versus fractions, the EWS-ratio is always the larger EWS divided by the smaller EWS. A FLAME user would simply keep in mind whether that change in EWS would be associated with an increase or a decrease in ROS (for example, will the fire go 6X faster, or 6X slower?). If the arithmetic is easy, the user can simply do the division. For example, if the larger EWS is 8 mi/hr and the smaller one is 2 mi/hr, the EWS-ratio = 8/2 = 4X. For cases where the arithmetic is not so easy, table B1 in appendix B allows a simple look-up of the EWS-ratio; it is nothing more than a paper calculator. That EWS ratio is used to enter the left column of table 2.

Part 3: Application in the Field

The Field Worksheet, Stage by Stage

The worksheet is organized to follow the three 'application stages' described in the section *Flexibility in application*, initial, standard, and complete application. As seen in figure 10, where the sheet is divided left-right, the left side records 'current' conditions and the right side records 'expected' conditions. In the following discussion each application phase will be detailed, using the appropriate subsection of the worksheet. Notations and examples will explain each worksheet entry. Worked examples follow the illustration of the three application phases. Although this description is intended to illustrate the FLAME application process, it is not a complete training manual.

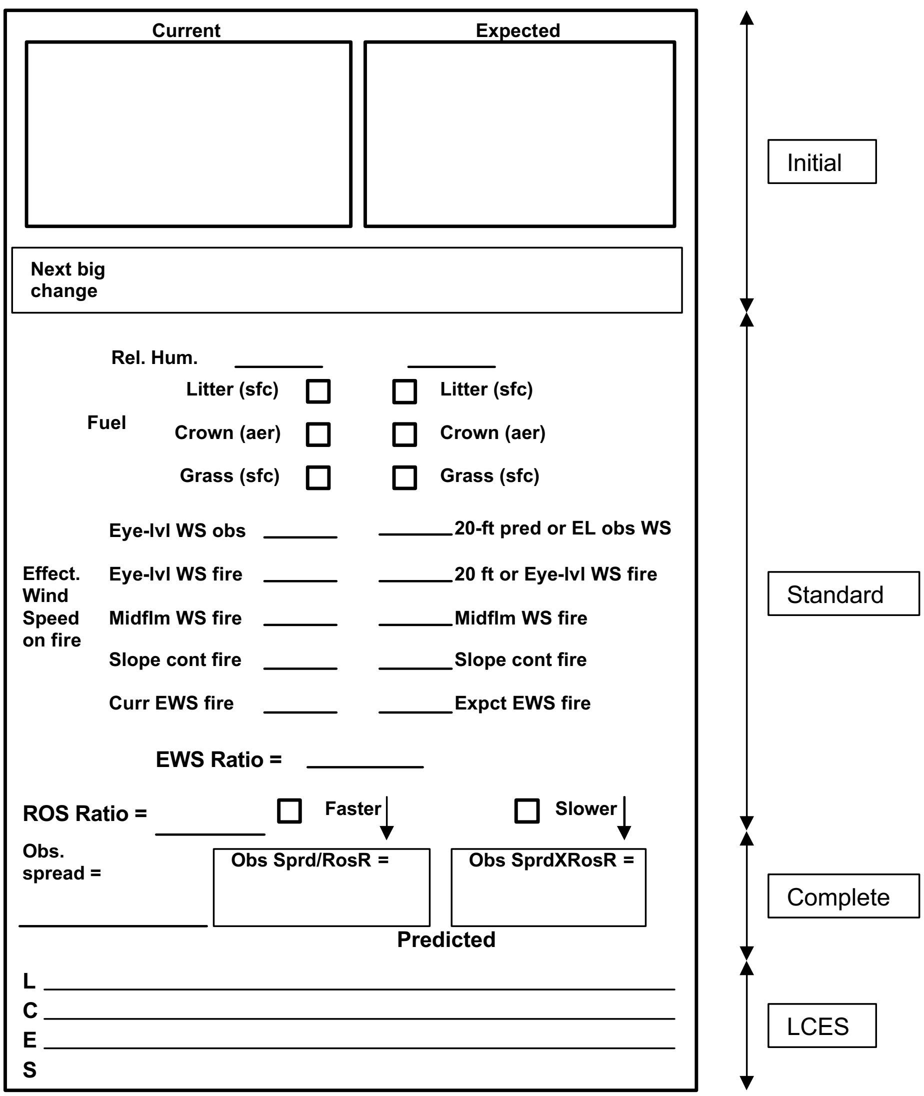


Figure 10—FLAME worksheet. Down to the 'EWS-ratio' entry the left side is for 'current' conditions and the right side for 'expected' conditions. Fuels are listed in order from slowest to fastest; the EWS spaces follow the adjustment process from raw values to EWS on the fire. The 'LCES' portion allows for notes about how those guidelines will be implemented.

Initial FLAME application—Considering the current and expected fire behavior, and identifying the next big change, make up the initial FLAME application. The following three examples show how the current and expected conditions can be depicted in various styles. The style or art work is not important. The critical thing is that the firefighter is prompted to consider those conditions; to be able to complete the pictures means having made a complete fire behavior assessment. If some box is empty you have not fully assessed the current and expected fire behavior and potential changes. No assessment is ever perfect or finished, but it represents the best you know with the present information and can reveal important gaps in your information.

Depict the current fire behavior and fire environment, and the situation you expect after the next big change. You can sketch a profile of the area, such as the two slopes, with the fire and fuel-types shown. You can sketch a map view, a diagram of the fire area. Show the winds you expect with arrows. Or you can simply list the key points of the description of fire and conditions. Note the 'next big change', and some idea of when it will come, in the space under the sketch.

Figures 11 and 12 show the components of the initial-application phase of the worksheet, and three examples of how they might be filled out.

Standard FLAME application—The heart of the *FLAME* process, the standard application, requires the specification of the fuel types and effective windspeeds, both current and expected. From that the ROS-ratio is determined, indicating the magnitude of the next big change. The magnitude of the change in ROS-ratio is suggestive of the potential danger posed by the change.

The standard-application phase requires the firefighter to obtain specific observations of relative humidity (RH), fuel type carrying the fire, and effective wind acting on the fire. It also requires the firefighter to predict the expected conditions of RH, fuel type, and effective wind. That in turn prompts projection of the fire's progress and attention to the current weather forecast. **The most important effect of completing the standard application phase is that it leads the firefighter to obtain specific information on the key fire behavior variables, which can make obvious the absence of critical information.** Determination of the ROS-ratio also provides a measure of the magnitude of change pending, which conveys a sense of the level of potential danger.

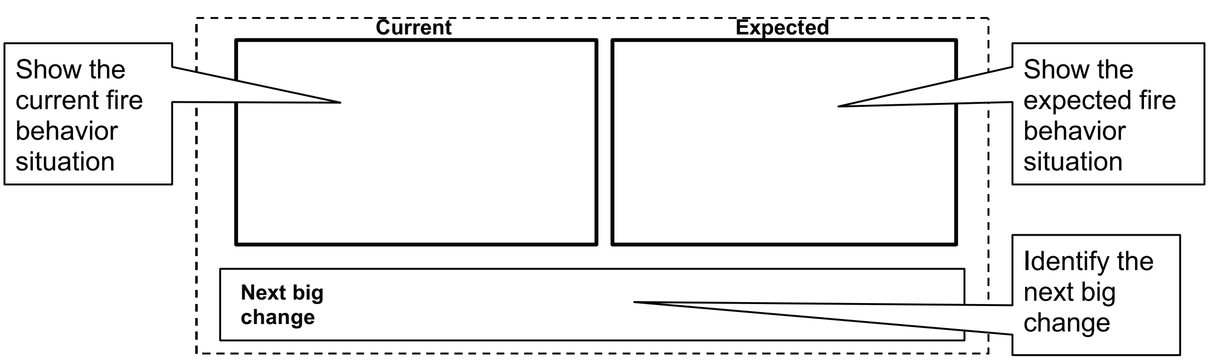


Figure 11—'Initial application' portion of the FLAME worksheet, annotated to describe the appropriate entries.

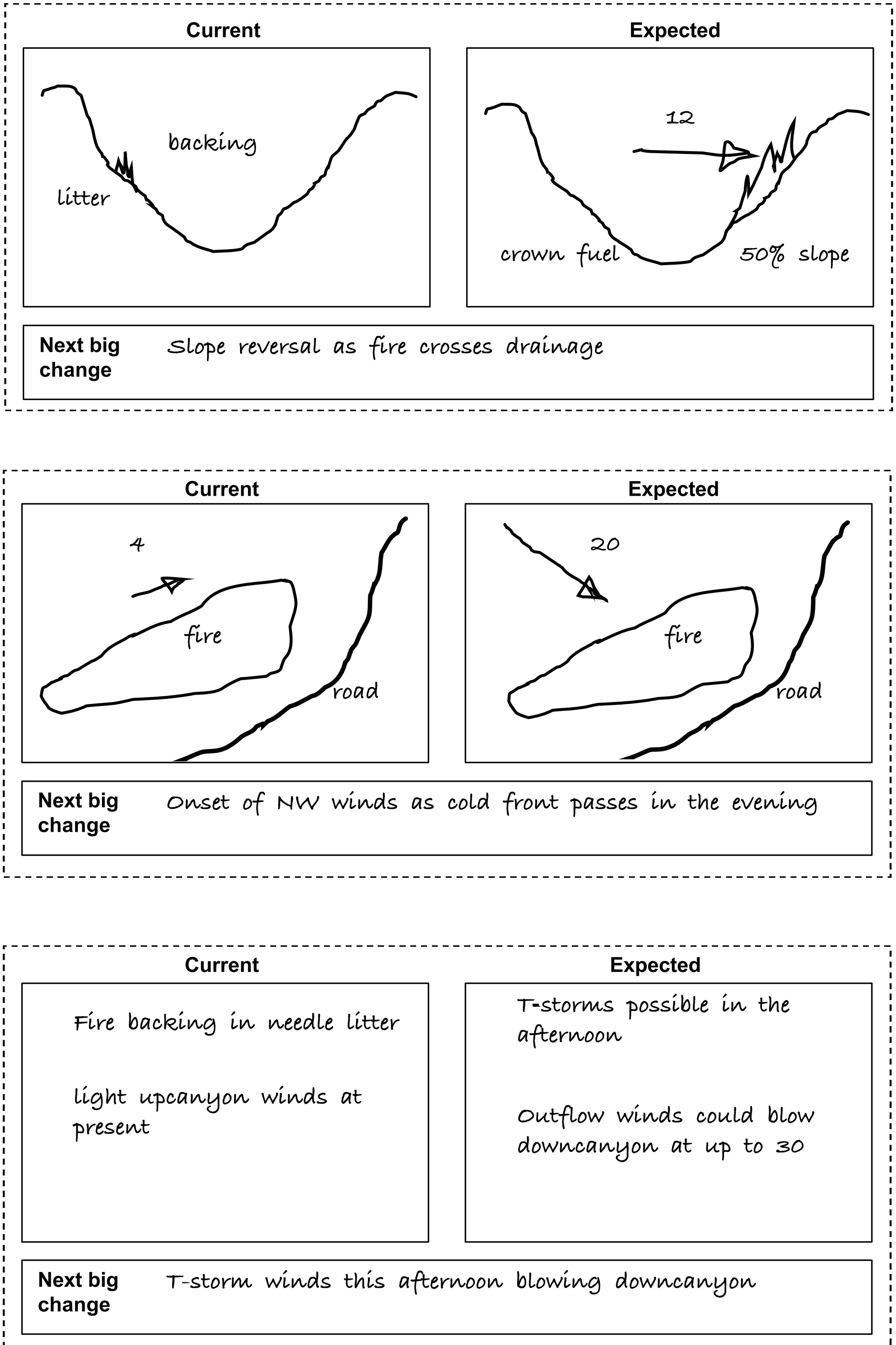


Figure 12—Three examples illustrating the current and expected conditions and identifying the next big change, using the worksheet format. The style of illustration is entirely up to the user, and three different situations are shown here as a terrain profile, a sketch map, and an outline to depict the current and expected conditions.

Figure 13 illustrates the components of the standard-application section of the worksheet and presents examples of how information would be developed in that section.

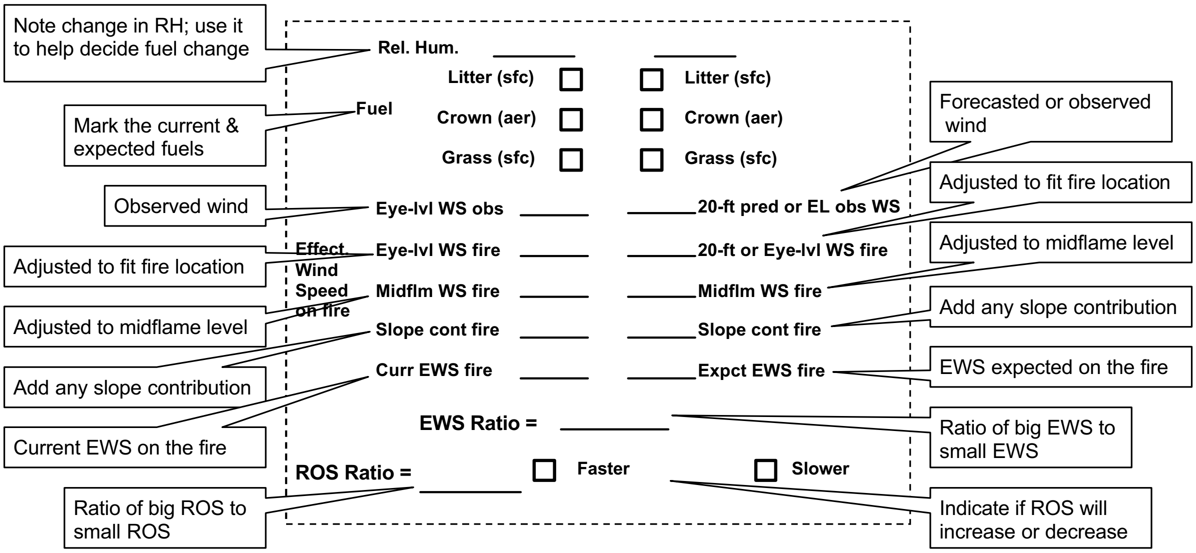


Figure 13—'Standard-application' portion of the FLAME worksheet, annotated to describe the appropriate entries. Entries on the left side represent current conditions, and on the right side the expected conditions. EWS-ratio and ROS-ratio express the degree of change between current and expected conditions.

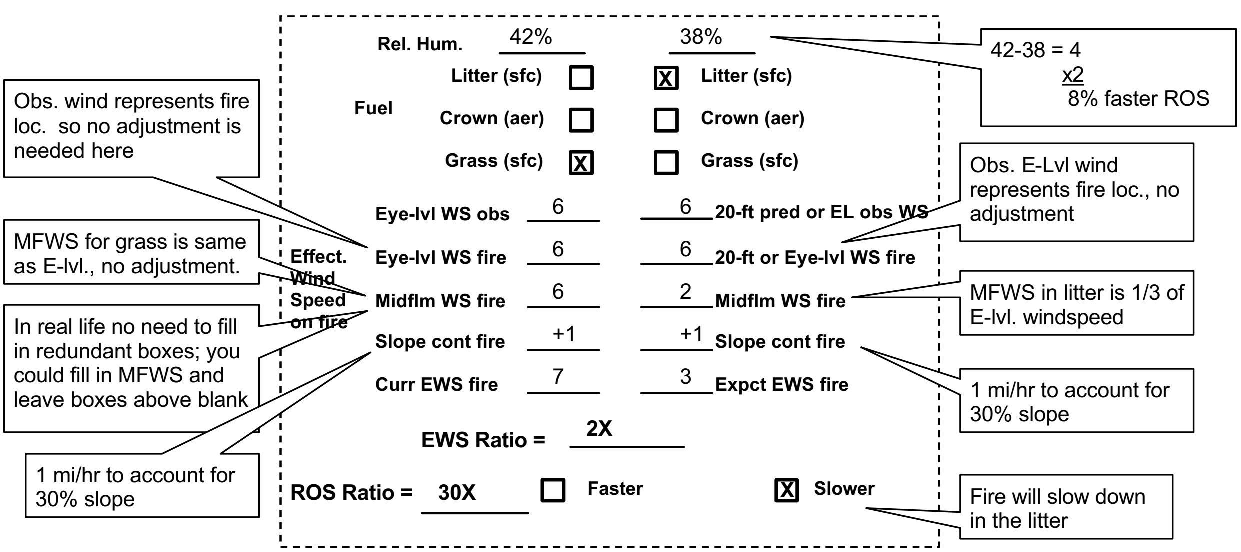
Following are three different fire behavior examples illustrating different styles.

Example 1: A fire burns up a 30 percent grassy slope and will spread into forest litter. You have observed the eye-level wind at a point on the same slope not too far from the fire. Overall conditions are not expected to change significantly, though the RH will drop to about 38 percent. Crown fire potential is minimal. The next big change will be the passage of the fire from open grass into sheltered litter.

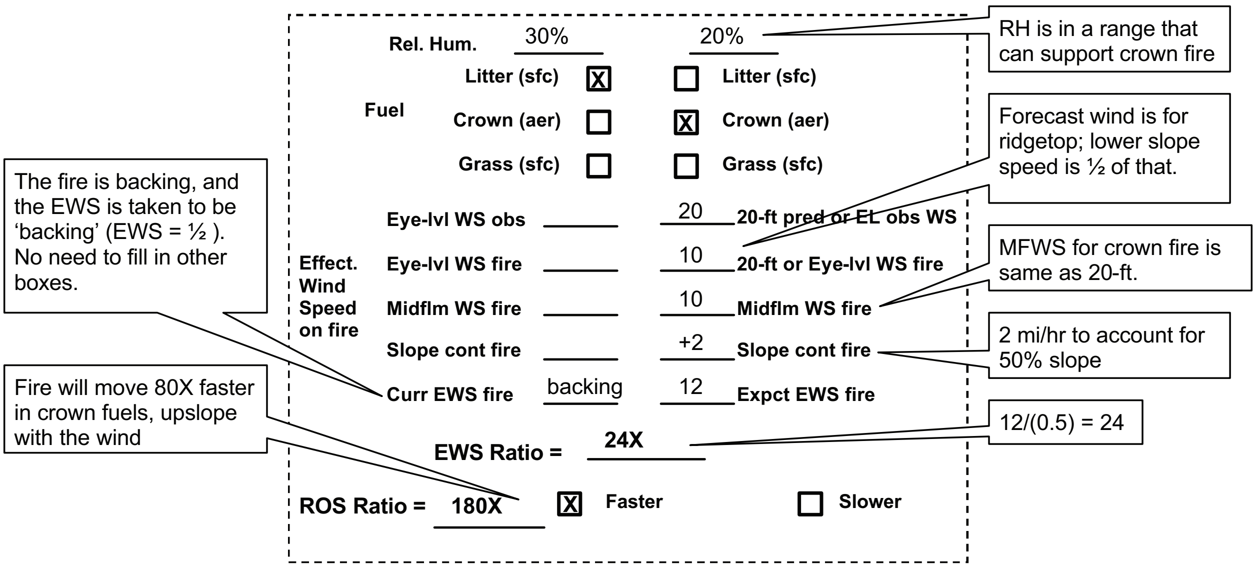
Current conditions: RH = 42 percent; Fuel is grass; Eye-level wind = 9 mph; Slope = 30 percent

Expected conditions: RH = 38 percent; Fuel will be litter; No large wind changes expected; Slope = 30 percent

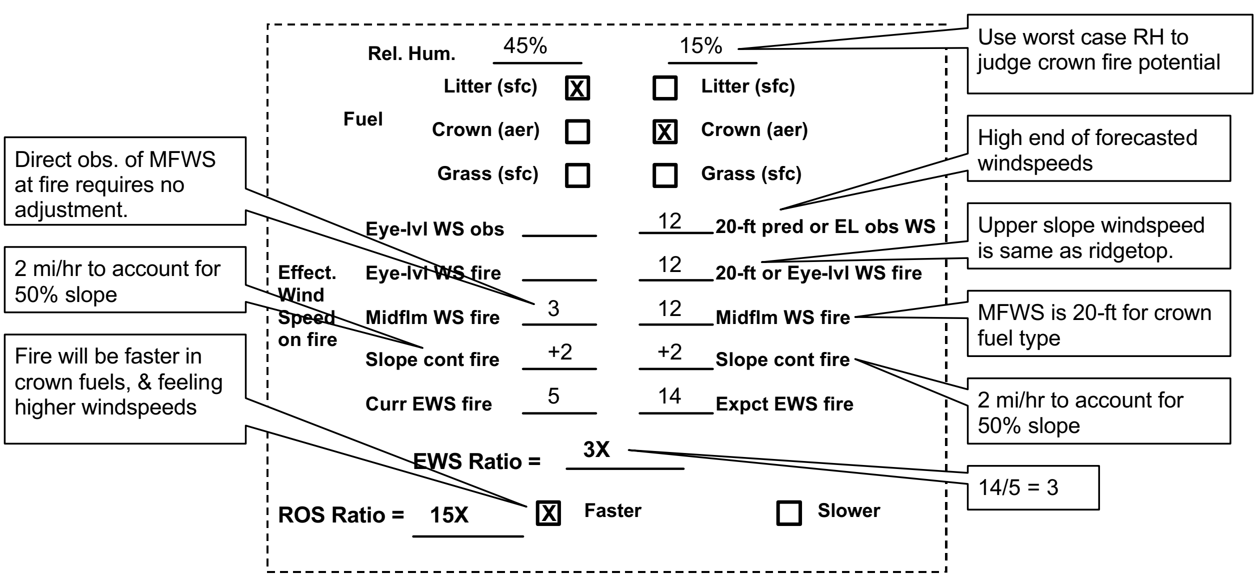
The completed worksheet section would look like this. The small effect of the RH drop can be estimated as in the upper right box.



Example 2: A fire backs down a slope in litter, RH = 30 percent. It is expected to cross the drainage and spread up the next slope (an upwind 50 percent slope) as a crown fire. The ridgetop windspeeds are forecast to be 20 mph, and RH to be 20 percent. The next big change will be the transition from backing litter fire to running crown fire, and it will affect the lower slope first. RH value helps evaluate the potential for crown fire, but no adjustment for RH change is made for crown fuels.



Example 3: A fire is burning up a 45 percent lower slope in litter, midmorning, RH = 36 percent. By afternoon it will reach the upper half of the slope and is expected to transition to crown fire. You directly observe the wind on the litter fire, at litter flame height, to be 3 mph upslope. The afternoon wind will be in the same upslope direction, and 20-ft windspeed is forecast to be 8 to 12 mph, RH will be 15 to 20 percent. The next big change will be the transition to crown fire this afternoon on the upper slope.



Complete FLAME application—Develops a fire spread-time by applying the expected change in ROS to the observed spread-time under current conditions. The spread is gauged against ‘natural yardsticks’ (such as a slope, an open field, utility or fence poles, road intersections, the distance the fire has moved). For example, a fire might be observed to move down a slope in 12 hours, or halfway across a field in 20 minutes. Such observations constitute the ‘observed spread’ (left hand space in fig. 13).

If the ROS increases, the fire would be expected to spread a similar distance in a fraction of the time. For example, if the ROS-ratio is 24X, then a fire backing down a slope in 12 hours would be expected to go back up the same slope, or up the opposing slope, a similar distance in $1/24^{th}$ of 12 hours, or one-half hour. In other words, the expected spread time when ROS increases is the observed spread time divided by the ROS-ratio (middle box in fig. 14).

Similarly, if the ROS decreases, then the expected spread time will be the observed spread time multiplied by the ROS-ratio (right hand box in fig. 14). For example, if a fire observed to cross half a field in 20 minutes slows down by 3X, then it will cross the other half of the field in about 60 minutes.

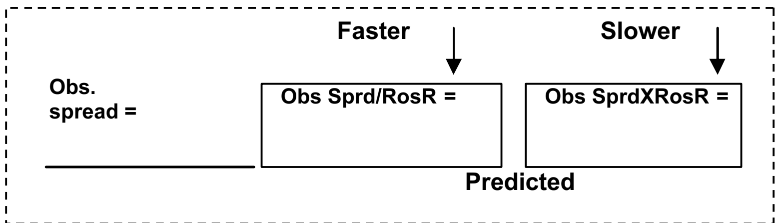
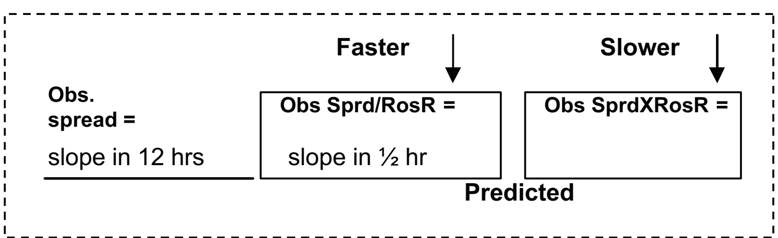
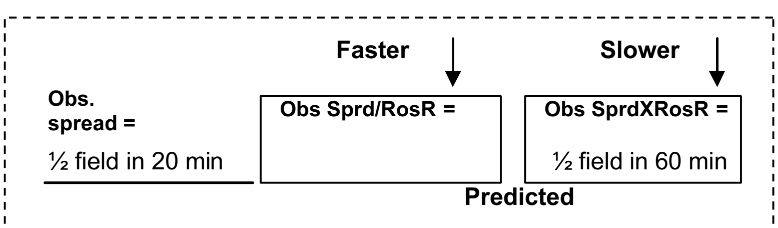


Figure 14—‘Complete application’ portion of the worksheet. Observed spread of the fire is noted on the left. The ‘faster’ or ‘slower’ expected fire ROS directs the user to the appropriate box, in which is the formula for calculating the expected spread time over a similar distance. In the case of faster expected ROS the predicted spread time will be the observed spread time divided by the ROS-ratio; in the case of slower ROS the predicted spread time will be the observed spread time multiplied by the ROS-ratio.

Example 1: A fire moves down a slope in 12 hours, and is expected to spread up the adjacent slope 24X faster, an ROS-ratio of 24X and an increase in ROS.



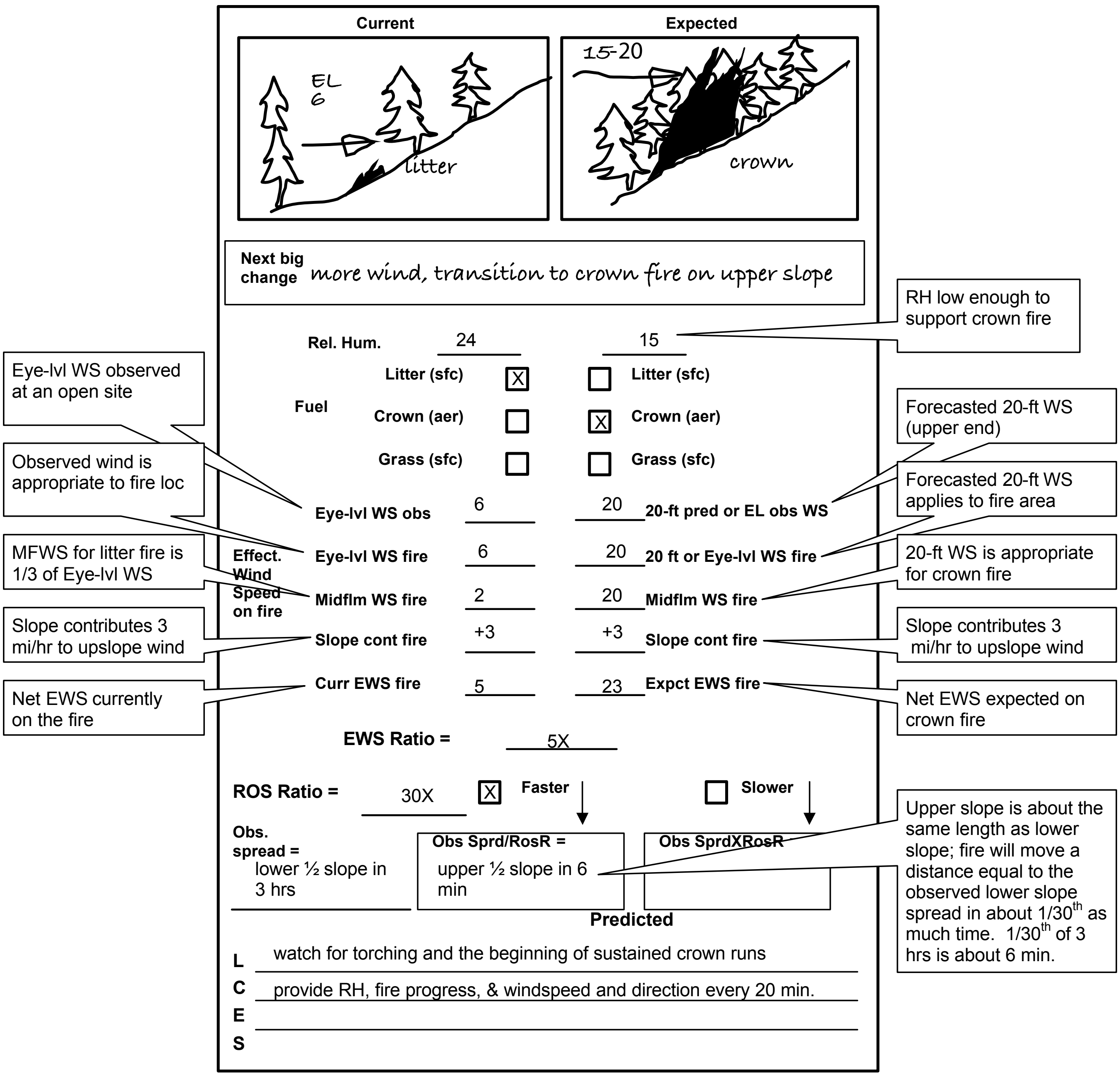
Example 2: A fire moves halfway across a field in 20 minutes. The wind is expected to decrease, and the fire is expected to move 3X slower after that, an ROS-ratio of 3X and a decrease in ROS.



Illustrating the FLAME Application Process in Full

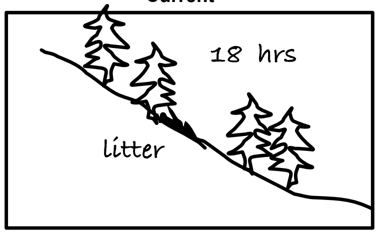
Example 1: A fire burns up a lower SW slope (over 60 percent) in litter under a stand of pine trees, where observation shows RH = 24 percent and eye-level windspeed 6 mi/hr. The fire advances at a rate that will cover the lower half-slope in about 3 hours. As the fire moves up the slope it will begin to feel more wind, RH is declining, and the fire will transition to a crown fire on the upper slopes. Forecasted winds are SW 15-20 mi/hr, RH dropping to 15 to 20 percent range. Consider a crown fire run on the upper slope.

The RH values help determine the potential for crown fire, but are not a significant guide to fine-tuning the predicted ROS-ratio.

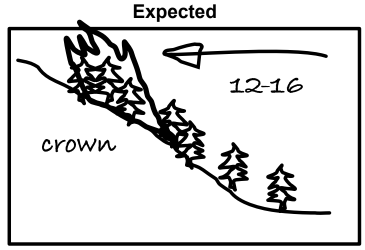


Example 2: Fire in litter under conifer and shrub stands is backing downslope into a small canyon; RH is 40 percent. It has backed the previous late afternoon and night and is expected to reach the canyon floor by midmorning, a total of 18 hours. General winds of 12 mi/hr are blowing above the nocturnal inversion in the up-canyon direction. With the development of up-drainage winds, combined with the general wind, the upslope wind in the afternoon is forecasted to be 12-16 mi/hr. Foliage is dry and will support crown fire; afternoon RH is expected to be in the high teens. Canyon slopes are 40 to 50 percent.

Current



Expected



Next big change: onset of upcanyon winds and beginning of crown fire, by early afternoon

	Current	Expected	
Rel. Hum.	40	17-19	RH low enough to support crown fire
Fuel: Litter (sfc)	[X]	[ ] Litter (sfc)	
Fuel: Crown (aer)	[ ]	[X] Crown (aer)	
Fuel: Grass (sfc)	[ ]	[ ] Grass (sfc)	
Eye-lvl WS obs		16 — 20-ft pred or EL obs WS	Forecasted 20-ft WS (upper end)
Effect. Wind Speed on fire: Eye-lvl WS fire		12 — 20 ft or Eye-lvl WS fire	Overall WS for entire slope, avg of upper & lwr
Midflm WS fire		12 — Midflm WS fire	20-ft WS is appropriate for crown fire
Slope cont fire		+2 — Slope cont fire	Slope contributes 2 mi/hr to upslope wind
Curr EWS fire	back	14 — Expct EWS fire	Net EWS expected on crown fire

The fire is backing, and the EWS is taken to be 'backing' (EWS = ½). No need to fill in other boxes.

EWS Ratio = 28X

14/(0.5) = 28

ROS Ratio = 200X [X] Faster [ ] Slower

Choose the ROS-ratio that falls between EWS=24 & EWS=30 in the FLAME table

Obs. spread = down major slope in 18 hrs

Obs Sprd/RosR = major slope run in 5 or 6 min possible

Obs SprdXRosR

Canyon slopes are all about the same height; fire will move a distance equal to the observed down slope spread in about 1/200th as much time. 1/200th of 18 hrs is about 5 or 6 min.

Predicted

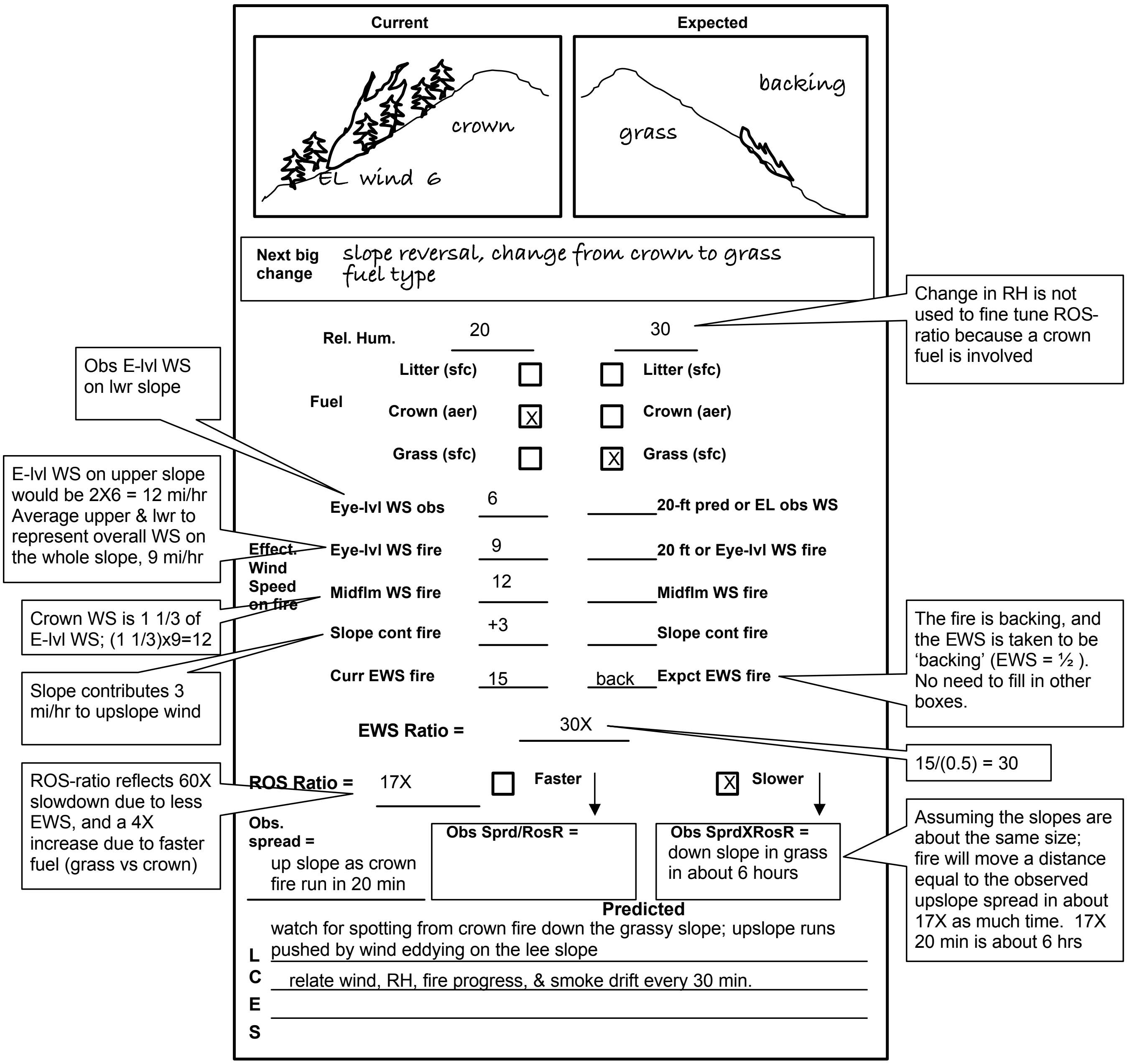
L watch for mixout of inversion, onset of gusty upslope winds; note any torching, sustained movement of crown fire on slopes above drainage

C report wind, RH, & smoke drift every 30 min.

E

S

Example 3: Fire will run to the top of a 60 percent slope as a crown fire in timber. Sustained runs have taken about 20 minutes to sweep up the slope in late afternoon. RH is 20 percent, but will be increasing to 30 percent shortly after sundown. Eye-level winds on the lower part of the timbered slope were observed to be 6 mi/hr. Over the ridgetop the lee slope is primarily grass.



Appendix A: Input Data for FLAME Application to Case Studies

FLAME outputs are compared to the reported fire behavior that has been reconstructed in the incident investigations. FLAME is applied as it might be by a firefighter who sees the 'current' fire behavior as the ongoing behavior that is characteristic of the early phases of the work shift, and considering 'expected' fire behavior that would arise from conditions that did occur in connection with the burnover. The expected conditions may not have been clearly seen or considered at the time, but they could have been. FLAME is here being tested as a tool applied to what could have been known.

The reported fire behavior is typically a mix of model outputs, informal observations, and reconstructions from travel times, videos, and photographs. Even though it is here termed 'actual' fire behavior it is subject to many assumptions and approximations. Still, the well investigated cases offer the best documented examples available of 'before and after' fire behavior in realistic situations.

The application of FLAME to these fatality cases is based on the fire behavior setting and events that took place, a test of FLAME in realistic situations. The purpose is to test the applicability and accuracy of FLAME, so the best known conditions are utilized, even though conditions may not have been that accurately known to fireline personnel at the time. There is no intent here to evaluate or to judge operational or safety decisions.

South Canyon Fire *(Butler and others 1998)*

FLAME is applied as if crews were evaluating the effects of a 'next big change' that included a crown run back upslope under the influence of the forecasted frontal winds.

'Current' fire behavior is taken to be the long, downslope spread of a backing fire from the ridgetop to into the West Drainage, once that spread was well established, on and after 3 July 1994. The average rate displayed by the fire over that interval was 32 ft/hr, and at that rate it would take about 60 hours to back down the slope. While there was some grass in the fuelbed, the fuel carrying the fire was predominantly litter.

'Expected' fire behavior is taken to be the upslope spread of the fire from the West Drainage bottom at a time estimated to be 1605 hours on the reconstructed perimeter map, a point below the crews and near the beginning of the upslope run, to where the constructed fireline left the ridgetop. Upslope winds are taken as the 30 mi/hr midpoint of the modeled '25 to 35 mi/hr' slope winds reported in appendix C of Butler and others (1998). The 10 percent RH is taken as an approximation from the Rifle RAWS record.

Actual ROS-ratio is calculated from the spread rates reconstructed in the report, and distances scaled from the map, over the time interval from 1605 to 1614 hours. FLAME ROS-ratio assumes an EWS increase from backing to 30 mi/hr, EWS-ratio = 60X, and a change from litter to crown fuels. Applied to the 60-hour downslope transit of the fire, FLAME predicts a 7 to 8 minute upslope run.

'Actual' ROS-ratio = (267 ft/min X 60 min/hr)/(32 ft/hr) = 500X; Reconstructed upslope run is 9 minutes

FLAME ROS-ratio = 500X; Prediction of 'expected' upslope run is about 7 minutes [(60 hr)/500 = 7.2 min)]. (This differs from the actual spread time largely due to the downslope and upslope spread distances being unequal.)

Dude Fire *(USDA 1999)*

FLAME is applied as if crews were evaluating the effects of a 'next big change' that included the possibility of a thunderstorm outflow, originating over the fire or on the other side of it, on the active fire edge above their proposed control line.

'Current' fire behavior is taken as the backing fire on the slope above the crews. The backing fire ROS is calculated with BehavePlus, assuming Fuel Model 9, 1- hr FM 3 percent, 10-hr 4 percent, and 100-hr 6 percent (based on NFDRS reported values), and slope about 20percent. The predicted ROS for a backing fire under those conditions is 0.5 ch/hr. From the estimated position of the fire on the slope above the crews (approximately 200 to 300 yards) that backing fire would have reached the bottom in roughly 20 hours.

'Expected' fire behavior is taken to be the downslope spread of the main fire toward the line being constructed, as a crown fire driven by 30 mi/hr outflow winds. Even though the windspeeds have been estimated as greater than that by firefighters on the incident, my experience is that windspeed estimates by most observers are not very accurate, especially when there is fire and smoke and danger involved, and tends to emphasize gust speeds rather than average speeds. In the Dude Fire Investigation Reports (1999), Goens estimates that the first 5 or 10 minutes the wind was at its estimated 40 to 60 mph maximum, and about half that for the next 30 minutes. The comparison here involves an observation of ROS that took place over about a half hour, so the relevant average wind is what prevailed during that half-hour run. That windspeed average is taken as about 30 mi/hr (avg. 50 mi/hr for 5 to 10 min., then avg. 25 mi/hr for 20 to 25 min.). Several indicators, including the torching of trees by the backing fire, show the potential for transition to crown fire.

After the onset of the winds the fire was observed to advance about 1.5 miles in 30 minutes, for an approximate ROS of 3 mi/hr or 240 ch/hr. Actual ROS-ratio is calculated from the observed ROS of the crown fire (240 ch/hr) and the modeled ROS of the backing fire in needle litter (0.5 ch/hr).

'Actual' ROS-ratio = (240 ch/hr)/(0.5 ch/hr) = 480X; Comments from the investigation refer to the crews having a couple of minutes to see the fire as it runs down the slope toward them.

FLAME ROS-ratio = 500X; Prediction of downslope run to reach the crews is about 2 or 3 minutes [(20 hrs)/500 = 2.4 min], which is in line with comments from the crews.

Thirtymile Fire *(USDA 2001)*

FLAME is applied as if crews were evaluating the effects of a crown fire pushed by the afternoon upcanyon winds.

'Current' fire behavior is that which prevailed during the hours of the early suppression efforts and is termed 'Initial Phase' in the report. The fire behavior consisted predominantly of surface spread in litter, both flanking and backing, with some light downcanyon wind. The modeled ROS is reported as 1.3 ch/hr. FLAME Application assumes backing and flanking fire in litter.

'Expected' fire behavior is the sustained crown fire that moved up the canyon in the late afternoon and is termed 'Deployment Phase' in the report.

The modeled ROS is reported as 125 ch/hr. The 20-foot windspeed up the canyon is reported as being 9 to 11 mi/hr, and in the FLAME application is taken to be 10 mi/hr.

'Actual' ROS-ratio = (125 ch/hr)/(1.3 ch/hr) = 96X

FLAME ROS-ratio = 100X (based on an average of backing and flanking current fire behavior)

Cramer Fire *(USDA 2003; Kelley Close, Investigation FBAN, personal communication)*

FLAME is applied as if crew on the ridgetop were evaluating the possibility that the fire that had been backing into the drainage could spread up the drainage under the influence of westerly winds and become a crown fire.

'Current' fire behavior is taken as predominantly in litter on the slope above Cache Bar Creek. The fire had originally moved over the ridge and into the drainage the previous night and had backed actively all but the several hours before dawn. The total fire movement downslope into the drainage is estimated as taking about 17 hours and extends into the early afternoon. The backing distance, scaled from the map, is about 0.2 miles, or 1060 ft. The overall backing ROS is estimated to be 1 ft/min. There is reported to be some grass in the surface fuels, but for this application the spread is presumed to be predominantly in litter (and may account for the estimated 1 ft/min ROS being a little higher than would be predicted for just litter).

'Expected' fire behavior is the spread that moved up the canyon in the afternoon, becoming crown fire in low brush and eventually in trees, under the influence of increasing westerly winds (which blow up the canyon, gradually becoming more NW and impinging strongly on NW slopes at the head of the canyon). Windspeeds during that period average about 10 to 12 mi/hr at Lodgepole RAWS, and are taken as reasonable for winds in the canyon. Highest winds are estimated at over 20 mi/hr on the top of the NW slopes. To characterize the overall wind flow throughout the upcanyon spread of the fire, the 20-ft general windspeed is taken as the average of 12 and 24 mi/hr, or 18 mi/hr. Windspeeds at the bottom of the slopes would be approximately half that or 9 mi/hr. So the overall 20-ft windspeed associated with the upcanyon and upslope spread of the fire, throughout the depth of the canyon is roughly 14 mi/hr. Since much of the spread was in low brush, with flame heights less than the tree heights, the flame level winds are estimated to be approximately eye-level or about 11 mi/hr. Many assumptions are built into this windspeed, but it is not unreasonable for the average that prevailed throughout the vertical range of the fire as it spread along the drainage and up onto the upper wind-exposed slopes. The average overall ROS of the updrainage/upslope run is estimated from the reconstructed fire perimeters to be 124 ft/min. The reconstructed ROS on the upper slopes was considerably greater, but the average ROS is what is used to compare to the overall ROS increase estimated from FLAME. The movement of the fire up the drainage (as scaled from the map) is about 4X the distance that it backed down into the drainage.

'Actual' ROS-ratio = (124 ft/min)/(1 ft/min) = 124X; Reconstructed overall upcanyon spread took about 34 minutes (1450 hrs to 1524 hrs).

FLAME ROS-ratio = 160X; Predicted upcanyon spread would be about 26 minutes [4X(17 hr)/160 = 26 min].

Tuolumne Fire *(CDF Fire and USDA 2004, 2005; Larry Hood, Investigation Team FBAN, personal communication)*

FLAME is applied as if crews were evaluating the effects of a wind gust on the backing fire edge, as they constructed control line nearby.

'Current' fire behavior is described as fire in litter backing slowly into a steady upcanyon wind of 3 to 5 mi/hr. Backing ROS is modeled using fuel model 9, 1-hr FM 4 to 5 percent, wind 4 mi/hr with no appreciable influence of slope on the backing fire spread. Modeled ROS = 0.5 ch/hr, or approximately ½ ft/min. At that rate the travel time to the crew working approximately 7 to 30 ft away is roughly 15 to 60 min.

'Expected' fire behavior is anticipated to be a mix of surface fire and crown fire spread, as a gust of wind blows across the fire edge and pushes the fire toward the crew. There are no actual onsite observations that provide a measure of the conditions that prevailed. The wind shift is estimated in the report to be between 90° and 120°. I have estimated a wind gust of 12 mi/hr, deviating by between 90° and 180° from upcanyon and blowing at an angle outward across the fire edge toward the crews. Gusts of 12 mi/hr were observed at the Buck Meadows RAWS station on the canyon rim above the fire, and it is common for gusts to exceed the average windspeed on a well-mixed afternoon by somewhat over 2X. Also, I lived, worked, sailed, and operated portable weather stations in that unit for many years, and I have observed the common occurrence of turbulent gusts in the major canyons deviating strongly from the average upcanyon direction, even blowing in the opposite direction. The expected conditions assumed here are hypothetical, but are plausible and would have been a realistic expectation upon which to base a FLAME application for a crew working close to the fire edge and therefore 'within reach' of even a momentary surge of the fire.

Actual ROS ratio is not accurately known. Estimates of the duration of the flareup, made by crew members and by Air Tactics 440, fall in the range from about 10 to 30 seconds.

FLAME ROS-ratio = 90X (the average of a transition to crown fuels with continuing spread in litter). The expected travel time of the fire to the crews when the wind gust hits is approximately 10 to 40 sec. [(15 to 60 min)/90 = (10 to 40 sec)].

Appendix B: Lookup Tables

Table B1—EWS-ratio lookup table. Larger EWS on left, smaller EWS across top. Look up the EWS-ratio (=EWS_{LARGE}/EWS_{SMALL}) for corresponding large and small EWS values. For example, the EWS-ratio for a backing fire that will in the future have an EWS of 12 mi/hr is 24X. Tabled values are rounded off to avoid unnecessary detail.

EWS-ratio Table

Smal > v Lrg	Bck	Flnk	2	3	4	5	6	7	8	10	12	14	16	20	24	30
40	80	40	20	13	10	8	7	6	5	4	3	3	2.5	2	2	1.5
36	72	36	18	12	9	7	6	5	5	4	3	3	2	2	1.5	1
32	64	32	16	11	8	6	5	5	4	3	3	2	2	1.5	1.5	1
28	56	28	14	9	7	6	5	4	4	3	2	2	2	1.5	1	
24	48	24	12	8	6	5	4	4	3	2	2	2	1.5	1	1	
20	40	20	10	7	5	4	3	3	3	2	2	1.5	1.5	1		
16	32	16	8	5	4	3	3	2	2	1.5	1	1	1			
14	28	14	7	5	4	3	2	2	2	1.5	1	1				
12	24	12	6	4	3	2.5	2	2	1.5	1	1					
10	20	10	5	3	2.5	2	1.5	1.5	1	1						
8	16	8	4	3	2	1.5	1	1	1							
6	12	6	3	2	1.5	1	1									
5	10	5	2.5	2	1	1										
4	8	4	2	1	1											
3	6	3	1.5	1												
2	4	2	1													
Flnk	2	1														

Table B2—Rate-of-spread ratios as a function of changes in fuel and changes in effective windspeed. The left-hand column shows the EWS-ratio, the factor by which EWS changes. Each column corresponds to a change between particular fuel types (or to no change). Table values express the ROS-ratio that results from the combined change in EWS and fuel. The left side applies to cases in which fuel and wind changes reinforce. Cases in which changes in wind and fuel have opposing effects are handled with the rightmost two columns. Highlighted ROS values define a range that includes situations associated with fireline fatalities.

FLAME Table

		EWS biggest in faster fuel			EWS less in grass	
EWS-ratio	No fuel change	Litter to/from crown	Litter to/from grass	Crown to/from grass	Crown to/from grass	Litter to/from grass
No chg 1	**1**	**4**	**14**	**4**	*4*	*14*
2	**2**	**10**	**30**	**8**	***2***	*5*
3	**4**	**15**	**60**	**13**	**1**	*3*
4	**5**	**20**	**80**	**20**	**2**	*3*
5	**7**	**30**	**100**	**27**	**2**	*2*
6	**9**	**35**	**130**	**35**	**3**	*2*
8	**12**	**50**	**180**		**4**	**1**
10	**16**	**60**	**240**		**5**	**1**
12	**20**	**80**	**300**		**6**	**2**
16	**30**	**100**	**440**		**8**	**2**
20	**40**	**140**	**600**		**10**	**3**
24	**50**	**180**	**700**		**13**	**3**
30	**60**	**220**	**1000**		**17**	**4**
40	**80**	**300**	**1300**		**23**	**6**
50	**110**	**400**	**1800**		**30**	**8**
60	**140**	**500**	**2200**		**40**	**10**
80	**200**	**700**	**3100**		**60**	**16**

References

Andersen, H.E. 1982. Aids to Determining Fuel Models for Estimating Fire Behavior. General Technical Report INT-122. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station.

Barry, R.G. 1992. Mountain Weather and Climate 2nd Ed. Routledge.

Bishop, J. 1999. FireLine Assessment MEthod—A practical means for predicting wildland fire behavior from fireline observations. National Interagency Fire Behavior Workshop Proceedings. Phoenix, AZ. 1-5 March 1999.

Bishop, J. 2005. Better Fireline Safety Decisions Using The FireLine Assessment MEthod, FLAME. Unpublished.

Bishop, J. 2006. The FLAME (FireLine Assessment MEthod) Idea in a Nutshell. S-290 Course Materials.

Blumen, W., ed. 1990. Atmospheric Processes Over Complex Terrain. American Meteorological Society, Vol. 23, Number 45.

Butler, B.W.; and others. 1998. Fire Behavior Associated with the 1994 South Canyon Fire on Storm King Mountain, Colorado. Research Paper RMRS-RP-9. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Butler, B.W.; and others. 2000. A Method for Evaluating the Effectiveness of Firefighter Escape Routes. Proceedings of 2000 International Wildfire Safety Summit, Edmonton, AB, Canada. 10-12 Oct. 2000.

CDF Fire and USDA. 2004. CDF Helitack 404 Crew Burnover. CDF Greensheet & USFS 72-hour Report.

CDF Fire and USDA. 2005. CDF Helitack 404 Crew Burnover Accident Investigation Report. Tuolumne Fire. CA-STF-2191.

Cheney, P.; Sullivan, A. 1997. Grassfires, fuels, weather and fire behavior. Australia: CSIRO Publishing.

Close, K. 2005. Cramer Fire Investigation Fire Behavior Analyst. Personal communication.

Close, K. 2005. Fire Behavior vs. Human Behavior: Why the Lessons from Cramer Matter. Unpublished.

Hartford. R.A.; Rothermel, R.C. 1991. Fuel Moisture as Measured and Predicted During the 1988 Fires in Yellowstone Park. Research Note INT-396. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station.

Houze, R. 1993. Cloud Dynamics. San Diego, CA: Academic Press.

Mason, P.; Sykes, R. 1979. Flow over an isolated hill of moderate slope. Quarterly Journal of the Royal Meteorological Society. 105: 383-395.

Maclean, J. 1999. Fire on the Mountain. New York, NY: William Morrow and Co.

Oke, T. 1987. Boundary Layer Climates 2nd Ed. Methuen & Co.

Range, P.; and others. 1982. Great Basin Rate-of-Spread Study, Fire Behavior Fire Effects. Reno, NV: U.S. Department of the Interior, Bureau of Land Management, Nevada State Office.

Rothermel, R.C. 1972. A Mathematical Model for Predicting Fire Spread in Wildland Fuels. Research Paper INT-115. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station.

Rothermel, R.C. 1983. How to Predict the Spread and Intensity of Forest and Range Fires. General Technical Report INT-143. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station.

Rothermel, R.C. 1991. Predicting Behavior and Size of Crown Fires in the Northern Rocky Mountains. Research Paper INT-438. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station.

Shaw, R. 1988. Boundary-Layer Meteorology. Davis: University of California.

Taylor, P.; and others. 1987. Boundary-Layer Flow Over Low Hills. Boundary-Layer Meteorology. 39: 107-132

U.S. Department of Agriculture. 2003. Accident Investigation Factual Report, Cramer Fire Fatalities. 0351-2M48-MTDC. Salmon, ID: U.S. Department of Agriculture, Forest Service, Region 4, Salmon Challis National Forest, North Fork Ranger District.

U.S. Department of Agriculture. 1999. Dude Fire Staff Ride. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Region.

U.S. Department of Agriculture. 2001. Thirtymile Fire Investigation Report. Washington, DC: Forest Service.

Walmsley, J.; and others 1989. Simple Guidelines for Estimating Windspeed Variations due to Small-scale Topographic Features—an Update. Climatological Bulletin. 23: 3-14

Whiteman, D. 2000. Mountain Meteorology. New York, NY, and Oxford, England: Oxford University Press.

Influence of Slope on Fire Spread Rate

B.W. Butler[1], W.R. Anderson[2], and E.A. Catchpole[2]

***Abstract**—Data demonstrate the effect of slope on heading and backing fires burning through woody fuels. The data indicate that the upper limit of heading fire rate of spread is defined by the rate of spread up a vertical fuel array, and the lower limit is defined by the rate of spread of a backing fire burning downslope. The minimum spread rate is found to occur at nominally –16 degrees slope.*

Introduction

Terrain slope can be a primary influence on wildland fire behavior (Weise 1993; Murphy 1963). This effect can be observed on any fire burning in mountainous terrain; however, few data exist that explore this phenomenon in a quantitative manner. This study reports the results of a set of experiments that were designed to provide direct measurements of fire spread and intensity as a function of terrain slope. The fuel used was shredded aspen (*Populus tremuloides*) heart wood, otherwise known as excelsior.

While some work has explored the relationship between fire spread rate and slope, understanding and data are limited. Curry and Fons (1938, 1940) posited that slope resulted in increased heat transfer between the flame and fuel ahead of it and that the effect of slope is relatively low in the absence of wind, but that the combined effect of wind and slope can be dramatic. Barrows (1951) indicates that as the slope increases so does the average size of the fire. McArthur (1968) suggests that slope can significantly affect fire rate of spread, especially immediately following ignition. He suggests that when compared to flat terrain, heading fire spread rates will increase by two times on 10 degree slopes and four times on 20 degree slopes. Murphy (1963) conducted a set of experiments using a paste consisting of wood flour mixed with sodium nitrate in a 4:1 ratio as the fuel. This mixture resulted in smoldering combustion. Both heading and backing fires were observed at slopes of 0, 14, 27 degrees over a range of wind speeds varying from 0 to 4.4 m/s in increments of 0.4 m/s. The data showed that backing fire rate of spread exceeded heading fire rate of spread for all slopes and wind speeds less than 2.7 m/s. For higher wind speeds the heading fire rate of spread significantly exceeded the backing fire spread rates. Weise (1993) presents results from a set of 65 fire experiments subjected to slope angles between –30 and +30 percent and wind speeds from –1.1 to 1.1 m/s. He compares the measurements to several published models for the slope and wind influence on fire spread rate. His data indicate that wind is the dominant variable affecting fire spread. Viegas (2005) discusses the relation between fire spread rate and

In: Butler, Bret W.; Cook, Wayne, comps. 2007. The fire environment—innovations, management, and policy; conference proceedings. 26-30 March 2007; Destin, FL. Proceedings RMRS-P-46CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 662 p. CD-ROM.

[1] Research Mechanical Engineer, U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Missoula, MT. bwbutler@fs.fed.us

[2] University of New South Wales, Australian Defence Force Academy, Canberra ACT 2600, Australia

terrain slope in the context of a model of fire spread in upward sloping canyons. He approximates the effect of terrain slope as an artificial wind parameter, recognizing that the theoretical upward flame spread limit for fire burning along a semi-infinite solid is approximated as an exponentially increasing function, which agrees with other reported studies (Alpert and Ward 1984). Other studies have been presented that explore the relation between flame spread rate on cloth and solid surfaces for purposes of determining spread rates in structural fires (for example, Markstein and DeRis 1973). The studies referenced above indicate that slope is a critical component in wildland fire spread; however, the data are insufficient to fully understand the pertinent physical mechanisms occurring in slope-driven fire growth.

For this study a set of experiments were designed to measure fire spread rate for sloped fuel beds ranging from –16 to 31 degrees. Table 1 lists the experiments and associated conditions. All tests were conducted at nominally 6 percent fuel moisture (dry mass basis), 27 °C ambient air temperature and 20 percent relative humidity.

Table 1—Sloped fire experiments.

Test	Fuel	Packing ratio	Slope (%)	Fuel depth (cm)	Objectives
1	EXSC	0.01	–30, 0, 15, 30, 45, 60	2.5	Fire spread on slope
2	EXSC	0.03	–30, 0, 15, 30, 45, 60	2.5	Fire spread on slope
3	EXSC	0.005	–30, 0, 15, 30, 45, 60	2.5	Fire spread on slope
4	EXSC	0.01	–30, 0, 15, 30, 45, 60	7.62	Fire spread on slope
5	EXSC	0.03	–30, 0, 15, 30, 45, 60	7.62	Fire spread on slope
6	EXSC	0.005	–30, 0, 15, 30, 45, 60	7.62	Fire spread on slope
7	EXSC	0.01	–30, 0, 15, 30, 45, 60	15.24	Fire spread on slope
8	EXSC	0.03	–30, 0, 15, 30, 45, 60	15.24	Fire spread on slope
9	EXSC	0.005	–30, 0, 15, 30, 45, 60	15.24	Fire spread on slope

Methods

Figure 1 is a photograph of the experiment apparatus. The fuel consisted of shredded aspen (*Populus tremuloides*) heartwood, selected for nominally uniform size shape (approximately 2.5 x 0.8 mm cross-section) and because it is readily formed into a randomly oriented fuel array with uniform bulk density and controllable bed depth. The depth and bulk density were adjusted by varying the mass of fuel per unit volume of the fuel bed. Rather than reporting bulk density, we use the term "packing ratio" (volume of fuel per unit volume of fuel bed), a term more common to wildland fire. Bulk density is the product of packing ratio and fuel density. Efforts were taken to maintain the fuel particle moisture content as uniform as possible between burns by conditioning fuel beds prior to the experiment at fixed temperature and humidity (nominally 27 °C and 25 percent RH) and burning the experiments at the same conditions. Measured fuel moistures ranged from 5 to 8 percent on a dry mass basis. The fuel tray was 1 m wide by 4.6 m long; slope angle was measured from the horizontal plane. The fires were ignited by applying electric current to a coiled nichrome wire placed in a 2 cm deep by 1 m wide tray of gasoline/diesel mixture at the base of the starting location for the fuel bed.

Figure 1—Photograph of experiment, upward spreading fire, excelsior fuel, bed measured 1 m wide by 3.5 m long.

Fire rate of spread was measured by dividing the length of the fuel bed by the time required for the flame front to move from the ignition location to the opposite end of the fuel bed. Time for all fuel on the bed to complete burning was not measured. In some cases fire rate of spread was also gathered from analysis of video footage. Generally these two methods agreed within ±10 percent.

Results

Figures 2 through 4 present rate of spread data from the slope burns. The data have been normalized by dividing by the zero slope rate of spread. The horizontal axis is slope measured from the horizontal in degrees.

Figure 2 presents the data from the 2.5 cm deep fuel arrays. For all three packing ratios and all but the steepest slopes, these fires burned as individual flamelets along each individual fuel particle. In the case of the 0.005 packing ratio, the fire did not burn at all except for the steepest (31 degree) slope. The data from the fuel beds with packing ratio of 0.01 and 0.03 show a 25 percent decrease in spread rate between horizontal conditions and 16 degree downward sloped beds. No increase in spread rate was observed for slopes from 0 to 10 degrees. For slopes between 10 and 25 degrees and packing ratios of 0.01 and 0.03, fire spread rates increased slightly with slope. A dramatic acceleration in spread rate was observed from 25 to 31 degrees.

The burn data from the 7.6 cm deep fuel beds are presented in figure 3. These data suggest that for slopes less than 25 degrees, fuel bed rate of spread increases with increasing packing ratio. But as slope increases to 30 degrees, the relation reverses, and the more tightly packed bed burns approximately 15 percent slower than the bed with the lowest packing ratio. The data also indicate that when backing down a 16 degree downward slope, the rate of spread is 17 percent less than for flat conditions.

Figure 4 presents the normalized rate of spread data from the 15 cm deep fuel beds. Trends similar to those observed in the 7.6 cm deep beds are observed over the slope range of –16 to +30 degrees. Additional data

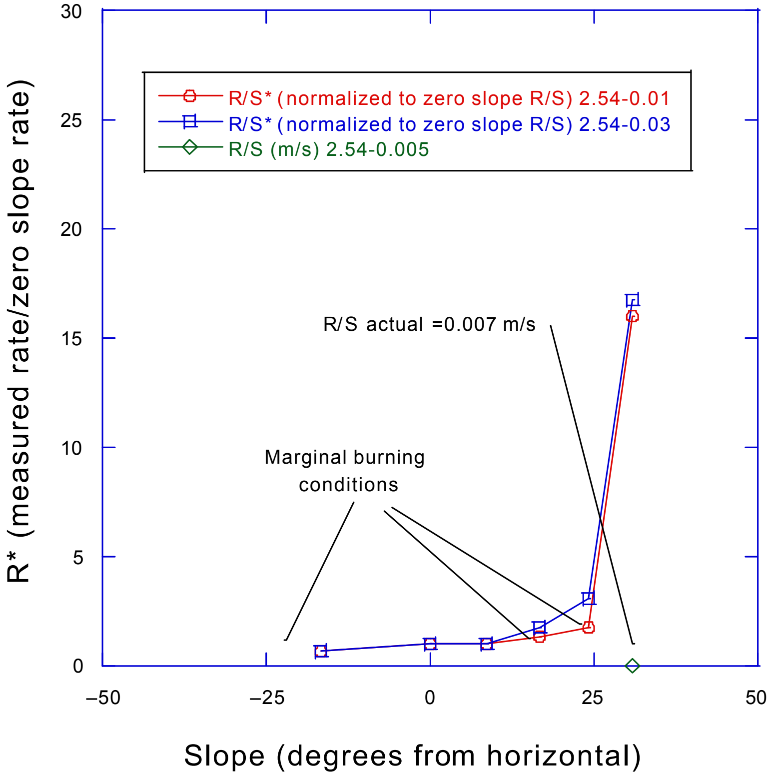


Figure 2—Normalized rate of spread for the 2.54 cm deep fuel beds. Bed depth (cm) and packing ratio values are listed at the end of each identifier in the legend.

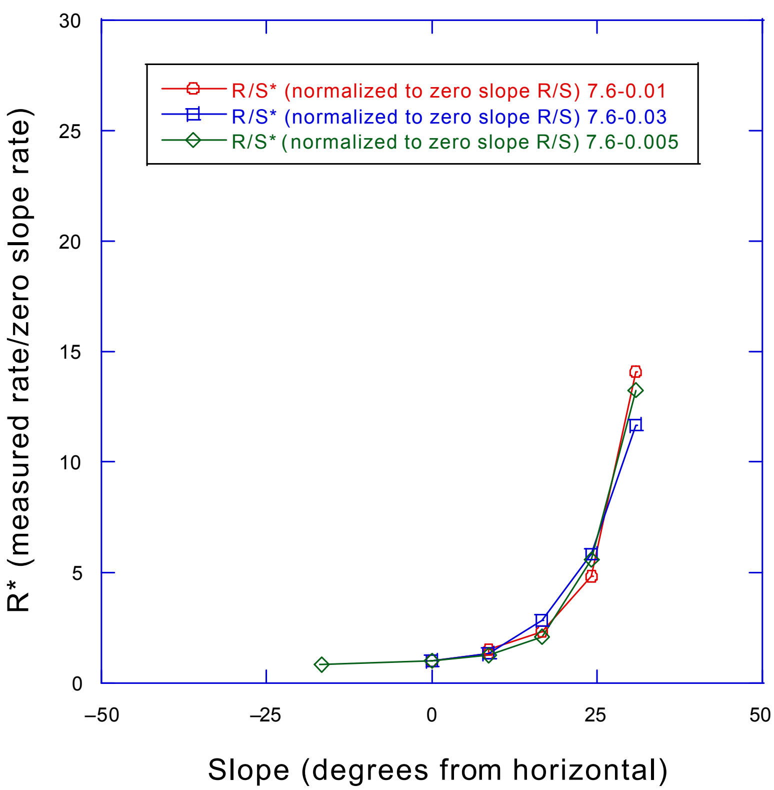


Figure 3—Normalized rate of spread for the 7.62 cm deep fuel beds. Bed depth (cm) and packing ratio values are listed at the end of each identifier in the legend.

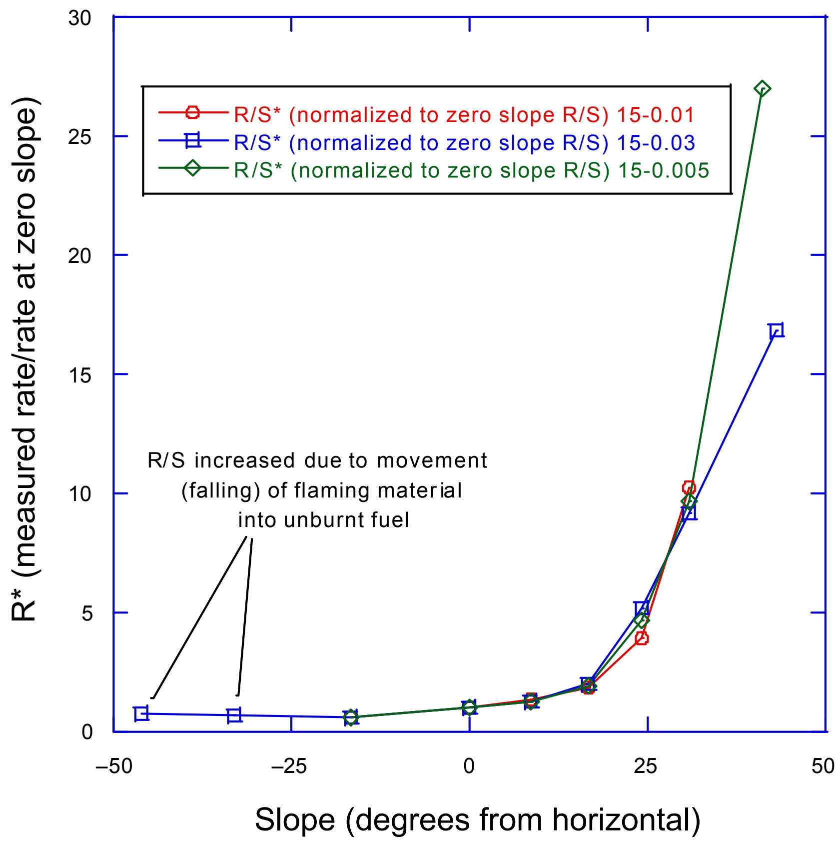


Figure 4—Normalized spread rate for 15 cm deep fuel beds. Bed depth (cm) and packing ratio values are listed at the end of each identifier in the legend.

were collected for steep down slope backing fires to a slope of –47 degrees. These data indicate that the minimum rate of spread occurs at approximately 15 degrees downslope. For steeper slopes, the downhill rate of spread increases. The increase is attributed to burning fuel "falling" down into the bed accelerating the overall spread rate. A steeper slope of 43 degrees was explored in the lowest and highest packing ratios. These data show for these relatively steep slopes that the lower packing ratio bed spreads significantly faster. For the steepest slopes, the fires burned quickly up the 4 m long bed (approximately 20 seconds), but took significantly longer to burn down through the bed, indicating that spread occurred over the topmost layer of the fuel array.

Discussion

The data indicate at least three unique burning regimes. The first is indicated by individual flamelets burning separately along each fuel particle. This type of burning occurred in the 2.5 cm deep fuel beds for slopes less than 25 degrees. The fire spread process for the slopes less than 25 degrees seems to be dominated by energy transfer along the individual strands, with radiant or convective energy transport insufficient to "bridge" the gap between individual particles. As slope increased above 25 degrees, an abrupt increase in spread rate with slope occurred (see fig. 2) where the fire changed from flamelets burning along fuel strands to a more coherent flame front. This change suggests a corresponding shift in the fundamental physics behind the fire spread process. We posit that radiant and convective energy transfer provides sufficient heating of the fuel ahead of the fire front to produce a more uniform flame front.

As bed depth is increased from 2.5 to 7.6 cm, a uniform flame front was observed in all cases (see fig. 3). Minimum spread rates occurred not at flat slopes (0 degrees) but at downward spreading slopes of –16 degrees. As downslope (backing fire) slope was increased further, the rate of spread was observed to increase (see note on fig. 4). For slopes between –16 and + 10 degrees the rate of spread increases at a rate roughly linearly proportional to slope. Fuel array packing ratio was not observed to be significant in this slope range. For upward spreading fires between 10 and 25 degrees, the fire rate of spread accelerates and the fuel arrays with the highest packing ratio burn fastest. As slope increases further, it appears that the fires with the highest packing ratios do not accelerate as fast as the lower packing ratios. At slopes greater than 25 degrees, spread rate was observed to increase again in a roughly linear but much greater proportion to slope.

Figure 4 presents the data from the deepest fuel bed (15 cm). Fire spread rates seemed to respond similarly at this depth to the observations for the 7.6 cm deep beds. Again the minimum spread rate occurred at roughly –16 degrees downslope. A roughly linear increase in fire spread rate with slope is observed from –16 to +16 degrees. From 16 to 25 degrees the data indicate some separation as a function of packing ratio with the more tightly packed beds burning faster. As slopes increase above 25 to 45 degrees, the lower beds with lower packing displayed much faster increases in spread rates than the more tightly packed beds. From these data we identify a third burning regime where convective energy transfer dominates the energy transfer process. The lower resistance to convective flow that is present in the less tightly packed beds results in the fastest fire spread rates. The beds with tightest packing, and highest loading, resulted in the tallest flames, but the fact that the lower packing ratio fires burned faster indicates that while radiant energy transfer is still present and probably necessary, it does not seem to dominate. However, the beds with lower packing ratios will also be conducive to the transport of radiant energy farther into the bed, which may lead to an increase in pre-heating. But this mechanism is believed to be secondary as the bulk of the flame transport and spread for the steepest slopes seems to occur along the top surface of the fuel array.

A transition zone, characterized by an increase in the spread rate of the less tightly packed beds that was more rapid than tightly packed beds, seemed to occur in all of the fuel beds as slopes exceed 25 degrees (see fig. 5). The result is a dramatic shift in the spread rate. This is supported by the observation that the fastest spread rates are exhibited by the beds with the lowest packing ratio. These lower density fuel arrays would be less restrictive to fluid flow and thus could be associated with enhanced convective heating.

Conclusions

The data presented suggest three burning regimes with respect to fires on slopes. The first is dominated by fire spread along individual fuel particles and can be characterized as primarily a conductive process. However, as either fuel

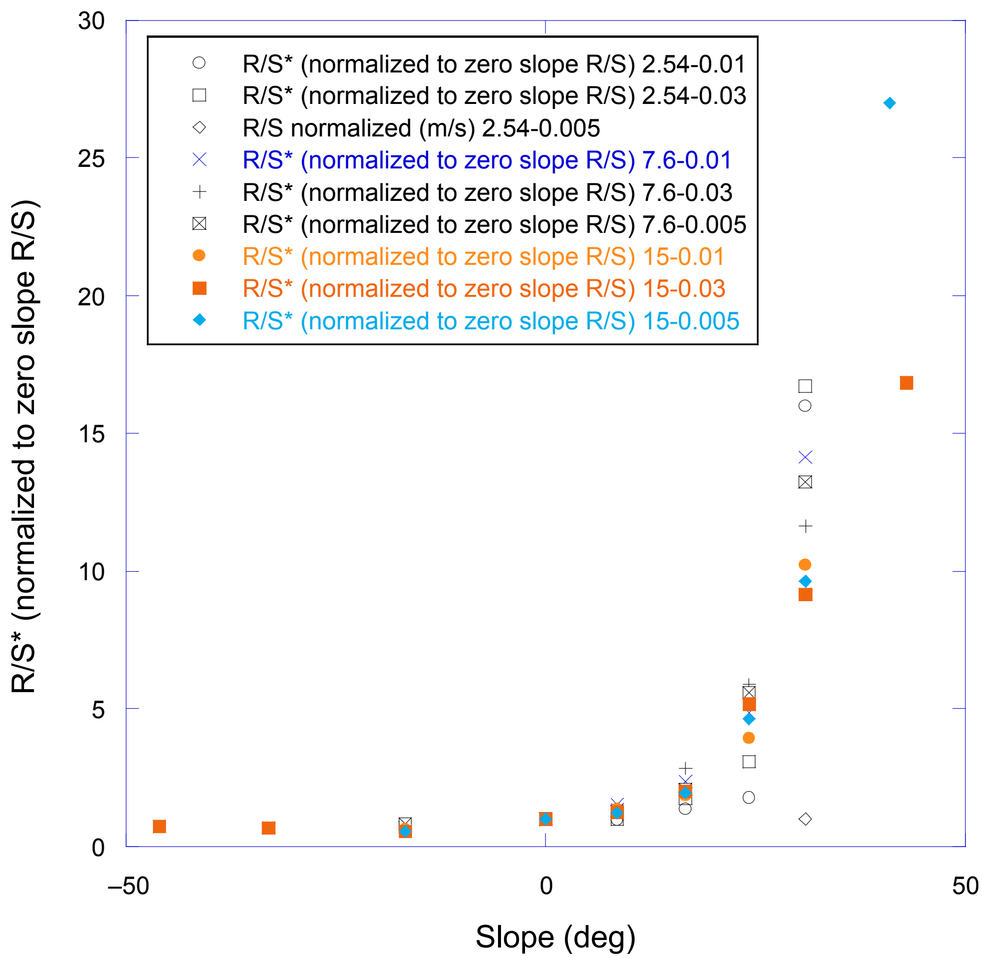


Figure 5—Normalized spread rate for all fuel beds. Bed depth (cm) and packing ratio values are listed at the end of each identifier in the legend.

particle density or fuel bed depth increases, fires begin to burn as a coherent front. The behavior of this front in the mid slope range (that is, slopes less than 25 degrees) indicates that fuel bed bulk densities favoring increased fuel loading burn slightly faster; we posit that this is indicative of a radiatively controlled regime. Greater fuel loading will likely result in larger and taller flames, which implies more radiatively efficient emitters of radiant energy. As slopes increase further (that is, greater than 25 degrees) beds that are less tightly packed begin to burn faster. This implies a convective dominated regime where fluid flow within and over the surface of the fuel array dominates the flame spread rate. The data indicate the need for further experiments and comparison of the data against existing fire/slope relations.

Acknowledgments

This work has been supported by the Joint Fire Science Program and the USDA Forest Service. The assistance of Bob Schuette, Paul Sopko, Kyle Shannon, and Josh Jones in setting up and completing the experiments is sincerely appreciated.

References

Alpert, R.L.; Ward, E.J. 1984. Evaluation of Unsprinklered Fire Hazards. Fire Safety Journal 7, 127-143

Barrows, J.S. 1951. Fire behavior in northern Rocky Mountain forests. Pub. No. 29. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station.

Curry, J.R.; Fons, W.L. 1938, Rate of spread of surface fires in the ponderosa pine type of California. J. Agr. Res. 57:239-267.

Curry, J.R.; Fons, W.L. 1940. Forest fire behavior studies. Mech. Engng. N.Y. 219-25.

Markstein, G.H.; DeRis, J.N. 1973. Upward Fire Spread over Textiles. Proc. Fourteenth Symposium (Intl) on Combustion. The Combustion Institute: 1085-1097.

McArthur, A.G. 1968. Fire Behaviour in Eucalypt Forests. Leaflet No. 107. Ninth Commonwealth Forestry Conference, India, 1968.

Murphy, P.J. 1963. Rates of fire spread in an artificial fuel, MSc. Thesis. Bozeman, MT: Montana State University.

Viegas, D.X. 2005. A mathematical model for forest fires blowup. Combust. Sci. and Tech. 177:27-51.

Weise, D.R. 1993. Modelling wind and slope-induced wildland fire behavior. Ph.D. Dissertation. Berkeley: University of California at Berkeley. 130 p.

Modification of VanWagner's Canopy Fire Propagation Model

James Dickinson[1], Andrew Robinson[2], Richy Harrod[3], Paul Gessler[4], and Alistair Smith[5]

***Abstract**—The conditions necessary for the combustion of canopy fuels are not well known but are assumed to be highly influenced by the volume through which the canopy fuels are dispersed, known as canopy bulk density (CBD). Propagating crown fire is defined as a continuous wall of flame from the bottom to the top of the canopy, implying crown fire propagation is actually independent of the vertical fuel distribution. We hypothesize that all foliar canopy fuel is available for the propagation of canopy fire. Therefore, we focus our effort on simplifying Van Wagner's (1977) canopy fire propagation model to accept a canopy fuel metric that uses only foliar biomass per unit area (FBA) rather than the more complex and commonly used CBD. The multiplication of leaf area index (LAI) and the specific leaf area (SLA) of a given tree species results in FBA, making FBA easily related back to ecologically meaningful terms at a range of spatial scales. A variety of instruments can be used to estimate LAI with high accuracy, and SLA values have been published for many species found in fire prone forests of the West. Alternatively, allometric equations can be used to compute FBA using individual tree-level measurements. Using Van Wagner's (1977) data we modify his propagation model and successfully match his published results. In addition, we use Forest Inventory and Analysis data from northern Idaho to compare the critical rate of spread (cROS) predicted by the modified model (using FBA) with the predictions of the original model (using CBD). We find that the two models are statistically equivalent (α = 0.10).*

Introduction

Canopy fire challenges accurate modeling of fire spread because quantification of the canopy fuel stratum is difficult (Cruz and others 2003; Keane and others 2005). Particular difficulty arises, as canopy fires can exist in either 'passive' or 'active' modes. In passive canopy fires, individual trees or groups of individuals ignite and burn from the bottom to the top of the crown, resulting in mixed impacts on the environment (Ryan and Noste 1983). In active canopy fires the combustion propagates as a solid wall of flame through a landscape filled with trees in conjunction with a surface fire (Van Wagner 1977). In addition, this combination of active canopy and surface fire often burns at high intensity having significant impact on soils, vegetation, and wildlife habitat (Grier 1975; Ryan and Noste 1983; Romme 1995; Haggard and Gaines 2001). Such fires may exhibit flame lengths exceeding 30 m with rates of spread exceeding 50 m/min (Stocks and others 2004). Active canopy fire also poses great risk to fire personnel, the public, and private property (Scott 1998; Clark and others 1999; Scott and Reinhardt 2001).

In: Butler, Bret W.; Cook, Wayne, comps. 2007. The fire environment—innovations, management, and policy; conference proceedings. 26-30 March 2007; Destin, FL. Proceedings RMRS-P-46CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 662 p. CD-ROM.

[1] Fire Ecologist, U.S. Department of Agriculture, Forest Service, Okanogan-Wenatchee National Forests, Chelan, WA. jddickinson@fs.fed.us

[2] Senior Lecturer of Statistics, University of Melbourne, Melbourne, Victoria, Australia.

[3] Deputy Fire Management Officer, U.S. Department of Agriculture, Forest Service, Okanogan-Wenatchee National Forests, Wenatchee, WA.

[4] Associate Professor of Remote Sensing and Spatial Ecology, University of Idaho, Moscow.

[5] Assistant Professor of Forest Measurements, University of Idaho, Moscow.

For these reasons fire managers have great interest in preventative treatment of forested landscapes capable of sustaining active canopy fires (Hof and Omi 2003; Scott 2003; Peterson and others 2005) and also in predicting the behavior of these fires when they initiate (Stocks and others 2004). These management applications require knowledge of the minimal conditions sustaining canopy fire to properly plan fuels treatments or to evaluate impending conditions that threaten crews during suppression actions.

Most fire planning tools and spatially explicit fire models depend upon the original Van Wagner's (1977) model (we refer to this model as VWcbd) to characterize the minimum conditions necessary to sustain active canopy fire (Keane and others 2000; Scott and Reinhardt 2001; Finney and others 2003; Reinhardt and Crookston 2003; Finney 2004). Other research has attempted to quantify the available canopy fuel for combustion, called canopy bulk density (CBD) to parameterize VWcbd for application (Keane and others 2000; Fule and others 2001; Hummel and Agee 2003; Riano and others 2003; Gray and Reinhardt 2003; Perry and others 2004; Riano and others 2004; Falkowski and others 2005; Peterson and others 2005; Keane and others 2005).

To date, no study has compared the effect that using different methods of CBD estimation might have on the output of the VWcbd. Therefore, this paper introduces the reader to two common methods of estimating CBD and statistically compares the outputs of the VWcbd model using these inputs. We also develop and compare a modified version of VWcbd, which we call VWfba, that utilizes a simpler metric of foliar biomass per unit area (FBA) as the fuel input.

Crown Fire Defined

Van Wagner (1977) described a conceptual canopy fire model using "a stationary wall of flame with a conveyor belt carrying fuel into the flame." The rate of that conveyor belt must maintain a minimum critical rate of spread (cROS) to deliver a sufficient quantity of combustible fuel per unit time to maintain the wall of flame in the canopy space (Van Wagner 1977).

Van Wagner modeled canopy fire interactions for fuel, flame front rate of spread, and the *minimum* fireline intensity necessary to maintain canopy fire in a fashion similar to Byram's (1959) index. This surface fire index relates fireline intensity, the rate of spread of a flame front, and the quantity of *combusted* fuel (Byram 1959; Scott and Reinhardt 2001). By representing the flame front as a line moving at some rate across a plane of homogenously distributed fuel mass (multiplied by a constant heat yield) the result is a fireline intensity that is the product of the rate of flame movement and the homogeneous fuel (Byram 1959). Like Byram's (1959) index, the VWcbd assumes a homogeneously distributed fuelbed, albeit through a volume rather than across an area (Van Wagner 1977). The assumption of a homogeneous fuel bed with a constant heat yield per unit of fuel makes VWcbd identical to Byram's (1959) index in form.

The Van Wagner (1977) model differs only in form by its calibration to the *minimal* conditions necessary for active canopy fire to persist. Van Wagner assumed that the fuel present in a stand would have a constant heat of ignition (per unit mass), and thus avoided the necessity of calculating the energy in the propagating heat flux. This changed the crucial element to a simple argument that relates only the critical quantity of fuel consumed per unit time required for flame maintenance, divided by the available fuel quantity (equation 1). The result of this equation is the critical rate of spread (cROS, represented by 'R_o' in equation 1) required for the fire to consume the available fuel ('*d*') such that the critical mass flow rate ('S_o') is satisfied.

$$R_o = \frac{S_o}{d} \text{ (Van Wagner 1977)} \quad (1)$$

Where: R_o : cROS for active canopy fire ($m.s^{-1}$)
S_o : critical mass flow rate for canopy fire, (0.05 $kg.m^{-2}.s^{-1}$)
d: foliar (canopy) bulk density ($kg.m^{-3}$)

Van Wagner's definition of canopy fire as a wall of continuous flame from bottom to top of the canopy must be met to satisfy the implicit assumption that canopy fire has initiated (Van Wagner 1977; Scott and Reinhardt 2001). The use of a single value to represent a distribution of fuel through the canopy space removes any effect that a vertical distribution of fuel may have upon canopy fire, requiring a second implicit assumption that horizontal canopy fire propagation occurs regardless of the vertical distribution of the fuel. The quotient resulting from the division of the available fuel by volume (the definition of CBD) is simply a fraction of the total fuel load (the sum of which is still available for combustion) and is irrelative to the effect that the vertical distribution may (or may not) have on canopy fire.

Regardless of how a metric might incorporate the vertical distribution component, it must be input to a model calibrated for that fuel metric. Likewise, a metric with no vertical distribution component used in a properly calibrated model, would not preclude the use of vertical distribution as a parameter in the model. It would simply require the incorporation of the vertical distribution to be explicitly included in the model. The fuel input to such a model would be useable at a range of scales depending only upon the method used to calculate the available canopy fuel.

Our overarching assumption is that the Van Wagner (1977) model appropriately relates the basic properties necessary to describe the lower boundary conditions required for active canopy fire combustion. Namely, that an active canopy fire spreading between two points on the landscape must consume a minimum quantity of fuel per unit time in order to persist as a canopy fire. The quantification of fuel is vital to a model of the combustion process but need not incorporate the vertical distribution into the fuel metric as traditional canopy fuel methodologies have done.

Van Wagner's (1977) published data are used here to recalibrate the model for use with FBA in place of the standard CBD input. The VWcbd and the VWfba models are applied to a regionwide nonspatial Forest Inventory and Analysis (FIA) database, and an equivalence test is used to compare the estimates of cROS from the VWcbd and VWfba models.

Methodology

In this section we introduce two methods used to calculate the fuel input necessary for VWcbd. We then modify the existing VWcbd for the use of foliar biomass to create the VWfba model. Finally, we introduce our data and the statistical methods used to test the equivalence of the VWcbd and VWfba.

Summary of CBD Methods

We present FBA as a more simple alternative to the several existing methods for calculating CBD (Sando and Wick 1972; Brown 1978; Cruz and others 2003; Riano and others 2003; Reinhardt and Crookston 2003; Perry and others 2004) though only the FFE (Reinhardt and Crookston 2003) and Cruz and others (2003) methods are used for comparison because they represent the two unique approaches to estimating CBD.

The widespread use of the complex FFE method by Federal land managers and researchers (Hummel and Agee 2003; Andersen and others 2005; Perry and others 2004; Falkowski and others 2005; Peterson and others 2005) is facilitated by its implementation in the Fire and Fuels Extension to the Forest Vegetation Simulator (FFE-FVS) computer software (Reinhardt and Crookston 2003) and the proprietary Fire Management Analyst Plus suite of computer software (FPS 2001).

When applied to a stand inventory list, FFE calculates the foliar biomass assuming constant density of foliar biomass through the length of the individual tree-crown space. FFE calculates the amount of biomass contained in every vertical 0.3048 m (1 ft) of the volume space for each tree (Scott and Reinhardt 2001). Finally, the foliar biomass for all individuals in the stand is summed within each vertical 0.3048 m above the ground and is plotted (see fig. 1). This represents stand biomass (kg/m^2) distributed by height above ground (m), as a sum of all individual trees (that is, vertical distribution of foliage within the canopy space) (Sando and Wick 1972).

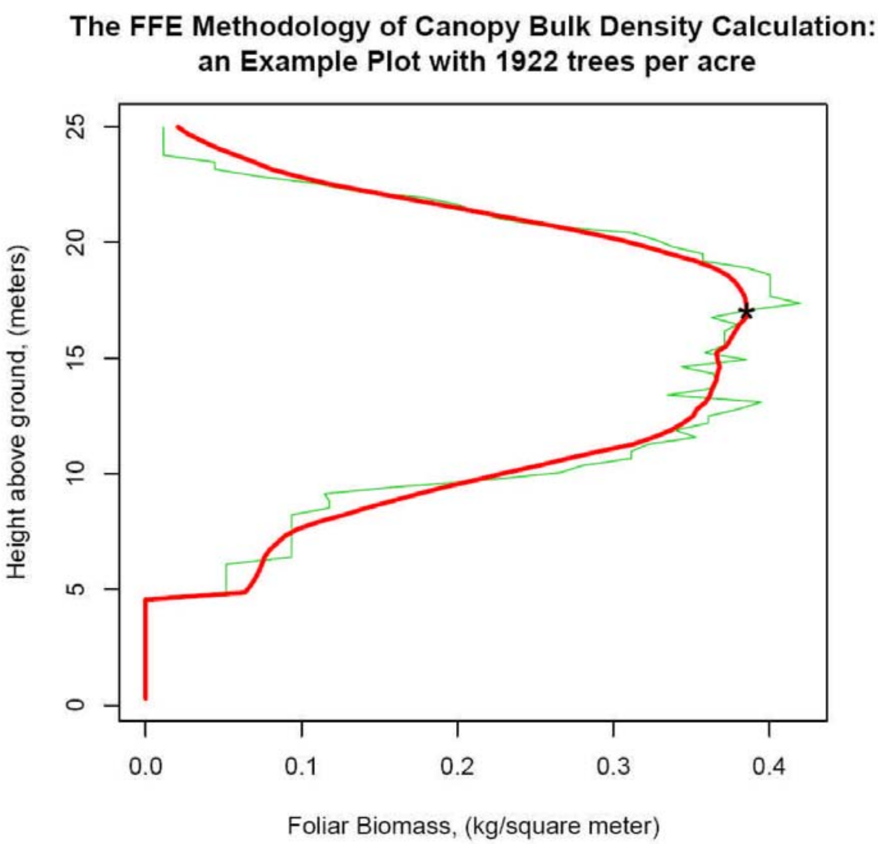


Figure 1—FFE methodology of canopy bulk density calculation. The maximum of the 13-ft (3.96 m) running mean (marked with a star) read from the x-axis as the maximum average foliar biomass per square meter per average vertical meter, or "effective CBD" (kg/m^3).

FFE calculates the maximum 0.3048 m (1 ft) increment of a 3.96 m (13 ft) running mean applied to the vertical profile of foliar biomass (see fig. 1) (Reinhardt and Crookston 2003). This produces an effective CBD value that is not equivalent to the traditional CBD definition (Scott and Reinhardt 2001). Rather, effective CBD provides a value that is the maximum of a running average (fig. 1) and represents the greatest average fuel value, presumed to be the least resistant stratum for canopy fire propagation through a stand (Scott and Reinhardt 2001). Despite the lack of direct correspondence to the CBD definition, it is frequently used as input to VWcbd.

Cruz and others (2003) calculate the foliar biomass for all trees in a stand and divide this by the product of the average crown length multiplied by the area of the stand. Biomass is assumed to have equal distribution through the volume of the canopy. This method appears to be similar to the method used by Van Wagner (1977) for calculation of experimental fuels data. We refer to this method as the "Cruz" method for the remainder of this paper.

Modification of Van Wagner's Model

Our research modifies VWcbd (equation 2a) (Van Wagner 1977) by altering the value that represents the mass flow rate (S_o, equation 2a), which represents the minimum quantity of fuel required to be combusted per unit time to sustain canopy fire propagation. To determine S_o, Van Wagner identified forested stands for canopy fire experimentation and recorded stand information including stems per hectare, basal area, tree height, height to crown base, and biomass per unit area (table 1). The stands were then ignited with three out of four fires judged to burn as active canopy fires by Van Wagner (table 1).

$$R_o(ms^{-1}) = \frac{S_o}{d} = \frac{0.05(kgm^{-2}s^{-1})}{d(kgm^{-3})} \qquad \text{(Van Wagner 1977)} \qquad (2a)$$

$$S_o = R_o \cdot d \qquad (2b)$$

R_o is the critical minimum rate of spread for active canopy fire
S_o is the critical mass flow rate for solid crown flame
d is the canopy bulk density

Van Wagner (1977) used one stand ('R1' in table 1), considered 'an incipient' active canopy fire, for model calibration. The observed rate of spread of fire in stand 'R1' was multiplied by CBD to determine the required mass flow (S_o in equation 2b). It was apparent that this resulting value was less than necessary for active canopy fire, so Van Wagner set S_o at a constant value

Table 1—Summary of data taken from Van Wagner (1977) used for model recalibration.

Test fire name	Fire type	Basal area (m^2)	Trees/ha	Tree height	Height to live (m)	Biomass per m^2	CBD (kg/m^3)	Actual ROS (m/sec)
C6	active	50	3200	14	7	1.8	0.23	0.46
C4	active	50	3200	14	7	1.8	0.26	0.28
GL-B	active	25	1800	18	6	1.22	0.12	0.41
R1	developing	50	3200	14	7	1.8	0.23	0.18

slightly greater (0.05 $kgm^{-2}s^{-1}$). This established the minimum mass flow value necessary because a slower fuel consumption rate would result in fire behavior similar to the incipient canopy fire behavior of 'R1' (Van Wagner 1977).

Our alternative VWfba was created by dividing Van Wagner's value of S_o= 0.05 $kgm^{-2}s^{-1}$ by the CBD for stand 'R1' (0.23 kgm^{-3}) (equation 3a). The result is a cROS of 0.217 ms^{-1} for stand 'R1'. The cROS is multiplied by the FBA (foliar biomass per unit area, table 1) of stand 'R1' resulting in a product of 0.39 $kgm^{-2}s^{-1}$ (equation 3b) giving the predictive equivalent to Van Wagner's published value using CBD of S_o = 0.05 $kgm^{-2}s^{-1}$ (equation 3c). The final form of the VWfba model is shown in equation 4.

$$0.05(kgm^{-2}s^{-1}) \div 0.23(kgm^{-3}) = 0.217(ms^{-1}) \tag{3a}$$

$$0.217(ms^{-1}) * 1.80(kgm^{-2}) = 0.39(kgm^{-1}s^{-1}) \tag{3b}$$

$$\frac{0.05(kgm^{-2}s^{-1})}{0.23(kgm^{-3})} = 0.217(ms^{-1}) = \frac{0.39(kgm^{-1}s^{-1})}{1.80(kgm^{-2})} \tag{3c}$$

$$R_o(ms^{-1}) = \frac{0.39(kgm^{-1}s^{-1})}{d(kgm^{-2})} \tag{4}$$

After recalibration of S_o, the VWfba model was applied to the rest of the data provided by Van Wagner (1977). The VWfba and VWcbd models provide comparable predictions of cROS. Additionally, VWfba identifies that stand "GLB Active" (fig. 2) exceeds the cROS and is an active canopy fire when VWcbd does not.

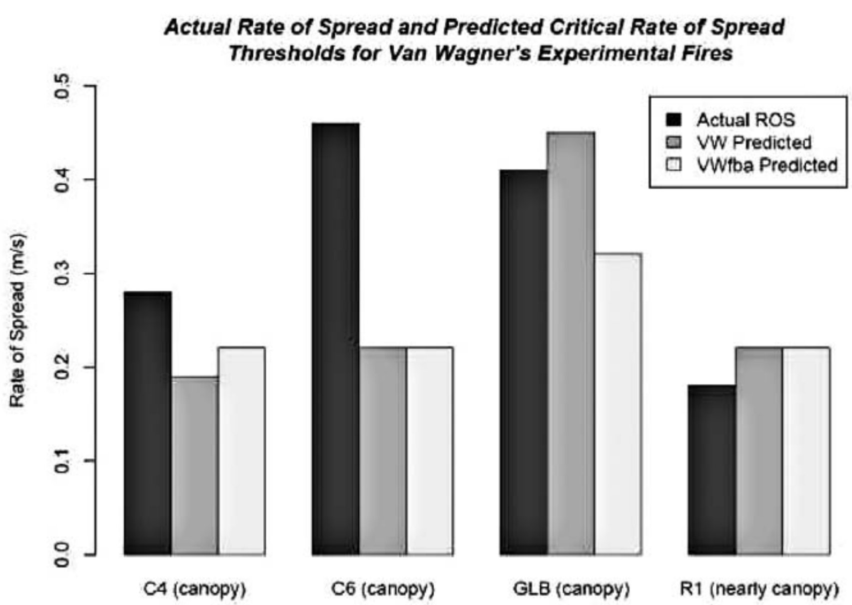


Figure 2—Summary of Van Wagner (1977) published results and the VWfba recalibration applied to original data. Where the 'Actual ROS' line exceeds the estimated lines a canopy fire should occur. Note that only the VWfba estimate is exceeded by the GLB fire.

Sample Data

We use a database of 2,626 FIA plots collected from the Inland Northwest region of the United States (UIFBL, 2006). FIA routinely collects data on trees, saplings, and seedlings at each plot; however, we selected only trees at least 7.56 cm (3 inches) in diameter at breast height (1.37 m) (USDA Forest Service 1990). Each of the 40,000 tree records in this database include the variables of tree diameter, height, percent live crown ratio, species, and the tree expansion factor (number of trees per hectare that record represents) and plot level variables (such as elevation, habitat type, aspect, and slope).

Fire and Fuels Extension Emulator

The size and format of our 40,000 record-database is not compatible with the import tool of FFE-FVS that requires separation of the tree level data from the plot level data. A stand-alone program provided by the FVS support group in Fort Collins, CO (FMFC 2002) was also considered for use, but single stand with a maximum 2,000 tree records would not work for our database containing 2,626 plots. Therefore, with permission (FMFC, personal communication), a standalone program was rewritten within the statistical package 'R' (R Development Core Team 2005) to directly interface with our database.

This code provides identical CBD values in comparison to the standalone FFE program. The allometric equations we use are identical to those used in the northern Idaho and Inland Empire variants of the FFE -FVS software (Brown 1978; Gholz and others 1979). Our revised program provides us with several important values that are not readily available from FFE. It provides a CBD value identical in method to FFE, an estimate for the method of Cruz and others (2003), and an estimate of the proposed FBA alternative.

Statistical Analysis

Model validation is often difficult because traditional statistics require that the null hypothesis be stated such that the two models are not significantly different (Welleck 2003). The ability to demonstrate similarity rather than difference based on probability arises by changing the null hypothesis from one of similarity to one stating that dissimilarity exists, and is called equivalence testing (Wellek 2003; Robinson and Froese 2004). Though the biomedical industry has long used equivalence tests to show that two samples are statistically similar, equivalence tests have not been widely applied to ecological modeling (Wellek 2003; Robinson and Froese 2004). Robinson and Froese (2004) use equivalence tests to validate model predictions of the diameter growth model contained within the Forest Vegetation Simulator.

This variety of statistical test requires that a region of indifference (ε), or a range of difference that is of negligible concern, be established (Robinson and Froese 2004). That is, a range of difference between sample metrics that is insignificant in practical application (Wellek 2003). After establishing a region of indifference, what is analogous to two separate trials of a one sided t-test on the difference between samples is carried out, one for differences greater than the test statistic, and one trial for differences less than the test statistic (Robinson and Froese 2004). This method is called a 'two-one-sided t-test' (TOST), and like a regular t-test, this test gains power as the sample size increases (Robinson and Froese 2004).

The null hypothesis of dissimilarity is rejected if the range of indifference overlaps into the rejection region for a one-tailed 95 percent confidence interval of the mean of the differences ($x_a - x_b = x_{diff}$) (Robinson and Froese

2004). The mathematics behind equivalence testing do not make p-values practical, so we use both a strict (small) and liberal (large) range of indifference to bracket our confidence in the hypothesis test (Wellek 2003).

These ranges of indifference bracket our confidence based not on probability, but on a judgment of how large the difference could be for the models to still be considered equivalent. In this paper, we choose a strict range of indifference such that $|\bar{x}_{diff} \pm \varepsilon| < 0.138$ m.s^{-1} (± 0.50 kph) for cROS, while the liberal range of indifference was established such $|\bar{x}_{diff} \pm \varepsilon| < 0.278$ m.s^{-1} (± 1.0 kph). The values were chosen as being insignificant ranges of difference from both a management and a modeling standpoint. We use a one sided type I error rate of 5 percent ($\alpha = .05$), which translates to two times a one-sided α (2 x .05 = .10) for our TOST test of equivalence.

It is unusual for any two models to produce identical outputs so we attempt to use the available data to explain differences that may exist between these models. To explain these differences we fit a multiple linear regression model (MLR) to the output of the VWcbd (using FFE method) and VWfba. The VWcbd and VWfba models do not exhibit consistent differences between them; for example, VWfba does not always estimate lower than VWcbd. Therefore, we evaluate the ratio of the cROS estimates from the VWcbd and VWfba models (VWcbd:VWfba) as the response variable.

Within the 'R' statistical package (R Development Core Team 2005) a saturated MLR model with two-way interactions was fit to the response values to find a response transformation that provides the best model fit. Evaluation of residual plots, QQ-normal plots, and Boxcox plots indicate that the best response transformation is a square root transformation.

Each predictor was then removed one at a time and we use the extra sum of squares F-test (Ramsey and Schafer 2002) using the "drop1" function (R Development Core Team 2005) to determine which estimators are significant based on their residuals.

Results and Discussion

Our data do exhibit some kurtosis; however, our large sample size lends resistance to any departures from normality (Ramsey and Schafer 2002). To verify that outliers were not affecting the results, we removed obvious outliers and reran the TOST. In each comparison of models, removing the outliers made the minimum region of indifference smaller. Hence, the null hypothesis was more clearly rejected with the outliers removed in each comparison, and we present our results with all data represented.

The mean of the differences between cROS for FIA plots using VWcbd-FFE and VWfba is only 0.010 ms^{-1} (table 2). Despite a comparatively large standard deviation the null hypothesis of dissimilarity is rejected. The sum of the minimum range of indifference and the mean of the difference (0.010 ± 0.027 ms^{-1}) is substantially less than the conservative range of indifference lending strong evidence (in lieu of a p-value) that the rejection of the null hypothesis is justified (table 2).

These same patterns are repeated for the comparison of VWcbd-Cruz and VWcbd-FFE, though the mean of the difference is larger than the previous comparison (0.050 ms^{-1}) (table 2). Again, the sum of the difference and the minimum range of indifference (0.050 ± 0.066 ms^{-1}) are well within the predefined conservative range of indifference leading to a comfortable rejection of the null hypothesis. In the final comparison between VWcbd-Cruz and

Table 2—Results of the equivalence test for FIA data.

FIA data					n = 2626
Models compared ($x_a - x_b$)	Mean of difference (ms^{-1}) (x_{diff})	SD of difference (ms^{-1})	H_o: dissimilarity Conservative (±.138 ms^{-1})	Liberal (±.278 ms^{-1})	Minimum range of indifference (ε)
FFE - FBA	0.010	0.499	**Reject**	**Reject**	**± 0.027**
Cruz - FFE	0.050	0.486	**Reject**	**Reject**	**± 0.066**
Cruz - FBA	0.060	0.814	**Accept**	**Reject**	**± 0.086**

VWfba, the mean of differences is larger than any of the previous comparisons (0.060 ms^{-1}) (table 2). The sum of this large bias between the models and corresponding large minimum region of indifference (0.060 ± 0.086 ms^{-1}) does not allow a rejection of the null hypothesis of dissimilarity under the conservative scenario, though it is still rejected at the liberal range. In all but one of these comparisons we reject the null hypothesis of dissimilarity.

The VWfba provides the slowest estimate of cROS between these three methods. These differences 0.010 ms^{-1} and 0.060 ms^{-1} are interpreted to mean that on average the VWfba model estimates the cROS necessary to sustain canopy fire to be less than the cROS predicted by the VWcbd-FFE and VWcbd-Cruz, respectively. This result is likely due the VWfba utilization of all available fuel and not some fraction of the available fuel, which means that the cROS does not need to be as high as the case where less fuel is available.

The small (0.010 ms^{-1}) difference between the VWcbd-FFE and VWfba method is surprising considering the drastically different methods of fuel estimation used in these models. Therefore, we attempt to explain only the differences between VWcbd-FFE and VWfba models using MLR. The total variance (R^2) explained by the saturated MLR is 57.8 percent (294 and 2331 degrees of freedom). Only the diameter at breast height of the tree of average basal area (dbh.bar) is a significant individual predictor. Nine other variables, all interactions, are found to be significant using the extra sum of squares F-test (table 3).

Colinearity of variables limits our ability to identify the contributed explanatory power of each significant variable. Instead, we fit many regressions using each individual variable, or constituent variables (in the case of interactions), to quantify the remaining variance not explained by the predictor(s). For each variable, table 3 lists the root mean square error (RMSE) of a model that incorporates only that variable (and its constituents). The RMSE of the response variable predicted using a mean parameter was fit for comparison. An individual variable associated with a low RMSE in table 3 is a stronger explanatory variable than a variable with a larger RMSE.

The interaction between total basal area (BA.sum) and total trees per acre (TPA.sum) has the lowest marginal RMSE, but this MLR model would have had two more parameters. While this interaction can be biologically explained, it is not easily interpreted. In contrast, the dbh of a tree with average basal area (dbh.bar) is directly related to the total basal area of a stand, which is highly influenced by the total number of trees in a stand (tpa.sum). The high explanatory power of this single variable is useful to know but provides no further insight to the differences between these models.

Table 3—Saturated multiple linear regression (MLR) model and significant predictors found using the extra sum of squares F-test.

Saturated multiple linear regression model		
sqrt(out1/out2) ~ foliage.sum : BA.sum : TPA.sum : sdi : dbh.bar : Slope : Aspect : HAB : EL		
Adjusted R-squared: 57.8 %	F-statistic: 13.25 on 294 and 2331 degrees of freedom	p-value: < .001
Intercept Estimate	Std Error	95% Confidence Interval
0.726	0.163	0.406 to 1.05

Note: "out1" is the output of the Van Wagner model using FFE fuel input and "out2" is the output of Van Wagner using FBA fuel input. Response variable is a ratio of these outputs, a measure of relative differences to avoid negative values for transformation purposes.

Variable	**Df**	**Marginal RMSE**
Total RMSE: 0.214		
BA.sum:elevation *	1	.208
sdi:elevation *	1	.210
foliage.sum:slope *	1	.211
dbh.bar *	1	.174
foliage.sum:BA.sum *	1	.212
foliage.sum:sdi *	1	.206
foliage.sum:HAB *	29	.191
BA.sum:TPA.sum *	1	.167
BA.sum:sdi *	1	.172
TPA.sum:sdi *	1	.174

Note: Total RMSE represents the RMSE of an intercept parameter fit to the response variable only; it is the root mean square error left after accounting for only the mean.

The VWcbd and VWfba estimates for the regional FIA data (n=2676) are equivalent to one another well within acceptable ranges of indifference established for these tests. We demonstrate that VWfba is equivalent to VW-cbd in the Inland Northwest when the sampling design of FIA is followed and the data used to describe a 0.40 ha (1 acre) stand. Rejection of the null hypothesis of dissimilarity suggests that either model can provide reasonable cROS estimates in this case study. Based on our analysis of comprehensive FIA data, we conclude that the use of VWfba is a reasonable alternative to VWcbd, in particular when compared to VWcbd-ffe. Unfortunately, MLR analysis of our data does little to explain the observed insignificant differences between the VWcbd-ffe and VWfba.

Some of the failure to quantify the accuracy of the VWcbd model may be attributed to the difficulty in measuring, evaluating, or estimating the canopy fuels (Keane and others 2005). Reinhardt and Scott (2005) report nearly 1000 person-hours required to physically measure several canopy biomass variables (including their vertical distribution) to calculate canopy fuel CBD for a single 10 m radius plot. This inability to physically measure the volume space used in CBD calculations has made it difficult to assess the utility of the model as put forth by Van Wagner (1977) (Keane and others 2005).

In contrast, VWfba is directly correlated to the foliar biomass within a stand and does not vary based on estimated canopy volume. The accuracy of allometric equations and the increasing use and accuracy of remote sensors that can be used to estimate foliar biomass in a stand make FBA more easily measured in the field in front of potential canopy fires. This measurability will make nonexperimental field evaluation of the VWfba model a more practical endeavor.

Like CBD estimates, FBA is limited by the accuracy of the technologies used to estimate foliar biomass (total available fuel). However, CBD methods have the added difficulty of measuring the necessary volume. The ability to field test, calibrate, refine, or even observe the efficacy of the VWcbd estimates has been limited mostly because of the complex, more difficult measurement of the CBD input. The principle of parsimony (Ford 2000) might be applied in this situation leading to the adoption of VWfba as a canopy fire model because it utilizes a simpler canopy fuel input. This makes the VWfba model simpler than the existing VWcbd model while providing a statistically significant *equivalent* estimate when compared to the current model.

Conclusions

The adoption of VWfba may allow for consistent fuel quantifications that are less influenced than CBD, by the highly varied canopy structure of forested stands. This consistency provides a benchmark by which to adjust Van Wagner's (1977) modified model, VWfba, for further improvement and refinement. We assert that the VWfba recalibration of Van Wagner's model provides statistically equivalent estimates and is consistent with the original field observations of Van Wagner.

The VWfba model proposed here only quantifies the fuel conditions necessary to sustain canopy fire between two points on the landscape with the intention of matching the performance of the original Van Wagner model. This model does not require knowledge about the vertical distribution of fuel, only that enough fuel exists between two points to sustain canopy fire. Future work with the VWfba model may require a coefficient to describe vertical distribution or a number of other parameters, but these coefficients will be independent of the combustible biomass estimate. This approach leads to a more subtle refinement of the model output independent of the quantity of fuel that is truly available to the advancing canopy fire.

The VWfba model should be applied to a variety of case studies where estimates of foliar biomass can be obtained for observed canopy fires. An example of this sort of validation could be the acquisition of LANDSAT imagery over an area subsequent to a canopy fire. Using estimates of foliar biomass derived from leaf area index (LAI) and specific leaf area (SLA), the resulting VWfba prediction could be compared to fire behavior observations from that fire. This type of field validation removes the necessity of estimating the probable fire spread direction and then placing fuel sampling personnel directly in the path of impending canopy fires, allowing the required fire observations to be conducted from a safe distance. Given the lack of literature suggesting that the use of VWcbd adequately provides estimates of the cROS threshold we would not necessarily expect the VWfba model to accurately estimate cROS in these field trials, but we would expect it to perform as well as the VWcbd model, if reliable CBD data could be collected for comparison.

Ultimately, acceptance of the VWfba model may lead to the development of a canopy fire behavior model that can be related simply to LAI. This would remove the necessity of knowing the tree species necessary to assign a SLA value. This refinement would provide a practical method to take remotely sensed imagery and convert it directly to a relevant canopy fuel characteristic involving one less step than the VWfba model proposed here.

References

Andersen, H.E.; McGaughey, R.J.; Reutebuch, S.E. 2005. Estimating forest canopy fuel parameters using LIDAR data. Remote Sensing of Environment 94: 441–449.

Bachelet, D.; Lenihan, J.M.; Daly, C.; Neilson, R.P. 2000. Interactions between fire, grazing and climate change at Wind Cave National Park, SD. Ecological Modeling 134(2-3) 229–244.

Brown, J.K. 1978. Weight and density of crowns of Rocky Mountain conifers. Research Paper INT – 197. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 56 p.

Byram, G.M. 1959. Combustion of Forest Fuels. In: Forest Fire Control and Use, 1st edition. New York: McGraw-Hill. Chapter 3: 61-89.

Clark, T.L.; Radke, L.; Coen, J.; Middleton, D. 1999. Analysis of small-scale convective dynamics in a crown fire using infrared video camera imagery. Journal of Applied Meteorology 38: 1401–1420.

Cruz, M.G.; Alexander, M.E.; Wakimoto, R.H. 2003. Assessing canopy fuel stratum characteristics in crown fire prone fuel types of western North America. International Journal of Wildland Fire 2003(12) 39–50.

Falkowski, M.; Gessler, P.E.; Morgan, P.; Hudak, A.T.; Smith, A.M. 2005. Characterizing and mapping forest fire fuels using ASTER imagery and gradient modeling. Forest Ecology and Management 217: 129-146.

Finney, M.A. Revised 2004. FARSITE: Fire Area Simulator-model development and evaluation. Research Paper RMRS-RP-4. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 47 p.

Finney, M.A.; Britten, S.; Seli, R. 2003. FlamMap2 Beta Version 3.0.1. Missoula, MT: Fire Sciences Lab and Systems for Environmental Management.

FMFC. 2002. U.S Department of Agriculture, Forest Service, Forest Management Service Center. Acquired from: http://www.fs.fed.us/fmsc/index.php Accessed: May 08, 2005.

Ford, E.D. 2000. Scientific method for ecological research. New York: Cambridge University Press. Chapter 9: 242.

FPS. 2001. Fire Program Solutions, LLC. Acquired from: http://www.fireps.com/ Accessed: April 05, 2005

Froese, R.E. 2003. Re-engineering the Prognosis basal area increment model for the Inland Empire. PhD Dissertation. Moscow: University of Idaho, Forestry, Wildlife and Range Sciences. Chapter 2: 10–21.

Fule, P.Z.; Waltz, A.E.; Covington, W.W.; Heinlein, T.A. 2001. Measuring forest restoration effectiveness in reducing hazardous fuels. Journal of Forestry November, 24–29.

Gholz, H.L.; Grier, C.C.; Campbell, A.G.; Brown, A.T. 1979. Equations for estimating biomass and leaf area of plants in the Pacific Northwest. Research Paper 41. Corvallis: Oregon State University, School of Forestry Forest Research Lab. 39 p.

Gray, K.L.; Reinhardt, E.D. 2003. Analysis of algorithms for predicting canopy fuel. 2nd International Wildland Fire Ecology and Fire Management Congress and 5th Symposium on Fire and Forest Meteorology. Orlando, FL, Nov. 16-20, 2003.

Grier, C.C. 1975. Wildfire effects on nutrient distribution and leaching in a coniferous ecosystem. Canadian Journal of Forest Research 5: 599–607.

Haggard, M.; Gaines, W.L. 2001. Effects of stand-replacement fire and salvage logging on a cavity-nesting bird community in eastern Cascades, Washington. Northwest Science 75(4) 387–396.

Hof, J.; Omi, P. 2003. Scheduling removals for fuels management. Proceedings RMRS-P-29. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 367–377.

Hummel, S.; Agee, J.K. 2003. Western spruce budworm defoliation effects on forest structure and potential fire behavior. Northwest Science 77: 159–169.

Keane, R.E.; Mincemoyer, S.A.; Schmidt, K.M.; Long, D.G.; Garner, J.L. 2000. Mapping vegetation and fuels for fire management on the Gila National Forest Complex, New Mexico. Gen. Tech. Rep. RMRS-GTR-46-CD. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. CD-ROM: 131 p.

Keane, R.E.; Reinhardt, D.; Scott, J.; Graky K.; Reardon, J. 2005. Estimating forest canopy bulk density using six indirect methods. Canadian Journal of Forest Research 35(3): 724-739.

Perry, D.A.; Jing, H.; Youngblood, A.; Oetter, D.R. 2004. Forest structure and fire susceptibility in volcanic landscapes of the eastern high Cascades. Conservation Biology 18(4) 913–926.

Peterson, D.L.; Johnson, M.C.; Agee, J.K.; Jain, T.B.; McKenzie, D.; Reinhardt, E.D. 2005. Fuel planning: Science synthesis and integration – forest structure and fire hazard. Gen. Tech. Rep. PNW-GTR-628. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 30 p.

R Development Core Team. 2005. R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing. ISBN 3-900051-07-0; URL http://www.R-project.org.

Ramsey, F.L.; Schafer, D.W. 2002. The statistical sleuth: a course in methods of data analysis, 2nd edition. Pacific Grove, CA: Duxbury. Chapter 10: 280–285.

Reinhardt, E.D.; Crookston, N.L. 2003. The fire and fuels extension to the forest vegetation simulator. Gen. Tech. Rep. RMRS-GTR-116. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 209 p.

Riano, D.; Chuvieco, E.; Condes, S.; Gonzalez-Matesanz, J.; Ustin, S.L. 2004. Generation of crown bulk density for pinus sylvestris L. from lidar. Remote Sensing of Environment 92: 345–352.

Riano, D.; Meier, E.; Allgower, B.; Chuvieco, E.; Ustin, S.L. 2003. Modeling airborne laser scanning data for the spatial generation of critical forest parameters in fire behavior modeling. Remote Sensing of Environment 86: 177–186.

Robinson, A.P.; Froese, R.E. 2004. Model validation using equivalence tests. Ecological Modelling 176: 349–358.

Romme, W.H.; Turner, M.G.; Wallace, L.L.; Walker, J.S. 1995. Aspen, elk, and fire in northern Yellowstone National Park. Ecology 76(7) 2097–2106.

Ryan, N.C.; Noste, N.V. 1983. Evaluating prescribed fires. Wilderness Fire Symposium, Missoula, MT, Nov. 15-18, 1983.

Sando, R.W.; Wick, C.H. 1972. A method of evaluating crown fuels in forest stands. Research Paper NC-84. Saint Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station.

Scott, J.H. 1998. Sensitivity analysis of a method for assessing crown fire hazard in the northern Rocky Mountains, USA. International Conference on Forest Fire Research. 14th Conference on Fire and Forest Meteorology, Vol. 2; 2517– 532. Luso, Portugal, November 16-20, 1998.

Scott, J.H. 2003. Canopy fuel treatment standards for the wildland-urban interface. Proceedings RMRS-P-4. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 29–38.

Scott, J.H.; Reinhardt, E.D. 2001. Assessing crown fire potential by linking models of surface and crown fire behavior. Research Paper RMRS-RP-29. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 59 p.

Scott, J.H.; Reinhardt, E.D. 2005. Stereophoto guide for estimating canopy fuels characteristics in conifer stands. Gen. Tech. Rep. RMRS-GTR-145. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 49 p.

Stocks, B.J.; Alexander, M.E.; Wotton, B.M.; Stefner, C.N.; Flannigan, M.D.; Taylor, S.W.; Lavoie, N.; Mason, J.A.; Hartley, G.R.; Maffey, M.E.; Dalrymple, G.N.; Blake, T.W.; Cruz, M.G.; Lanoville, R.A. 2004. Crown fire behaviour in a northern jack pine-black spruce forest. Canadian Journal of Forest Research 34: 1548–1560.

USDA Forest Service. 1990. Idaho forest survey field procedures (1990-1991). Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 181 p.

Van Wagner, C.E. 1977. Conditions for the start and spread of crown fire. Canadian Journal of Forest Research 7: 23–34.

Wellek, S. 2003. Testing statistical hypotheses of equivalence. New York: Chapman and Hall/CRC.

Ignition and Flame Travel on Realistic Building and Landscape Objects in Changing Environments

Mark A. Dietenberger[1]

Abstract—*Effective mitigation of external fires on structures can be achieved flexibly, economically, and aesthetically by (1) preventing large-area ignition on structures from close proximity of burning vegetations and (2) stopping flame travel from firebrands landing on combustible building objects. In using bench-scale and mid-scale fire tests to obtain fire growth properties on common building construction and landscaping plants, a model is being developed to use fast predictive methods suitable for changing environments imposed on the parcel lot consisting of structures and ornamental plants. When fully implemented and validated, the property owners and associated professionals will be able to view realistically in real-time (or faster) the various fire scenarios with the ability to select building materials and shapes as well as select ornamental plant species and placement for achieving the desired fire mitigation. Because of the analytical model's ability to respond to the changing "parcel" environments of wind, temperature, humidity, moisture, sunshine, and wildfire sources of heat and embers, as well as to variations in building construction and ornamental plants, means that analysis can be done eventually for various neighborhoods. The mathematical formulation presented at the 2006 BCC Symposium is partially shown here and some results are compared with (1) our refurbished and modified Lateral Ignition and Flame Travel Test (ASTM E1321 and E1317), (2) specialized testing of Class B burning brand (ASTM E108) in the Cone Calorimeter (ASTM E1354), (3) room-corner tests with OSB (ISO 9705), and (4) Cone Calorimeter tests of fire resistive materials such as FRT plywood and single-layer stucco-coated OSB. A preliminary Fortran dll file has been generated for use in other models, such as ecoSmart Fire.*

Introduction

With the increasing fire hazards from wildfires, particularly in Southwestern United States, the homes built in the wilderness/urban interface (WUI) will come under increasing regulatory pressures to adopt exterior fire resistive structures, in addition to managing landscape vegetation. However, it is not always clear as to the effective strategy for wildfire mitigation, even to a fire protection expert. Indeed, homeowners and builders could benefit greatly from a calculation tool for evaluating the wildfire hazards to their structures. Fire threats in the WUI basically come in two forms: (1) the long-duration exposure from firebrands spotting and (2) the short-duration exposure from heat flux and/or flame impingement of the wildfire nearing the structure.

The fire hazard threat of high heat flux or flame impingement from short-duration wildfire exposure is primarily mitigated with vegetative management in the defense zones around the combustible structure. The kind of vegetative management needed to prevent structural ignition will depend on the

In: Butler, Bret W.; Cook, Wayne, comps. 2007. The fire environment—innovations, management, and policy; conference proceedings. 26-30 March 2007; Destin, FL. Proceedings RMRS-P-46CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 662 p. CD-ROM.

[1] Research General Engineer, U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI. mdietenberger@fs.fed.us

fire resistant construction, moisture condition of landscape vegetation, and the positions/types of ornamental vegetations relative to the combustible structure. To establish the nonthreatening distances of rapidly burning ornamental vegetations away from a given structure, which may or may not be fire resistant, one should ideally use a fire hazard calculation tool, such as being partially developed in this paper. The insidious threat from long-duration firebrands' exposure, as particularly blown in from a distant huge wildfire, is really the main driving force in requiring fire resistant structures in the WUI. Obviously, the owner needs to place wire screens over chimneys, vents, and around decks and some windows to prevent ember penetration into the highly combustible interiors of buildings (Manzello and others 2006). However, it is not clear as to how much fire resistance is needed for the construction exteriors. The homeowner could well decide that the wood deck is expendable as long as the fire (possibly originating in the deck crevice with firebrands, Manzello and others 2006) does not spread into the fire resistant home. The patio door and windows should also be made resistant to the worst-case firebrand, which is likely the Class A or B simulated firebrand in the ASTM E108 test. The Class A firebrand can also be thought of as multiple firebrands collecting in a corner wall, where the upward flame spread on combustible sidings is likely. The use of an exterior FRT wood siding or similarly fire resistive material will instead prevent such flame spread, thereby limiting the damage/ignition to the region of direct exposure from the firebrands. Our main point is that reasonable and economical design of an exterior fire resistant material needs to consider the firebrand threats, even with effective vegetative management.

We believe the speed of computer computation has reached the point of bettering the real time calculation of damage, ignition, and fire growth on combustible objects. Since the CFD codes such as the Fire Dynamics Simulator are far from reaching such a point, we present here certain analytical solutions of the dynamic processes of surface heating to ignition/flame travel that leads to overall fire growth. The key numerical procedure is using stepping boundary conditions to discretize the analytical time integration and which then becomes a fully recursive computation method as a bonus. The mathematical formulation presented at the 2006 BCC Symposium (Dietenberger 2006a) is partially shown here and some results are compared with (1) our refurbished and modified Lateral Ignition and Flame Travel Test (ASTM E1321 and E1317), (2) specialized testing of Class B burning brand (ASTM E108) in the Cone Calorimeter (ASTM E1354), (3) room-corner tests with OSB (ISO 9705), and (4) Cone Calorimeter tests of fire resistive materials such as FRT plywood and single-layer stucco-coated OSB.

Ignition Predictions With Changing Conditions

The prediction of surface temperature for reaching ignition conditions that take into account the changing boundary conditions, and yet avoid the use of time-consuming finite difference methods, resulted in an innovative mathematical formulation of transient heat transfer problem. In an earlier paper (Dietenberger 2006b) we published a recursive analytical solution for transient heat and moisture transfer in a finitely thick hygroscopic material with step changes of certain boundary conditions. For many materials, moisture is not a consideration and we show here just the solution for temperature change, $T(\hat{x},t)$, profile due to boundary conditions of stepping changes in surface heat fluxes, $\dot{q}''(\ell,t)$ and back side heat fluxes, $\dot{q}''(0,t)$, here as,

$$T(\hat{x},t) \cong \sum_{i=0}^{n}\left[\frac{\Delta\dot{q}''(\ell,t_i)}{K_{q,\ell}} S(\alpha,\hat{x},t-t_i) - \frac{\Delta\dot{q}''(0,t_i)}{K_{q,0}} S(\alpha,\ell-\hat{x},t-t_i)\right] \quad (1)$$

where $\hat{x}$ is dimensional depth, t is current time, K_q is thermal conductivity coefficient, C_q is heat capacity, ρ is dry body density, α is thermal diffusivity, and $S(\alpha,\hat{x},t)$ is the series expansion solution,

$$S(\alpha,\hat{x},t) = \frac{\alpha t}{\ell} + \ell\left\{\frac{3\hat{x}^2-\ell^2}{6\ell^2} - \frac{2}{\pi^2}\sum_{n=1}^{\infty}\frac{(-1)^n}{n^2}\exp\left[\frac{-\alpha t}{1}\left(\frac{n\pi}{\ell}\right)^2\right]\cos\left(\frac{n\pi\hat{x}}{\ell}\right)\right\} \quad (2)$$

Rarely do classical heat conduction texts discuss such stepping heat fluxes, probably because the summation in equation 1 can be burdensome. However, such texts do not offer the possibility of converting equation 1 to a recursive summation, which is simple and efficient to implement as a computer routine, which we have done for this work. If irradiance, $\dot{q}_r''$, is applied to one surface, the material responds with radiative and convective cooling on the exposed side, and conductive cooling on the unexposed side as in the boundary conditions,

$$\Delta\dot{q}''(\ell,t_i) = \left\{\begin{matrix} \alpha_{s,i}\dot{q}_r''(t_i) + \varepsilon_{s,i}\sigma[T_a^{\ 4}(t_i) - T^4(\ell,t_i)] + h_{c,i}[T_a(t_i) - T(\ell,t_i)] \\ -H(t_i-t_1)\left\{\alpha_{s,i}\dot{q}_r''(t_{i-1}) + \varepsilon_{s,i}\sigma[T_a^{\ 4}(t_{i-1}) - T^4(\ell,t_{i-1})] + h_{c,i}[T_a(t_{i-1}) - T(\ell,t_{i-1})]\right\}\end{matrix}\right\} \quad (3),$$

$$\Delta\dot{q}''(0,t_i) = C_{insulate}[T(0,t_i) - T_a(t_i)] - H(t_i-t_1)C_{insulate}[T(0,t_{i-1}) - T_a(t_{i-1})]$$

then eventually the predicted surface temperatures will reach a steady-state value in which the convective and radiative heat losses to the air and conductive heat losses to backside insulation is equal to radiant energy absorbed. The heaviside function, $H(t_i - t_1)$, is used to specify that prior to heat exposure the sample is at a uniform temperature, and therefore has zero heat fluxes at both surfaces. If the irradiance is high enough, then the surface will reach ignition temperature, T_{ig}, prior to reaching steady state temperature. To more accurately capture the time at ignition, we used time steps of one second or less, although a large time step is feasible if the boundary conditions change slowly enough as with the diurnal heating cycle.

As can be seen from equation 3 the changes in the boundary conditions with time can be used. That is, we can arbitrarily vary irradiances, convective flow, atmospheric temperature, and surface conditions with time. The method can also be extended to multilayered samples in which interfacial zones can be treated as "conductive backside cooling" heat transfers. To consider ignition due to flame impingement, we have the imposed heat flux from the 100 kW propane ignition burner (or the firebrand flames), $\dot{q}''_w$, in our room-corner burn tests to use in place of the term, $\alpha_s\dot{q}''_r + \varepsilon_s\sigma(T_a^{\ 4} - T(\ell,t)^4) + h_{ci}(T_a - T(\ell,t))$, in equation 3, as,

$$\dot{q}''_w = \sigma\ (\alpha_s\varepsilon_f T_f^{\ 4} + \varepsilon_s(1-\varepsilon_f)T_a^{\ 4} - \varepsilon_s T(\ell,t)^4) + h_{cf}(T_f - T(\ell,t)) \quad (4)$$

The parameters that are known in the case of fluxmeters in the wall are $\dot{q}''_w = 55kW / m^2$, $T(\ell,t) = 298\ K$ and absorptivity and emissivity as $\alpha_s = \varepsilon_s = 0.97$. Using averaged measured flame temperature, $T_f = 173\ K$, we derived values of flame emissivity and convective coefficient as, $\varepsilon_f = 0.391$ and $h_{cf} = 0.0165kW / m^2\ K$ to reproduce the fluxmeter heat flux. Our test materials typically have lower surface emissivity, $\varepsilon_s = 0.88$, and using the above values for other parameters the imposed heat flux becomes 51 kW / m^2 instead. Therefore we would expect the time to ignition on the wall to correlate best with the cone heater flux of 50 kW / m^2, as was found by Karlson (1993). However, he used a multiplication factor of 1.7 times the time to ignition from the cone calorimeter to obtain the actual time to ignition for the room-corner test, which is equivalent to adding about 11 seconds (90 percent level) to ignition time due to burner lagging.

Fire Growth Simulation With Changing Conditions

In an earlier paper reporting on our ISO9705 tests (Dietenberger and Grexa 1996), we described the complex-variable Laplace transform solution of the Duhamel integral for flame spread, HRR, and pyrolysis area that involved four stages requiring solution restarts: (1) ignited corner area due to a sluggish propane burner, (2) upward spread of corner flame to the ceiling, (3) lateral spread of top-wall flame for the unlined ceiling, and (4) the preflashover rapid downward spreading of the entire three walls flame. This analytical solution was modified for application to the changing conditions of the WUI fire scenario, and the formulation reported in the 2006 BCC Symposium (Dietenberger 2006a) is briefly repeated here. First step in the analysis is the description of the extended flame flux profile as an imposed flux applied over surface distance, y_c, followed by an exponential decay with characteristic length, δ_f, as in

$$\dot{q}''_{wf}(y) = \dot{q}''_{w0}\left[H(y) + \left(\exp\left\{\frac{-(y-y_c)}{\delta_f}\right\} - 1\right)H(y-y_c)\right] \qquad (5)$$

where $H(y)$ is the heaviside function. With the length of constant flux, y_c, identified with the pyrolysis front, y_p, the characteristic length was found to be proportional to extended flame length and correlated as, $\delta_f = (y_f - y_p) / c_f$, with value of c_f approximately as 1.3 for upward spread. With this spatial profile of flame heat flux, we then analyzed for the quasi-steady speed, v_p, of the pyrolysis front by using the formula, $y - y_{ig} = v_p(t_{ig} - t)$, in equation 5 to represent the sliding movement of imposed heat flux profile over a given spot until ignition temperature is reached. With this substitution, Duhamel's supposition integral is the convolution of material's thermal response to a constant imposed flux with time changing imposed flux as in

$$T_{ig} - T_m = \frac{d(T(\ell,t))}{dt} \otimes \dot{q}''_{wf}(v_p(t_{ig} - t) + y_{ig}) = (T(l,t)) \otimes \frac{d\dot{q}''_{wf}(y_{ig} - v_p(t - t_{ig}))}{dt} \qquad (6)$$

where the integration is taken from zero to the time of ignition, t_{ig}, to correspond to ignition temperature, T_{ig}. We note that equation 6 becomes exactly equation 1 providing the heat flux profile of equation 5 is approximated by incremental flux changes with incremental time steps, which we will show later in evaluating the LIFT test data. Because it is possible to have a wide variation in the characteristic flame length, depending on the direction of the flame spread, then the time step sizes will have to be highly adaptable to ensure a reasonably accurate and efficient descretization of equation 5 for its use in equation 1. If there are multiple flame spread directions on multiple combustible items, then it would be impossible to determine the optimum time steps. This is the fundamental reason why the CFD codes, such as the FDS, will fail to predict some types of flame spreading problems. To avoid this problem, the intricate analytical solution to equation 6 (instead of a discretization solution) for both thermally thick and thermally thin materials and with interpolation between the regimes is given Dietenberger (1991) as:

$$\delta f = v_F \tau m = v_F K_q \rho Cp \left(\frac{Tig - Tm}{\dot{q}''_{w0} - \dot{q}''_{iq}} \right)^2 \left(\frac{1}{2} + \sqrt{\frac{1}{4} + \left(\frac{K_q \, (Tig - Tm)}{\ell (\dot{q}''_{w0} - \dot{q}''_{ig})} \right)^{1.3}} \right)^{\left(\frac{-2}{1.3}\right)} \quad (7)$$

$$\text{where} \quad \dot{q}''_{ig} = \varepsilon_s \sigma (T_{ig}{}^4 - T(\ell,0)^4) + h_c (T_{ig} - T(\ell,0)) \quad (8)$$

One then realizes that all of the material's parameters for thermal response are contained in the material time constant, τ_m, during flame spreading. Closer examination of equation 7 shows that the flame travel rate, v_F, can be made quite small with large values for thermal conductivity, material density, heat capacity, material ignition temperature, and material thickness, or with small values for preheated surface temperature, flame heat flux, and flame footprint. Obviously, to completely stop flame spreading for any direction, the local flame foot heat flux has been reduced to the critical heat flux needed for ignition (via equation 8). The use of fire retardants merely improves upon this flame spread halting, even to the point of diminishing upward flame spreading under a strong radiant source. We note that supposed "constant" fire properties used in equations 7 and 8 are also changing with time, especially the flame foot and ignition fluxes.

As the next step in analytical modeling of fire growth, the flame oversize area, $A_f - A_p$, as a nonlinear function of HRR, Q_t, and flame width, w, for the corner flame (Dietenberger and Grexa 1996) is linearized at each time step as,

$$2w(y_f - y_p) = 0.0433(2w)^{1/3} Q_t{}^{2/3} \approx A_{fm} + \frac{\partial A_f}{\partial Q_t}(Q_t - Q_m) + \frac{\partial A_f}{\partial A_p}(A_p - A_{pm}) = c_f(a + bA_p + cQ_t) \quad (9)$$

The flame area for other geometries, such as the single vertical wall, a tunnel ceiling, or a circular pool fire, can be similarly linearized for their respective nonlinear functions. The fire growth problem, by rearranging equation 7, can now be stated concisely as the Voltera type integral as,

$$\frac{dA_p}{dt} = 2wv_F = \frac{a + bA_p + cQ_t}{\tau_m} + A_{ig,i}\Lambda(t - t_i) \quad (10)$$

where the total HRR is given by a sum of ignition-burner and material-flame-spreading heat release rates as,

$$Q_t = \sum_i \Delta Q_{b,i} H(t - t_i) + \sum_i A_p(t_i)\, Q''_m(t - t_i) + \int_0^{t - t_i} Q''_m(t - t_i - \xi)\, \dot{A}_p \, d\xi \quad (11)$$

$$\text{and} \quad Q''_m(t) = Q''_{m,ig}\, H(t) \exp(-\omega_m t) \quad (12)$$

whereas an exponentially decaying HRR profile (with decay coefficient, ω_m) is assumed for a given sample surface, with the peak HRR flux, $Q''_{m,ig}$, also changing with time as a result of the changing radiant source. The recursive Laplace solution to equation 10 given for each time step is (with $t^* = t - t_i > 0$),

$$A_p(t) = \left(\frac{a + c(Q_{mi} - A_{pi}Q''_{m,iq} + Q_{bi} + \Delta Q_{bi})}{\tau_m} + A_{pi}\omega_m\right)\left(\frac{\exp(s_1t^*) - \exp(s_2t^*)}{s_1 - s_2}\right)$$
$$+ A_{pi}\left(\frac{s_1\exp(s_1t^*) - s_2\exp(s_2t^*)}{s_1 - s_2}\right) + \left(\frac{a + c(Q_{bi} + \Delta Q_{bi})}{\tau_m}\right)\left(\frac{\omega_m}{s_1 - s_2}\right)\left(\frac{\exp(s_1t^*) - 1}{s_1} - \frac{\exp(s_2t^*) - 1}{s_2}\right) \quad (13)$$

$$Q_t(t) = Q_b(t) + Q_m(t) = Q_{bi} + \Delta Q_{bi} + \left(\frac{(a + cQ_{bi})Q''_{m,ig} - b(Q_{mi} - A_{pi}Q''_{m,ig})}{\tau_m}\right)\left(\frac{\exp(s_1t^*) - \exp(s_2t^*)}{s_1 - s_2}\right)$$
$$+ \frac{cQ''_{m,ig}}{\tau_m}\Delta Q_{bi}\left(\frac{\exp(s_1t^*) - \exp(s_2t^*)}{s_1 - s_2}\right) + Q_{mi}\left(\frac{s_1\exp(s_1t^*) - s_2\exp(s_2t^*)}{s_1 - s_2}\right) \quad (14)$$

where growth acceleration coefficients (in complex variable form) are,

$$s_i = \frac{b + cQ''_{m,ig} - \omega_m\tau_m}{2\tau_m} - (-1)^i\sqrt{\left(\frac{b + cQ''_{m,ig} - \omega_m\tau_m}{2\tau_m}\right)^2 + \frac{b\omega_m}{\tau_m}} \quad (15)$$

For brevity we define the recursive terms, $A_{pi} = A_{ig,i} + A_p(t_i)$, $Q_{bi} = Q_b(t_i)$, and $Q_{mi} = Q''_{m,ig}A_{ig,i} + Q_m(t_i)$. The size of the overflame area as a function of time is merely given with equation 9. Since equations 13 and 14 are framed in a recursive form, the coefficients and parameters treated as constants during a time step can be allowed to vary from time step to time step. Indeed the material time constant, τ_m, is in actuality a fairly strong function of time via the changing preheat temperature, T_m, in equation 7, which in turn is calculated with equation 1 using the time-changing external radiant flux boundary conditions. Therefore, one could conceive that the overall fire growth can switch from a damped fire spread to an accelerative fire spread, or vice versa, through the mere time variation of the material time constant. Because the roots are considered complex numbers, the above solutions are considered to be in the complex variable domain. Specialized computer algorithms were developed for complex evaluations so that the above functions could be programmed directly as a Fortran code called by the Excel spreadsheet. Because of the recursive nature of fire growth equations, it should be possible to consider various changing conditions without recalibrating the coefficients.

Class B Firebrand Tests in the Cone Calorimeter

To understand the challenges presented with a typical fire scenario in the WUI we burned the Class B firebrand of ASTM E108 in the Cone Calorimeter (ASTM E1354). A modified sample holder was used that allowed air flow into the sample as well as exposed the sample partially into the air. This necessitates us to turn the cone heater into the vertical position to keep it out of the way, and we opted not to use the cone irradiance, although we may do that in the future. Use of a Bunsen burner to ignite the brand would have been required in the ASTM E108 test to ensure a self-burning brand, but instead for our test the brand was partially soaked in methanol bath. With ignition started at the corners of the brand, the ensuring flame took several minutes to spread around the brand. The HRR history as shown in figure 1 somewhat increases linearly to a broad peak value of 10 kW and decreases gradually afterwards. Although a simple charring wood surface has a strong initial peak HRR and then decays approximately exponentially for many seconds, the phenomenon of flame spreading around the specimen is rapid enough to result in a net increasing HRR with time. Once flame spreading is finished, the HRR should decay somewhat exponentially, but the increasing glowing HRR makes the decrease in the overall HRR to be not so rapid. The fire growth process and the effect on the HRR profile is similarly imagined for flaming vegetations, roof fires, deck fires, and so on. The challenge for analytical fire growth modeling is to reproduce the HRR profile with the use of several burning regions in the model.

The heat flux from a burning firebrand, however, varies according to size, distance, shape, viewfactor, and time-dependent HRR profile. For example, in our cone calorimeter test of Class B brand we were able to place one fluxmeter directly underneath the 150 X 150 X 60 mm wood crib with a 5 mm gap and 25 mm inward from the edge and another fluxmeter located at 45 mm outward from the wood crib. The heat flux data are shown in figure 2, which clearly shows the effects of viewfactors of the developing flame on the measured value. That is, the outside-fluxmeter seems to mimic the HRR trend and has a peak heat flux of 6.7 kW/m^2, which is not enough to ignite most materials but can still char some materials. On the other hand, the underneath-fluxmeter at first could not view the flame, and when the flame came into view, the flux levels eventually reached 50 kW/m^2. Then after the flame subsided and the wood crib was glowing throughout, the flux became as high as 80 kW/m^2. This is the high flux that rapidly ignites most materials, and also some fire resistant materials, albeit with a little more time to ignition.

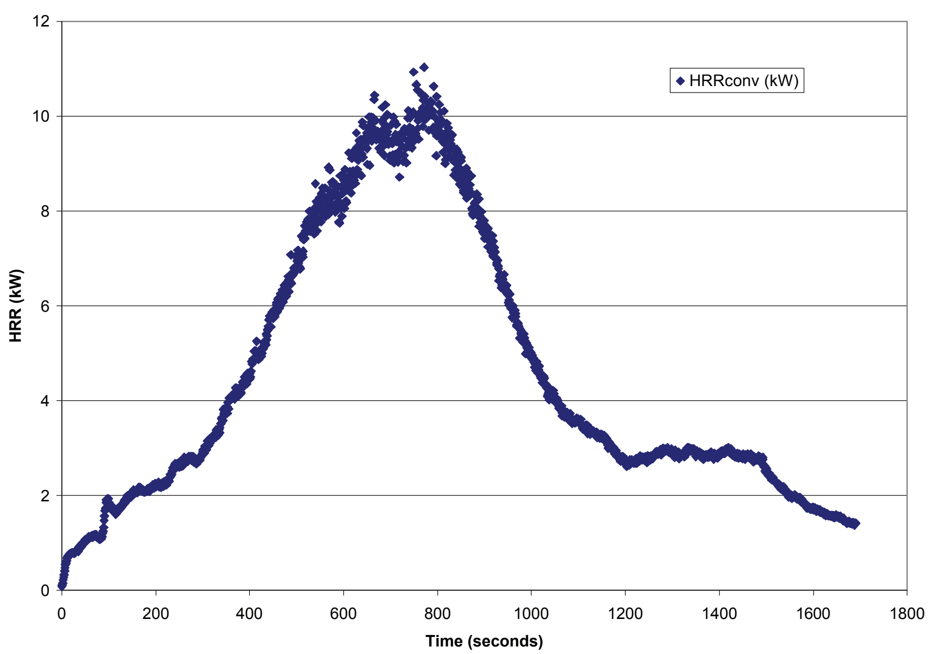


Figure 1—Heat release rate of class A brand.

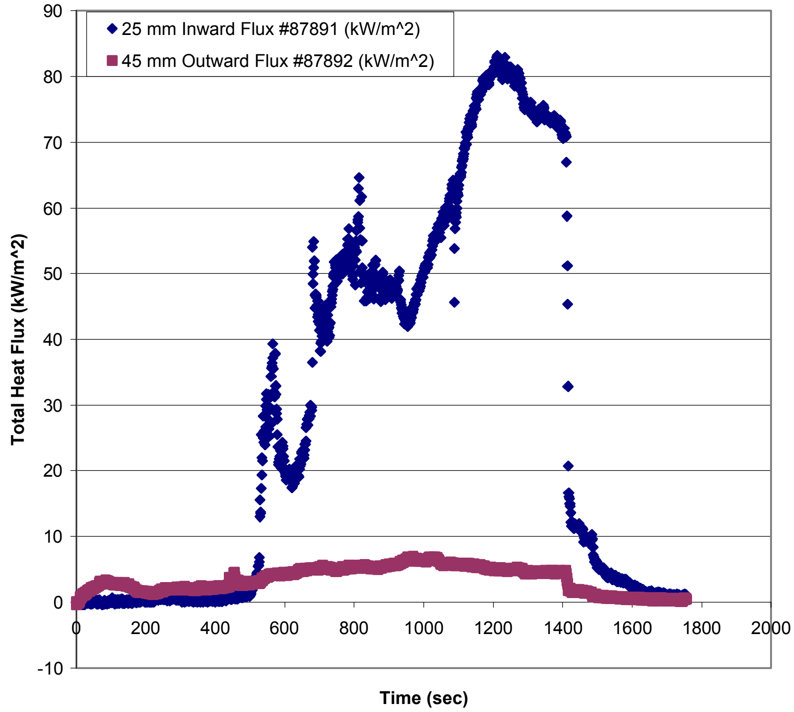


Figure 2—"A" brand heat fluxes.

Figure 3 shows the surface temperature response of dried redwood decking as calculated with equation 1 using the imposed heat flux profiles from figure 2 as the time dependent input data. The high temperatures obtained under the 80 kW/m^2 flux from the contact with wood crib glowing confirm the assertion that most combustible building materials will ignite. Yet, at a short distance away, the imposed heat flux exposure drops to the levels such that most combustible materials will not ignite.

These facts would place exterior cladding surfaces such as roofs and decks and unprotected interior flooring as highly susceptible to ignition by the "worse-case" firebrand. Therefore, designing fire resistant claddings to prevent flame spreading or avoid fire penetrating through the exposed layer after the inevitable ignition would be a desirable trait. Indeed, at least among wood materials, one could observe similar ignition behavior among different species, but that their flame spreading behavior is remarkably different.

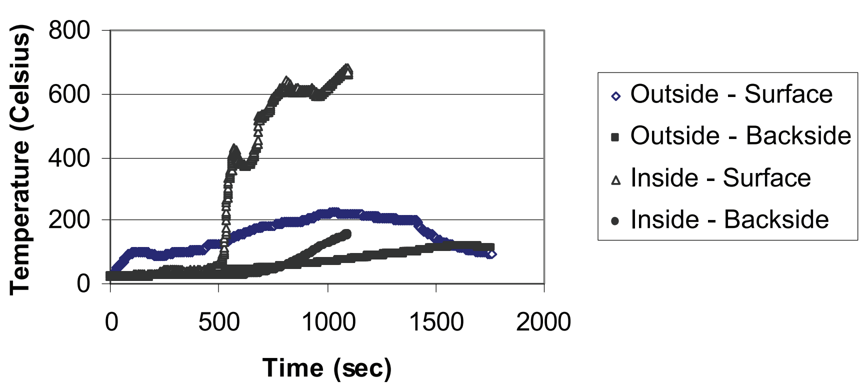


Figure 3—Analytical prediction of dried redwood response to class B brand heat exosure.

Refurbished Lift Apparatus and Analysis

Almost a couple decades ago we built the LIFT apparatus to duplicate the original at NIST BFRL, which was developed mainly by Margaret Harkleroad. The intent was to follow the ASTM E1321 standard to obtain ignition and flame spread properties for wood based materials. The standard called for the 6 inch by 30 inch vertically mounted specimen to be exposed continuously to the burner radiant heat until there was a distribution of surface temperature in equilibrium. This distribution of temperature then gave rise to a variation of lateral flame travel rate, which was to be measured manually. However, at the heat fluxes required, the wood was experiencing surface charring, which negated possibility of deriving flame travel property. Another factor creating difficulties was the unrealistic high convective flow exposures to cause ignition and flame travel, as compared to, for example, the low convective flow involving vitiated hot air in the lateral flame travel phase in the Room Corner test (ISO9705). Finally, we were dependent on the venturi tube to control the burner output with the air flow valve, which created a problem for us when the cyclic central air source caused a highly wandering burner output.

With the current emphasis on the WUI applications, installation of a mass flow controller on the air source, and utilization of faster and more accurate data acquisition, we embarked on refurbishing the LIFT apparatus. Our modified test protocol involves no surface preheating, numerous tiny surface thermocouples, and a crank-operated computer-recorded indicator for tracking flame position as function of time. The first detailed test involved the OSB that was set aside for the LIFT tests when the series of room-corner tests were done.

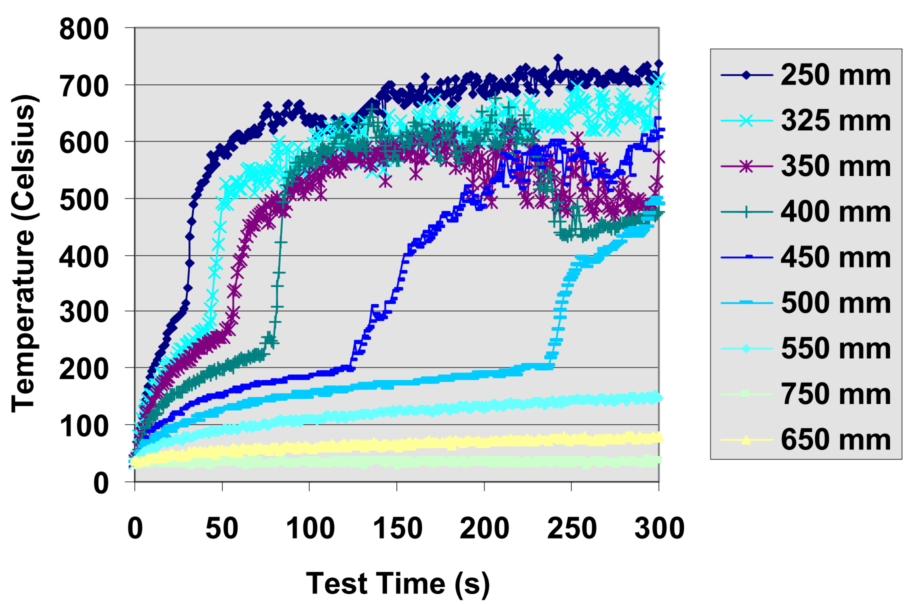


Figure 4—Surface temperatures measured on OSB surface in the LIFT flame travel test.

For the exposure to the 50 kW/m^2 radiant imposed flux at the 50 mm position from the specimen end, the data (not shown) shows surface temperatures profiles at various locations up to 200 mm which is consistent with the flame spread rapidly proceeding downwards from the pilot ignition. In figure 4, the surface temperatures profiles at positions greater than 200 mm is shown in which there was a lateral flame spread that decreased in the travel rate until the flame stopped spreading at around 550 mm. Although it is apparent when the flame has traveled over a thermocouple, it was not apparent as to what the ignition temperature is or just how the temperature rapid rise has occurred just prior to the flame front arrival. Indeed, with the rapid rise in temperature after a radiant preheat period indicates that a small flame-foot heating feature must be captured by a credible model of fire growth.

The typical temperature profiles were easily simulated with the recursive formulation of equation 1 using reasonable heat flux profiles shown in figures 5 and 6 with the corresponding temperatures predictions in figures 7 and 8 in comparison with the data. The thermophysical properties for OSB were taken from our previous ignitability results. The imposed heat fluxes had three phases to properly predict surface temperatures. The first phase is the few seconds increase in heat flux as a result of sliding the specimen into place. At the 50 mm location where the radiant flux was set at about 50 kW m^2, the calculated temperature response reached 301 °C at 12 seconds in figure 7. The third phase of heat flux is caused by the flame foot modeled with time-changing form of equation 5, having the flame foot heat flux of 60 kW/m^2 and a time constant of 0.4 seconds. The rapid exponentially upturn of the temperature was captured using 0.2 seconds time steps so that the surface temperature of 408 °C was obtained at 15.4 seconds (flame sheet arrival time). Further, but damped, temperature rise was in response to the imposed flux set at 110 kW/m^2. Similar pattern is noted for figure 8, which required a flame foot heat flux of 60 kW/m^2, time constant of 4.0 seconds, and flame sheet arrival time at 83 seconds. With the relative increase of the time constant by 10 times, meant that the local flame travel rate at 50 mm is also 10 times of that at 200 mm. Note that the net surface heat flux due to surface emitting radiation and reduction in convection heat flux has rapidly changing profile adequately captured by the analytical model to predict the temperature response.

It is interesting that no charring of the wood surface was needed for making close temperature predictions, allowing us to take the planned steps to validate the lateral flame travel rate formula given by equation 7. Since we have measurements from the thermopile in the flue gas and from fume stack thermocouple (ASTM E1317), we can derive the sensible HRR profile (Dietenberger 1994) and compare it with the model estimated HRR profile from equation 14. Success with this approach can be applied to other situations involving flame travel opposing the air flow, such as ground flame propagation or fire on a deck surface.

Selected Room-Corner Tests

Because the analytical fire growth model for changing conditions differs somewhat from the original model, we decided to focus on predicting the upward fire growth behavior in corner walls, particularly if no fudging of material properties was required and that it provided a good representation of the exterior environment (far below the flashover conditions). In the case

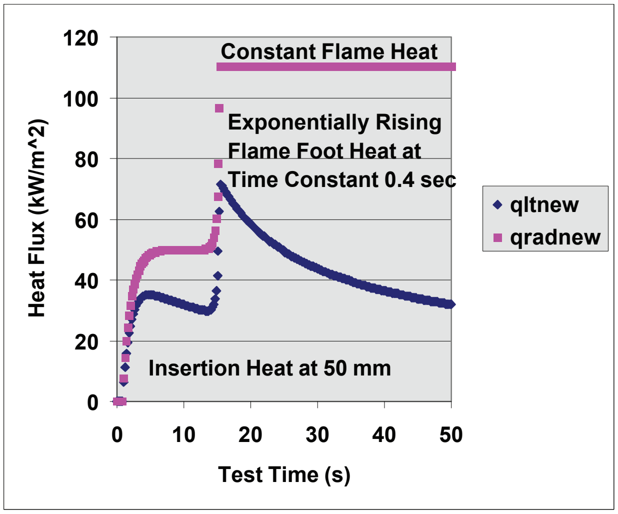


Figure 5—Imposed heat fluxes modeled for temperature predictions at the 50 mm location.

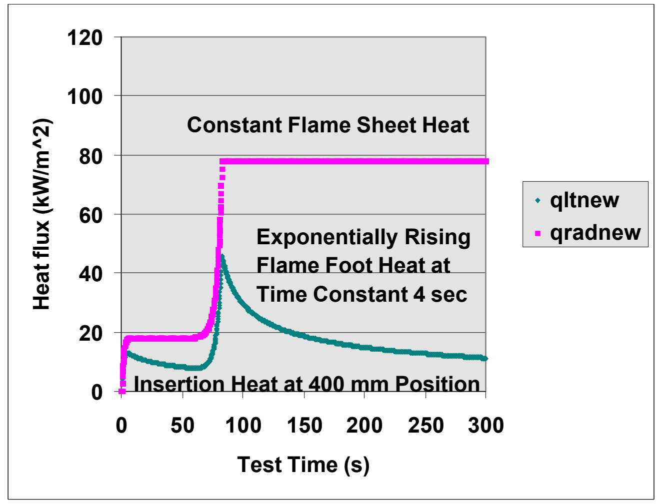


Figure 6—Imposed heat fluxes modeled for temperature predictions at the 400 mm location.

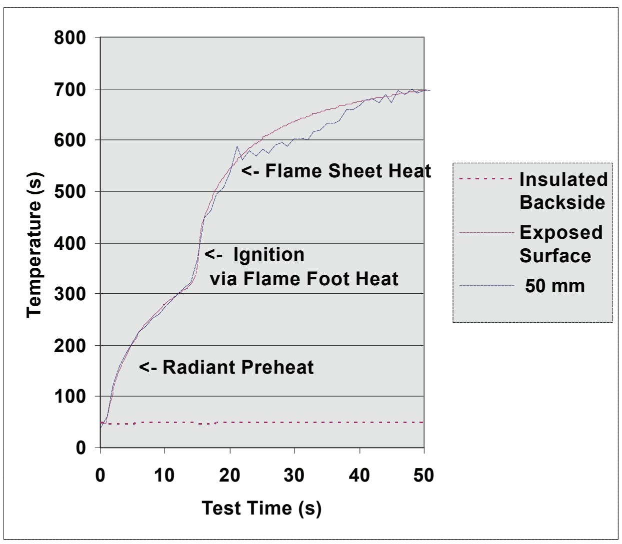


Figure 7—Prediction of measured surface temperature using imposed heat fluxes in figure 5.

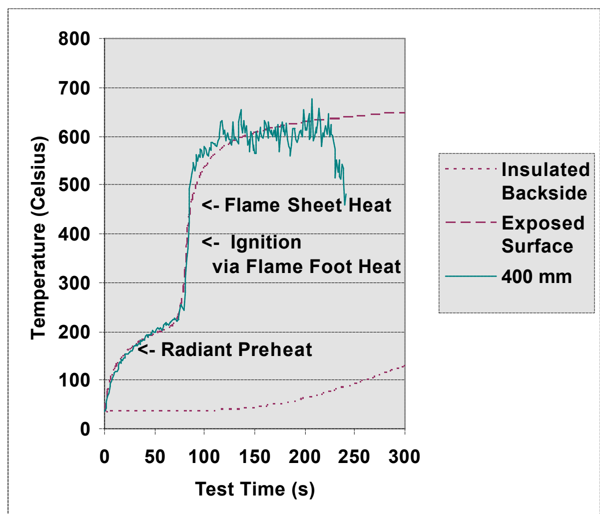


Figure 8—Prediction of measured surface temperature using imposed heat fluxes in figure 6.

of OSB we used the properties published earlier (Dietenberger and Grexa 1996). Figure 9 shows our Room-Corner flashover test with OSB linings on the walls and gypsum board on the ceiling. We also show with the dotted smooth curve the ignition burner going to 100 kW as it is observed by the gas analyzers, in which we take into account gas mixings in the test room and gas sensors and time travel of the sampled gas to the sensors. The OSB ignited 25 seconds after exposure to the ignition burner and led to an upward fire growth that is shown as the HRR profile rising above that of the ignition burner. The dashed smooth curve is predicted by equation 14 that was also numerically filtered with a time constant of 18 sec for gas lag in the

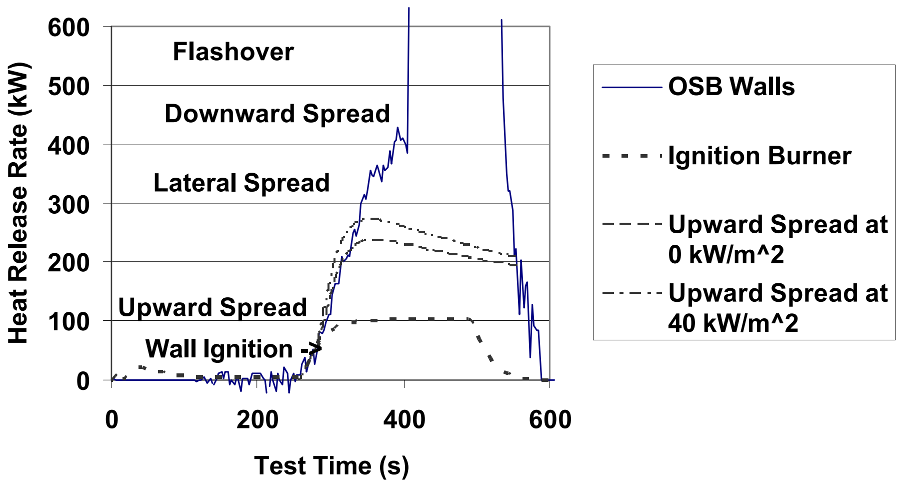


Figure 9—Analytical prediction and Room-Corner test for OSB on the walls that varies the external radiant flux from 0 to 40 kW/m^2.

room and a time constant of 10 seconds for the gas lag in the sensors. The dot-dashed smooth curve is the result of applying an external radiant flux, 40 kW/m^2, in addition to that from the ignition burner. This ignited the targeted region at about the same time (23.8 seconds) as the ignition burner. The "instantaneous" rise in the HRR to a higher peak HRR (and which has a delayed peak because of the numerical filters required to simulate gas mixings) demonstrate the capability of the recursive analytical fire growth model to adapt to changing conditions. Several other examples of changing conditions have been applied that showed reasonable results (not shown). Another type of changing conditions we have recently simulated is the effect of fire resistive linings on reducing and even stopping upward fire growth. Our examples include FRT polyurethane foam, FRT plywoods and the Type X gypsum board (shown at the conference presentation).

Conclusions

The introductory discussions on wildfire threats to construction and their mitigation have shown the need to understand damage, ignition, and fire growth as exposed to changing conditions on realistic combustible items, including those considered to be fire resistive. The calculations should ultimately be able to provide (1) the fuel clearance (both vegetation and structure) needed for mitigating large fire threats of high radiant flux/flame impingements on structures and (2) the mitigation of firebrand threat (from both woodland and neighborhood) to an uninvolved structure with several different and economical fire resistive claddings. Thus far we show how the use of data from the bench scale Cone Calorimeter and of various flame travel tests such as LIFT, Room-Corner test, Radiant Panel, and so on can be used in analytically based fire growth models adaptable to changing conditions. We believe that by providing a fire hazard tool based on fire growth algorithms associated with ornamental vegetations and fire resistive exteriors in changing environments as proposed here, that the client will be able to find an optimum and economical fire-safe construction and landscaping.

References

Dietenberger, Mark A. 1991. Piloted Ignition and Flame Spread on Composite Solid Fuels in Extreme Environments. Ph.D. Dissertation. Dayton, OH: University of Dayton.

Dietenberger, Mark A. 1994. Protocol for Ignitability, Lateral Flame Spread, and Heat Release Rate Using Lift Apparatus. In: Nelson, Gordon L. ed. Fire and polymers II. Materials and tests for hazard prevention: Proceedings of 208th National meeting of the American Chemical Society. August 1994. http://www.fpl.fs.fed.us/documnts/pdf1995/diete95c.pdf

Dietenberger, Mark A. 2006a. Analytical Modeling of Fire Growth on Fire-Resistive Wood-based Materials with Changing Conditions. In: 17th Annual BCC Conference on Flame Retardancy, May, 2006, Stamford, CT. Norwalk, CT: Business Communications Co.

Dietenberger, M.A. 2006b. Using a Quasi-Heat-Pulse Method to Determine Heat and Moisture Transfer Properties for Porous Orthotropic Wood Products. Journal of Thermal Analysis and Calorimetry Vol. 83, No. 1: 97-106.

Dietenberger, M.A.; Grexa, O. 1996. Analytical Model of Flame Spread in Full-Scale Room/Corner Tests (ISO9705), 6th Int. Fire & Materials Conf., San Antonio, TX, Feb. 22-23, Interscience Comm. Ltd.: 211-222.

Karlsson, Bjorn. 1993. A Mathematical Model for Calculating Heat Release Rate in the Room Corner Test. Fire Safety Journal.Vol. 20: 93-113.

Manzello, S.L.; Cleary, T.G.; Shields, J.R.; Yang, J.C. 2006. On the Ignition of Fuel Beds by Firebrands. Fire and Materials Vol. 30: 77-87.

This page is blank on purpose

Uncertainty Quantification in Rothermel's Model Using an Efficient Sampling Method

Edwin Jimenez[1], M. Yousuff Hussaini[1], and Scott L. Goodrick[2]

***Abstract**—The purpose of the present work is to quantify parametric uncertainty in Rothermel's wildland fire spread model (implemented in software such as BehavePlus3 and FARSITE), which is undoubtedly among the most widely used fire spread models in the United States. This model consists of a nonlinear system of equations that relates environmental variables (input parameter groups) such as fuel type, fuel moisture, terrain, and wind to describe the fire environment. This model predicts important fire quantities (output parameters) such as the head rate of spread, spread direction, effective wind speed, and fireline intensity. The proposed method, which we call sensitivity derivative enhanced sampling (SDES), exploits sensitivity derivative information to accelerate the convergence of the classical Monte Carlo method. Coupled with traditional variance reduction procedures, it offers up to two orders of magnitude acceleration in convergence, which implies that two orders of magnitude fewer samples are required for a given level of accuracy. Thus, it provides an efficient method to quantify the impact of input uncertainties on the output parameters.*

Introduction

One of the primary goals of wildland fire management is to minimize the negative impact of fire on property and society through prevention and research. To meet this goal, fire researchers employ a variety of tools such as satellite imagery, experiments, fire danger indices, as well as mathematical models. A mathematical model typically consists of a set of nonlinear equations that describe the interaction of the various environmental variables. These equations can be used to predict valuable fire environment information such as the head rate of spread and spread direction.

Fire models typically fall into one or more of the following categories: physics-based, derived empirically, or constructed from statistical considerations. A fire model that is physics-based uses physical principles such as conservation of mass and energy to derive a formula for the rate of spread and other quantities of interest (see Weber 2001 and the references therein for an in-depth discussion). It is also possible to use a statistical description of test fires to predict fire behavior occurring under similar conditions. The McArthur models (McArthur 1966) used for grassland and forest fires in Australia are one such example. Finally, laboratory experiments can be performed to empirically determine quantities such as the propagating flux, which can, in turn, be used to obtain an expression for the rate of spread. Rothermel's model (Rothermel 1972), a fire spread model that spans the physical and empirical classes, is perhaps the best known model in the United States, and although more recent models include a wider range of fire phenomena, it is still in wide use today.

In: Butler, Bret W.; Cook, Wayne, comps. 2007. The fire environment—innovations, management, and policy; conference proceedings. 26-30 March 2007; Destin, FL. Proceedings RMRS-P-46CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 662 p. CD-ROM.

[1] School of Computational Science, Florida State University, Tallahassee, FL. ejimenez@scs.fsu.edu.

[2] Research Meteorologist, U.S. Department of Agriculture, Forest Service, Center for Forest Disturbance Science, Athens, GA.

Not all fire models, however, can be employed as efficient fire prediction tools. Some of the more complex models, which couple atmospheric and fire behavior effects, for instance, are currently too computationally expensive to serve as viable real-time prediction tools. These complex models, nevertheless, assist researchers in gaining a more profound understanding of fire behavior.

Rothermel's Fire Spread Model

Rothermel's wildland fire spread model was one of the first models to describe the fire environment through equations derived, for the most part, from thermodynamic principles. The fire environment describes the complex chemical and physical interaction of fuels, terrain, and weather. The term fire behavior is used to describe the physical characteristics of a fire such as its rate of spread, fireline intensity, flame length, and so forth. In North America, where forests and grasslands provide an abundant source of wildland fuel, wildland fires are of particular interest. Wildland fuels are fuels that consist primarily of vegetation, both live and dead, but may also include organic layers within the soil. A surface fire, the type of fire Rothermel's model was developed for, spreads through a layer of contiguous fuel extending from the ground up to approximately 2 m.

Rothermel's model groups input parameters into four main categories: fuel type, fuel moisture, topography, and wind. Some simplifying assumptions regarding the fuels are that for a small area and short-time periods, the fuel is taken to be homogeneous. The output variables we shall consider are the *rate of spread* (*ros* in m/s), the *direction of maximum spread* (*sdr* in °), and the *effective wind speed* (*efw* in m/s).

Parametric Uncertainty in Fire Spread Models

To properly use a fire model, it is essential to understand its limitations and scope of applicability. However, even when fire models are used adequately, discrepancies between the observed phenomena and model results are inevitable as models are derived under idealized conditions. Model errors can result from several factors including inadequate physical description, numerical errors, and parametric uncertainty (Walters and Huyse 2002). In this work we concentrate our efforts solely on those errors originating from parametric uncertainty. In order to quantify the impact of parametric uncertainty, it is important to describe the uncertainty mathematically. Because the value of an input parameter is seldom known exactly, a common approach (and the one we will pursue) is to assign it a mean value and an associated probability density function. The standard deviation can then be taken as a measure of the uncertainty in the parameter value. The impact of parametric uncertainty on the results can then be estimated using, for instance, a Monte Carlo simulation.

Sometimes the uncertainty associated with an input parameter is not only a consequence of the intrinsic complexity of the phenomena being modeled. Instead, uncertainties may be the inevitable byproducts of economic and efficiency constraints. For example, it may be expensive or intractable to measure fuel data directly as in the case of a large area.

On the other hand, it is not always necessary to concern ourselves with the uncertainty associated with every single parameter. A sensitivity analysis (Saltelli and others 2004) can help us identify the input parameters that have the greatest influence on output variables. Those parameters that have only a marginal impact on the quantities of interest can be assigned constant characteristic values to reduce computational demands.

Problem Formulation

We will focus on quantifying the impact and propagation of parametric uncertainty only on the following output variables: the *rate of spread* (*ros* in m/s), the *direction of maximum spread* (*sdr* in °), and the *effective wind speed* (*efw* in m/s). Using the same notation as in Bachmann (2001) (the full set of equations as well as their derivatives can also be found there), Rothermel's steady-state rate of spread is given by

$$ros = \frac{I_R \xi (1 + \Phi_w + \Phi_s)}{\rho_b \varepsilon Q_{ig}}, \qquad (1)$$

where I_R is the reaction intensity, ξ is the propagating flux ratio, ρ_b is the ovendry bulk density, ε is the effective heating number, Q_{ig} is the heat of pre-ignition. Φ_w and Φ_s are the wind and slope correction factors, respectively. The output variables depend on the following parameters: fuel loading $w0_{d1}$, $w0_{d2}$, $w0_{d3}$, $w0_{lh}$, $w0_{lw}$, (in kg/m^2), surface-area-to-volume ratio sv_{d1}, sv_{d2}, sv_{d3}, sv_{lh}, sv_{lw}, (in 1/m), fuel moisture content m_{d1}, m_{d2}, m_{d3}, m_{lh}, m_{lw}, (in %), fuel bed depth *d* (in m), wind speed *wsp* (in m/s), wind direction θ (in °), aspect ratio *asp* (in °), and slope *slp* (in rad). The subscripts *d*1*, d*2*, d*3*, lh, lw,* denote the size classes traditionally used to categorize the different fuel moisture timelag classes (see Deeming and others 1978): dead fuel 0 – 0.6 cm, dead fuel 0.6 – 2.5 cm, dead fuel 2.5 – 7.5 cm, live herbaceous fuel, and live woody fuel, respectively. Throughout this paper we assume that those parameters that are not held constant follow a normal distribution with a given mean and standard deviation.

The primary focus of this work is to quantify the propagation and impact of parametric uncertainty via an efficient Monte Carlo method. The Monte Carlo convergence rate is accelerated through the use of a sensitivity derivative enhanced sampling method that exploits derivative information of the output functions with respect to the input parameters to make more judicious use of the samples generated in a simulation. We estimate the mean and standard deviation of the output variables using a traditional Monte Carlo method as well as with the sensitivity derivative enhanced sampling method (SDES). We compare the advantages of SDES over the Monte Carlo method via improvement ratios and timing performance. The distributions of output variables will also be generated. It should be noted that the computation of the required sensitivity derivatives accounts for only a fraction of the total cost of a simulation; these can be easily extracted using, for instance, an automatic differentiation package.

Numerical Method

To investigate the propagation and impact of input variable uncertainties, Bachmann and Allgower (2002) used a first-order Taylor method in place of a full-fledged Monte Carlo simulation to avoid the prohibitive computational expense incurred through a direct application of the classical Monte Carlo method. Indeed, because of its slow convergence rate and the costly generation of correlated input variables in the multivariate case, Monte Carlo methods are usually reserved to establish a reference against which other methods are compared. However, by identifying and generating stochastic versions of only those parameters to which the output variables are most sensitive and at the same time improving the convergence rate of traditional Monte Carlo methods, it is possible to perform simulations utilizing the original model to capture the more intricate behavior that a low-order approximation might otherwise sacrifice. The modified Monte Carlo method we describe below is a step toward this goal.

Although Monte Carlo methods have long been popular because they are simple to implement and use the underlying model as a ``black box,'' their slow convergence rate often proves to be too inefficient especially when multiple simulations are required. A common approach to improve the convergence rate, which is known to be proportional to the variance of the objective function, is to reduce the variance via a suitable reformulation of the problem. Variants of this approach encompass a large class of methods collectively known as variance-reduction methods. The SDES method, which we describe below, is a variance-reduction method that has already been employed with success in fields such as optimal control (Cao and others 2003, 2004) and computational fluid dynamics (Mathelin and others 2004). In this section we review the theory underlying the method; our discussion closely follows Cao and others (2004, 2006). The methods we shall employ are described in their proper mathematical setting, but for the reader who is unfamiliar with some of the concepts discussed below, the textbooks by Ross (1997) and Shiryayev (1984) should elucidate some of the mathematical details that are omitted.

Monte Carlo Method

Suppose X is a random variable with finite expectation and let $p(x)(x \in \mathbb{R})$ be an associated probability density function (pdf). If $f:\mathbb{R}\to\mathbb{R}$ is a smooth function of X, we recall that the expectation $Ef(X)$ of f is defined by

$$Ef(X) := \int f(x)p(x)dx, \tag{2}$$

where the integration is taken over the support of the pdf. The variance $Vf(X)$ is defined by

$$Vf(X) := E(f(X) - Ef(X))^2. \tag{3}$$

For brevity, we will sometimes write μ_x and σ_x^2 for the expectation and variance of the random variable X, respectively.

In the classical Monte Carlo method, we estimate $Ef(X)$ by

$$Ef(X) \approx \frac{1}{N}\sum_{i=1}^{N} f(x_i). \tag{4}$$

The N samples $x_1,\ldots,x_N$ are generated according to the probability density of X. The convergence of this estimate to $Ef(X)$ as $N\to\infty$ is guaranteed by the large number theorem (Shiryayev 1984; Ross 1997).

It is well-known that the approximation error made using (4) is proportional to $\frac{\sqrt{Vf(X)}}{\sqrt{N}}$. For computationally intensive problems this slow convergence might render the Monte Carlo approximation impractical. In the results section, the extent to which the sensitivity derivative Monte Carlo method alleviates this slow convergence will be shown.

Sensitivity Derivative Enhanced Sampling

Recently, Cao and others (2003, 2004) developed a variance-reduction method that exploits information regarding the sensitivity of f with respect to the random variable X (measured via derivatives of f with respect to X) to speed up the convergence of the Monte Carlo method. The result of their efforts was the sensitivity derivative enhanced sampling Monte Carlo method (SDES). The first-order SDES method is described below.

Given the first-order Taylor expansion of f about μ_x

$$J_1(x) := f(\mu_x) + f'(\mu_x)(x - \mu_x), \tag{5}$$

and using

$$\int p(x)dx = 1 \quad \text{and} \quad \int (x - \mu_x)p(x)dx = 0,$$

it is clear that

$$\int (f(x) - J_1(x))p(x)dx \quad = \int f(x)p(x)dx - f(\mu_x).$$

Upon rearranging for $Ef(X)$, this suggests the sensitivity derivative Monte Carlo approximation of the expectation of f

$$Ef(X) \approx f(\mu_x) + \frac{1}{N}\sum_{i=1}^{N}(f(x_i) - J_1(x_i)). \tag{6}$$

The N samples are again generated according to the pdf of X.

The following inequalities illustrate the extent to which the variance of (6) is reduced. Let

$$m_1 = \max_{s\in\mathbb{R}} |f'(s)| \quad \text{and} \quad m_2 = \max_{s\in\mathbb{R}} |f''(s)|.$$

Then

$$\begin{aligned} Vf(X) \quad &\le 2m_1^2 V(X) \\ V(f - J_1) \quad &\le \frac{m_2^2}{2}(V(X)^2 + E((X - \mu_x)^4)). \end{aligned} \tag{7) (8}$$

Where (7) and (8) indicate that the SDES method is most efficient when $V(X)$ is small ($V(X) << 1$). See Cao and others (2006) for a rigorous proof of these results as well as a generalization to the n^{th}-order SDES method.

SDES for Rothermel's Model

Although in this article we concentrate our efforts on Rothermel's model, we will state the mathematical model as a general nonlinear system of equations. The SDES method is applicable to any fire behavior model satisfying the appropriate smoothness assumptions.

Let the vector $X = (X_1, \ldots, X_m)$ represent the ensemble of input parameters that comprise the local fire environment and suppose $y = f(X)$ is a function of the random variable vector X. Here y may represent the effective wind speed efw, the maximum rate of spread ros, or the spread direction sdr. The vector X is composed of the fuel type, fuel moisture, terrain, and wind parameters. We shall denote the expectation of the parameter vector X by $\mu_x = (\mu_{x_1}, \ldots, \mu_{x_m})$ and the covariance of X by Σ. In this case the second-order SDES method is given by

$$Ef(X) \quad \approx \frac{1}{N}\sum_{i=1}^{N}(f(x_i) - J_2(x_i)) + f(\mu_x) + \frac{1}{2}\text{trace}(\nabla^2 f(\mu_x)\Sigma), \tag{9}$$

where

$$J_2(x) = f(\mu_x) + \nabla f(\mu_x)(x-\mu_x) + \frac{1}{2}(x-\mu_x)^T \nabla^2 f(\mu_x)(x-\mu_x).$$

Here ∇f and $\nabla^2 f$ denote the gradient and Hessian of f, respectively.

To further improve the efficiency of the present sampling method, we couple SDES with stratified sampling. The standard stratified sampling technique is discussed in Cao and others (2004), for example.

Results and Discussion

To compare the efficiency of SDES with traditional Monte Carlo methods, we compute the rate of spread ros, effective wind speed efw, and spread direction sdr using two of the original fuel models found in Rothermel (1972): the short grass and chaparral fuel models. The main fuel parameters are summarized in tables 1 and 2. The following parameters are held constant throughout for both fuel models: the dead fuel moisture at 8 percent, the live fuel moisture at 150 percent, and the low heat content at 18622 kJ/kg. We shall also examine the additional speed-up obtained by coupling SDES with standard stratified sampling.

The uncertainty associated with an input parameter is described by assigning it a normal distribution with a typical mean (taken to be the value given in the original model) and a corresponding standard deviation (typically between 10 and 50 percent of the mean value). Two types of computations will be performed for each fuel model. First, we take the fuel bed depth d and the 1-h surface area/volume ratio sv_{d1} to be normally distributed random variables; all other parameters are fixed. Then, we include a random wind speed wsp and wind direction θ in addition to d and sv_{d1}.

To measure relative errors and improvement ratios of Monte Carlo approximations versus SDES, we use the L_2-norm (Euclidean norm). Recall that the L_2-norm is defined for a vector $x = (x_1, \ldots, x_n)$ as $\|x\|_2 = (x_1^2 + \cdots + x_n^2)^{1/2}$.

Table 1—Chaparral fuel model parameters.

Parameter	Symbol	μ	σ	Units
1-h fuel load	$w0_{d1}$	1.12	--	kg/m^2
10-h fuel load	$w0_{d2}$	0.90	--	kg/m^2
100-h fuel load	$w0_{d3}$	0.45	--	kg/m^2
Live herbaceous fuel load	$w0_{lh}$	0.0	--	kg/m^2
Live woody fuel load	$w0_{lw}$	1.12	--	kg/m^2
1-h surface area/vol. ratio	sv_{d1}	6562	740	m^2/m^3
Live herb surface area/vol. ratio	sv_{lh}	4921	--	m^2/m^3
Live woody surface area/vol. ratio	sv_{lw}	4921	--	m^2/m^3
Dead fuel moisture of extinction	mx	20	--	%
Fuel bed depth	d	1.83	0.3	m
Midflame windspeed	wsp	2.3	0.5	m/s
Direction of wind vector (from upslope)	θ	45	20	°

Table 2—Short grass fuel model parameters.

Parameter	Symbol	μ	σ	Units
1-h fuel load	$w0_{d1}$	0.17	--	kg/m^2
10-h fuel load	$w0_{d2}$	0.0	--	kg/m^2
100-h fuel load	$w0_{d3}$	0.0	--	kg/m^2
Live herbaceous fuel load	$w0_{lh}$	0.0	--	kg/m^2
Live woody fuel load	$w0_{lw}$	0.01	--	kg/m^2
1-h surface area/vol. ratio	sv_{d1}	11483	1150	m^2/m^3
Live herb surface area/vol. ratio	sv_{lh}	4921	--	m^2/m^3
Live woody surface area/vol. ratio	sv_{lw}	4921	--	m^2/m^3
Dead fuel moisture of extinction	mx	12	--	%
Fuel bed depth	d	0.30	0.05	m
Midflame windspeed	wsp	2.3	0.5	m/s
Direction of wind vector (from upslope)	θ	45	20	°

If $E^{MC} = (E_1^{MC}, \ldots, E_M^{MC})$ is a sequence of relative errors obtained from M Monte Carlo simulations, then a measure of the average error is given by

$$\left\| E^{MC} \right\|_2 = \left(\frac{1}{M} \sum_{i=1}^{M} [E_i^{MC}]^2 \right)^{1/2}.$$

The L_2 improvement ratio is then computed from

$$I_2 = \frac{\left\| E^{MC} \right\|_2}{\left\| E^{SDES} \right\|_2}.$$

Suppose, for example, that we use a Monte Carlo and a first-order SDES simulation to approximate the rate of spread using 5,000 samples. If the improvement ratio is $I_2 = 10$, then the average relative error obtained from SDES is 10 times smaller than that obtained from a Monte Carlo method using the same number of samples. Put another way, if we use SDES we need only 500 samples to achieve the same accuracy as the Monte Carlo method.

Table 3 shows that even with a simple first-order SDES method the convergence rate over a traditional Monte Carlo simulation can be as much as 20 times faster. It is important to note that SDES might require the computation of several derivatives of the objective function. In our computations, an automatic differentiation package (see Stamatiadis and others 2000) was used to find the relevant derivatives. Table 4 illustrates that even when we couple SDES with stratified sampling (denoted by SSD1, for a first-order SDES with stratified sampling), the extra computational expense incurred is marginal.

Table 3—SDES error improvement ratios for first-moment estimates of the rate of spread using $N = 512$ and $M = 100$ different sets of samples.

Fuel model	MC ratio (2vars)	MC ratio (4vars)	S = 4 ratio (2vars)	S = 2 ratio (4vars)
Chaparral	29.8	5.1	11.4	3.4
Short grass	24.2	4.3	10.0	3.1

Table 4—Timing results (in seconds). Average computational time comparison of Monte Carlo versus first-order SDES coupled with stratified sampling (four strata).

N	(Chap) MC	(Chap) SSD1	(Shtgrs) MC	(Shtgrs) SSD1
32	4.297*E*–02	4.437*E*–02	4.063*E*–02	4.344*E*–02
64	8.188*E*–02	8.250*E*–02	7.922*E*–02	8.250*E*–02
128	1.617*E*–01	1.656*E*–01	1.567*E*–01	1.566*E*–01
256	3.231*E*–01	3.295*E*–01	3.113*E*–01	3.158*E*–01
512	6.423*E*–01	6.255*E*–01	6.216*E*–01	6.262*E*–01

Figure 1 illustrates that although the input parameters follow a normal distribution (as described in tables 1 and 2), this is not the case with the output functions efw, ros, and sdr. This is to be expected as the output functions depend nonlinearly upon the random parameters. Using four random variables in the chaparral fuel model, the mean values are given by $efw_{\mu} = 2.41$ m/s, $ros_{\mu} = 0.353$ m/s, and $sdr_{\mu} = 41.3^{\circ}$. The corresponding standard deviations are $efw_{\sigma} = 2.0325 \cdot 10^{-5}$ m/s, $ros_{\sigma} = 2.8921 \cdot 10^{-4}$ m/s, and $sdr_{\sigma} = 5.0674 \cdot 10^{-4}$. The standard deviation provides us with a measure of the uncertainty in the outputs.

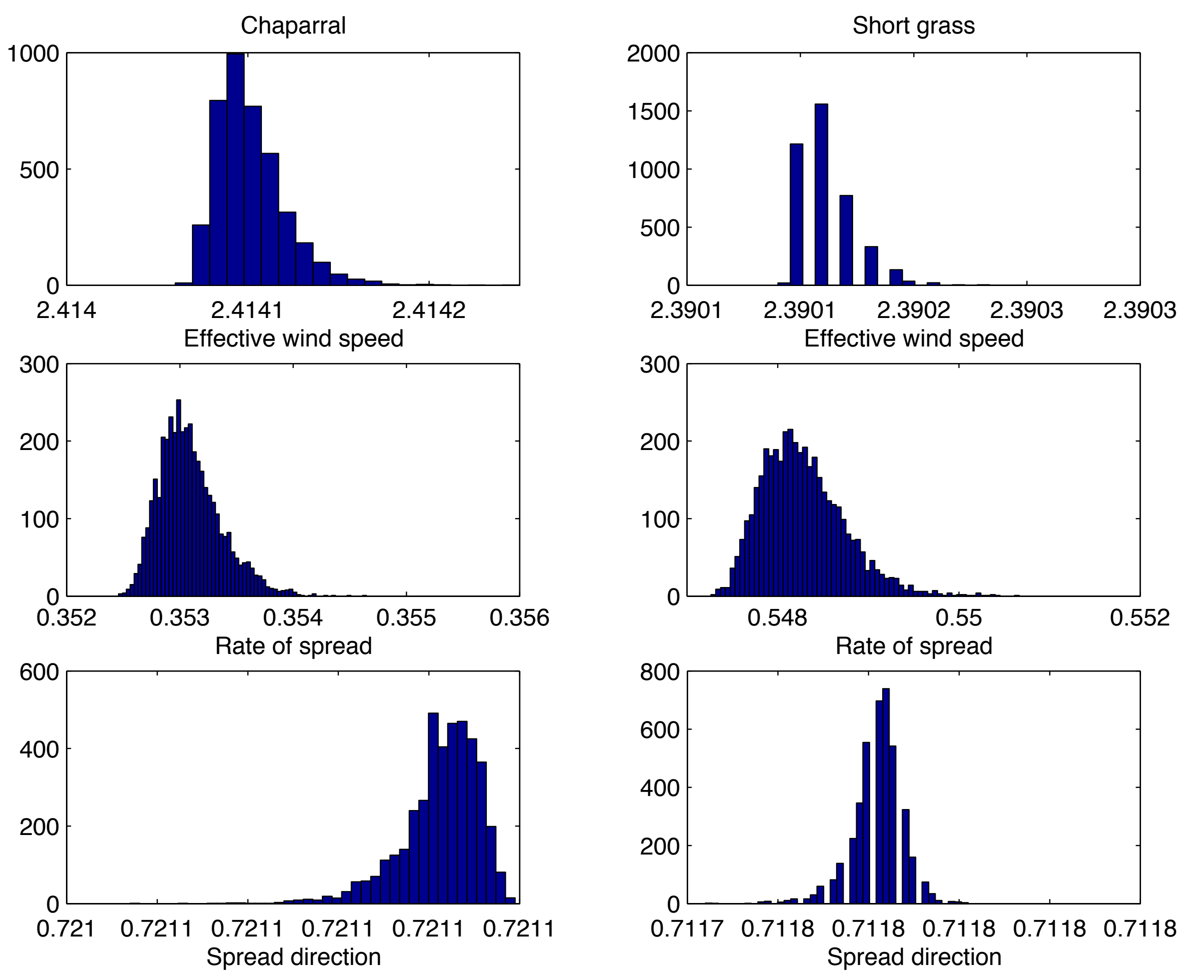


Figure 1—Output distributions of the effective wind speed, rate of spread, and spread direction using four random variables (d, sv_{d1}, wsp, and θ). The mean values for the Chaparral fuel model are given by $efw_{\mu} = 2.41$ m/s, $ros_{\mu} = 0.35$ m/s, and $sdr_{\mu} = 41.3°$.

Figures 2 and 3 show that the relative errors decay at the expected rate proportional to $1/\sqrt{N}$, where N is the number of samples used. Throughout, we use $M = 100$ different sets of samples and then average the relative errors. We observe that Monte Carlo coupled with stratified sampling is as much as five times faster than the traditional Monte Carlo method. In all cases we observe that first-order SDES produces results that are up to two orders of magnitude more accurate (when coupled with stratified sampling) than plain Monte Carlo. With this convergence rate, it would take a Monte Carlo method as many as 100 times more samples to achieve comparable results.

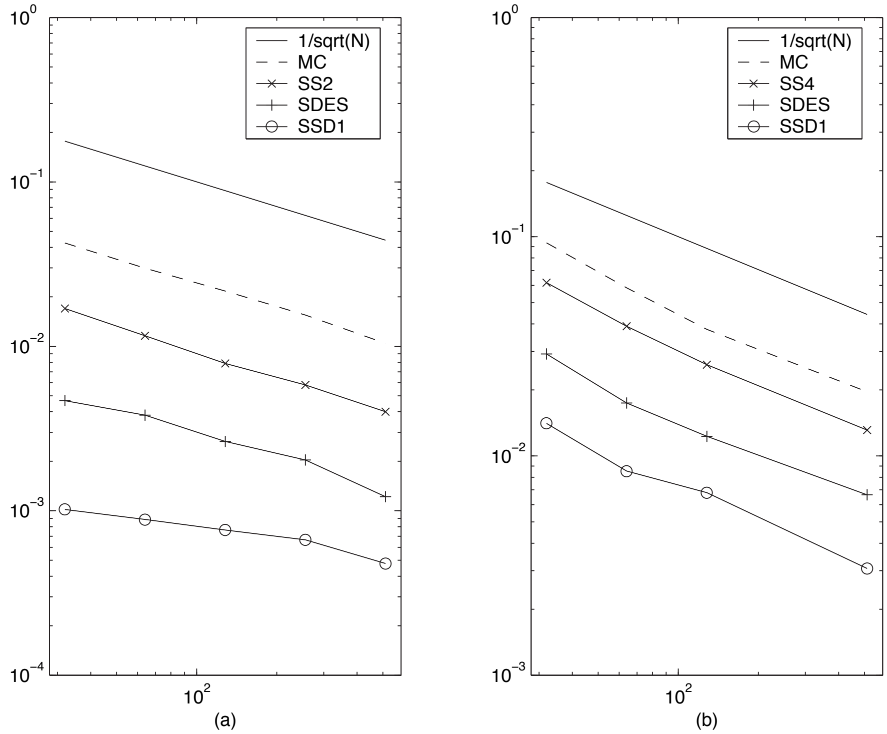


Figure 2—(Chaparral fuel model) Average relative errors in first moment estimates for the rate of spread *ros* using (a) two random variables $sv_{d1} \sim N(6562,740)$ and $d \sim N(1.83,0.3)$ and (b) four random variables $sv_{d1} \sim N(6562,740)$, $d \sim N(1.83,0.3)$, $wsp \sim N(2.3,0.5)$, and $\theta \sim N(45,20)$.

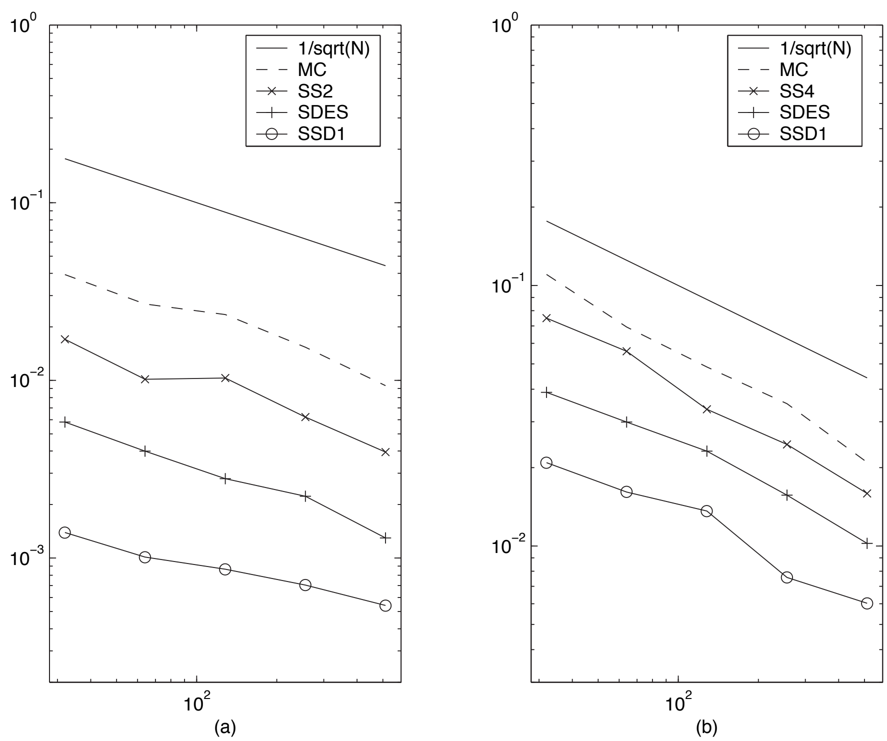


Figure 3—(Short grass fuel model) Average relative errors in first moment estimates for the rate of spread *ros* using (a) two random variables $sv_{d1} \sim N(11483,1150)$ and $d \sim N(0.30,0.05)$ and (b) four random variables $sv_{d1} \sim N(11483,1150)$, $d \sim N(0.30,0.05)$, $wsp \sim N(2.3,0.5)$, and $\theta \sim N(45,20)$.

Conclusions

Although the simplicity of the Monte Carlo method makes it an attractive method to use in simulations that use fire spread models such as Rothermel's model, its slow convergence can render its application infeasible especially in time-sensitive situations such as in the prediction of an ongoing fire. In this work we have demonstrated that the sensitivity derivative enhanced sampling method and its variants provide fire researchers an economic alternative to traditional Monte Carlo methods in quantifying parametric uncertainty. Quantifying the impact of parametric uncertainty is of utmost importance since key input parameters used by fire spread models are seldom known exactly. The speed-up of up to two orders of magnitude in the SDES gives fire managers the ability to effectively and efficiently run simulations in real-time using only minimal computational resources.

The results indicate that coupling SDES with stratified sampling can further accelerate the convergence rate. This suggests that coupling SDES with more sophisticated sampling techniques such as Latin hypercube sampling or orthogonal sampling, while not as easily implemented as stratified sampling, might improve the convergence rate even further. We will explore these possible enhancements in future investigations.

References

Bachmann, A. 2001. Collection of Derivatives of the Rothermel Model. 1-25.

Bachmann, A.; Allgower, B. 2002. Uncertainty propagation in wildland fire behaviour modeling. Int. J. Geographical Information Science. 16(2): 115-127.

Cao, Y.; Hussaini, M.Y.; and others. 2006. A variance reduction method based on sensitivity derivatives. Applied Numerical Mathematics. 56(6): 800-813.

Cao, Y.; Hussaini, M.Y.; and others. 2003. An efficient Monte Carlo method for optimal control problems with uncertainty. Computational Optimization and Applications. 26: 219-230.

Cao, Y.; Hussaini, M.Y.; and others. 2004. Exploitation of sensitivity derivatives for improving sampling methods. AIAA Journal. 42(4): 815-822.

Deeming, J.E.; Burgan, R.E.; and others. 1978. The National Fire Danger Rating System. Gen. Tech. Rep. INT-39. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 63 p.

Mathelin, L.; Hussaini, M.Y.; and others. 2004. Uncertainty propagation for a turbulent, compressible nozzle flow using stochastic methods. AIAA Journal. 42(8): 1669-1676.

McArthur, A.G. 1966. Weather and grassland fire behaviour. A.C.T. Leaflet 100. Canberra: Department of National Development, Forestry and Timber Bureau, Forestry Research Institute. 23 p.

Ross, S. 1997. A First Course in Probability. New York: Prentice-Hall.

Rothermel, R.C. 1972. A mathematical model for predicting fire spread in wildland fuels. Research Paper INT-115. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station.

Saltelli, A.; Tarantola, S; and others. 2004. Sensitivity Analysis in Practice: A Guide to Assessing Scientific Models, New York: John Wiley & Sons, Ltd.

Shiryayev, A.N. 1984. Probability. Amsterdam: Springer-Verlag.

Stamatiadis, S.; Prosmiti, R.; and others. 2000. Auto_deriv: Tool for automatic differentiation of a FORTRAN code. Computer Physics Communications. 127: 343-355.

Walters, R.W.; Huyse, L. 2002. ICASE Report No. 2002-1. Uncertainty analysis for fluid mechanics with applications.

Weber, R.O. 2001. Wildland Fire Spread Models in Forest Fires: Behavior and Ecological Effects. New York: Academic Press.

This page is blank on purpose

Differences in Simulated Fire Spread Over Askervein Hill Using Two Advanced Wind Models and a Traditional Uniform Wind Field

Jason Forthofer[1] and Bret Butler[1]

Abstract—*A computational fluid dynamics (CFD) model and a mass-consistent model were used to simulate winds on simulated fire spread over a simple, low hill. The results suggest that the CFD wind field could significantly change simulated fire spread compared to traditional uniform winds. The CFD fire spread case may match reality better because the winds used in the fire simulation were more accurate.*

Introduction

The influence of wind simulations from two microscale wind models on simulated fire spread over a simple, low hill was investigated. The models were a computational fluid dynamics (CFD) model and a mass-consistent model (Forthofer in prep.). The hill, called Askervein Hill, had previously been the site of a detailed field study of wind flow over isolated hills (Taylor and Teunissen 1983, 1985). The simulated winds were compared to these data. The mass-consistent model and the CFD model were able to accurately simulate the wind flow on the upwind side and top of the hill. On the downwind side of the hill, the CFD model showed lower wind speeds than the mass-consistent model. These lower speeds matched the measured data better. The simulated winds were then used in FARSITE (Finney 1998) simulations to identify how the different wind fields affected fire spread. For reference, the traditional method of using a spatially uniform wind field was also used in the fire spread simulations. The resulting fire progressions showed that the mass-consistent wind field produced fire spread similar to the uniform wind field case, but the CFD simulation was noticeably different. The uniform and mass-consistent wind based fire growth simulations did not show appreciable effects of reduced wind speed on the lee side of the hill. These results suggest that the CFD wind fields could significantly change simulated fire spread compared to traditional uniform winds. Also, the CFD fire spread case may match reality better because the winds used in the fire simulation were more accurate.

Discussion

Askervein Hill was the site of a large wind measurement field campaign in 1982 and 1983 (Taylor and Teunissen 1983, 1985). More than 50 wind measurement towers were placed in the hill area to characterize the surface

In: Butler, Bret W.; Cook, Wayne, comps. 2007. The fire environment—innovations, management, and policy; conference proceedings. 26-30 March 2007; Destin, FL. Proceedings RMRS-P-46CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 662 p. CD-ROM.

[1] Mechanical Engineer and Research Mechanical Engineer, respectively, U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Missoula, MT. Lead author at jaforthofer@fs.fed.us

flow field. The hill was 116 m tall and surrounded by flat ground. Towers were placed along three lines running over the hill, as shown in figure 1. We have compared simulations from two types of microscale wind models, a CFD model and a mass-consistent model, to the measured winds to evaluate their ability to reproduce the flow field.

Comparisons of the simulated and measured winds are shown in figure 2 for sensors placed along lines A, AA, and B. Both models predicted the flow on the upwind side of the hill and at the top of the hill well. The CFD model compared better on the lee side of the hill than the mass-consistent model. The noticeable overprediction here of the mass-consistent model is probably due to the model's inadequate representation of momentum, which becomes important on the lee side of the hill.

With the accuracy of the simulated flow fields assessed, hypothetical fire spread over the hill was computed using FARSITE (Finney 1998) with the two simulated wind fields and a traditional spatially uniform wind field. Table 1 shows the settings used in FARSITE for the spread simulations. As seen in figure 3, the CFD fire progression was markedly different than the mass-consistent and uniform wind cases. It appears that the low wind speeds on the lee side of the hill had a significant impact on the simulated fire spread. These low speeds were reproduced by the CFD model, but not well by the mass-consistent model and not accounted for by the uniform wind field (of course).

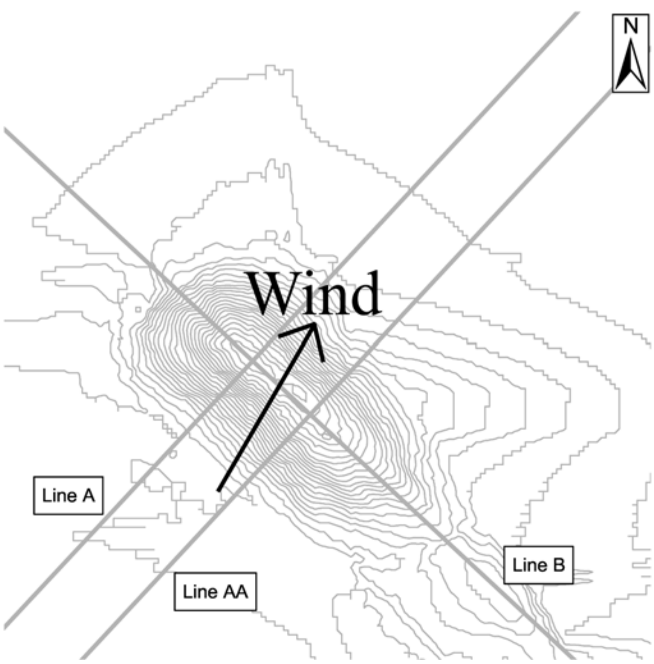


Figure 1—Contour map of Askervein Hill showing locations of lines A, AA, and B. The wind measuring devices were placed along these lines. The contour interval is 5 m.

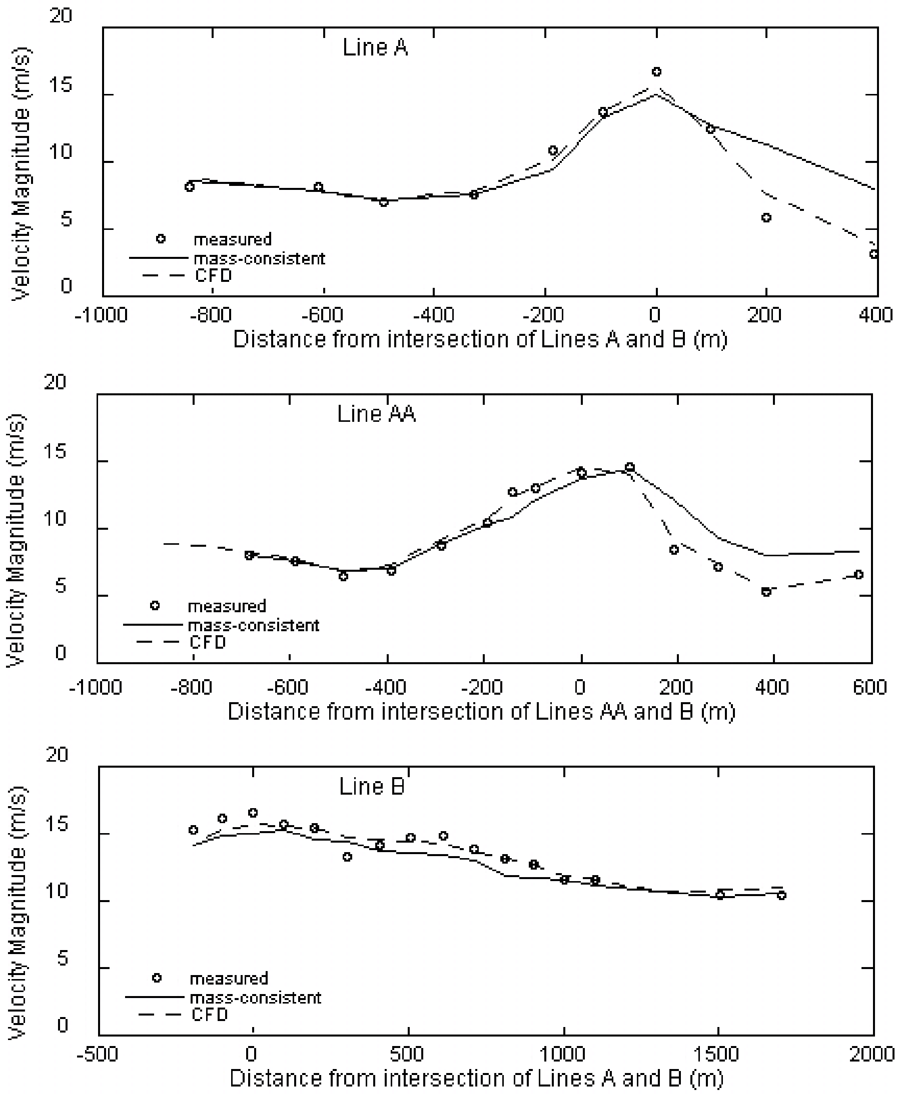
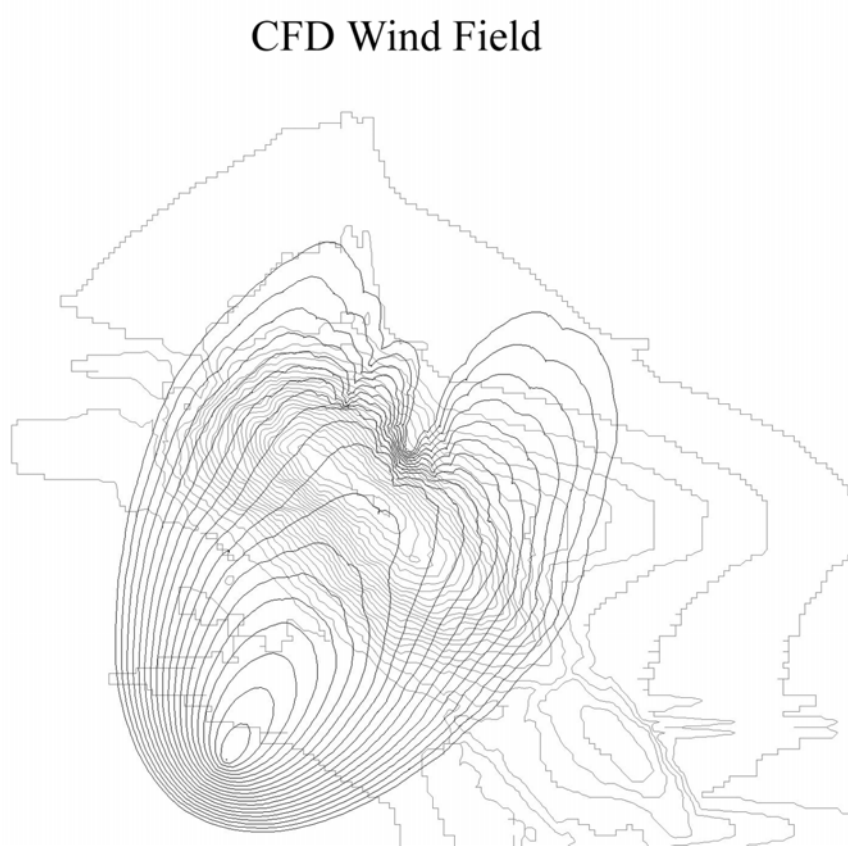


Figure 2—Simulated wind speeds from the mass-consistent and CFD models compared with measured wind speeds along lines A, AA, and B over Askervein Hill. The reported winds are 10 m above the ground.

Table 1—Inputs for FARSITE fire spread simulations.

Fuel model	2
Canopy cover	0 percent
Temperature	80 degrees F
Relative humidity	20 percent
1 hour fuel moisture	5 percent
10 hour fuel moisture	6 percent
100 hour fuel moisture	7 percent
Live herbaceous fuel moisture	100 percent
Live woody fuel moisture	100 percent
Fire spread rate adjustments	1
Time step	10 min
Perimeter resolution	25 m
Distance resolution	25 m
Only surface fire, no spotting	



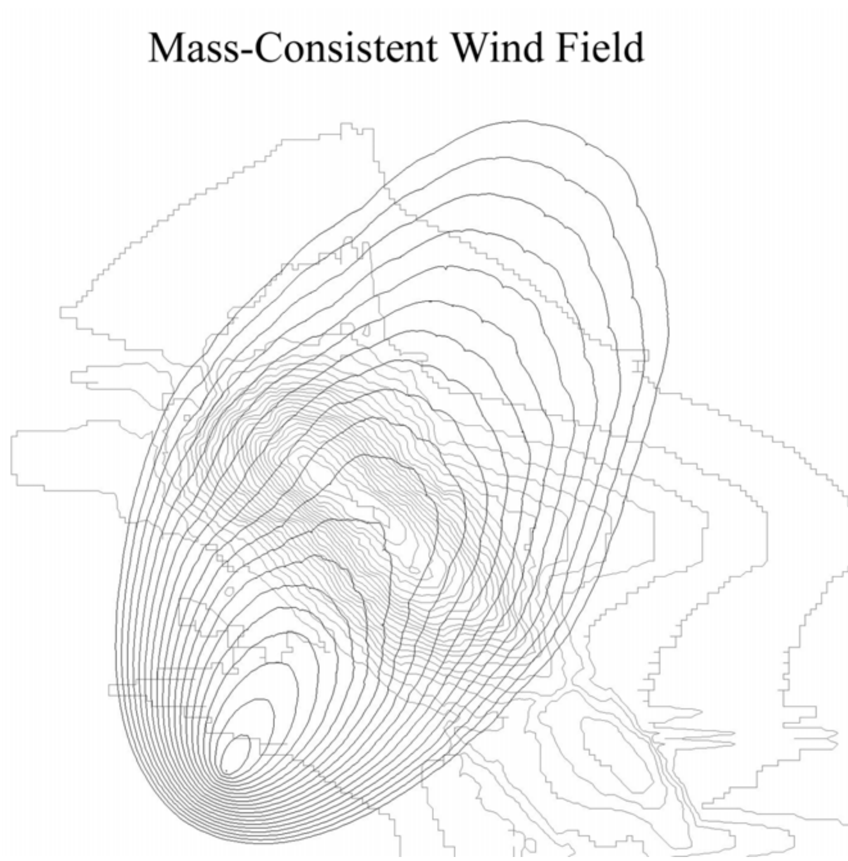
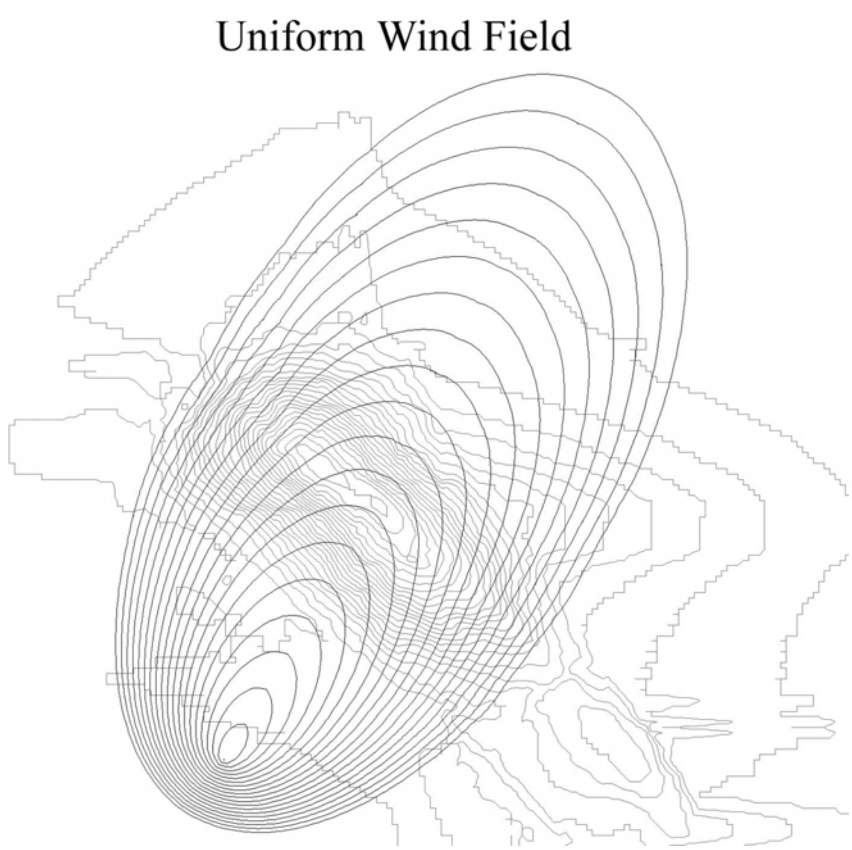


Figure 3—Comparison of three fire spread simulations for the Askervein Hill area using different wind fields. Dark lines denote the fire progression spaced 10 min. apart, light lines are the 5 m elevation contour lines. (Third simulation appears on the next page.)



Conclusions

This study indicates that spatially varying wind flow occurring from terrain modification can have a large impact on simulated fire spread. Accurate simulations of surface influenced wind flow are improved when the simulation model includes both mass and momentum conservation. It appears that this may be true even in cases of relatively simple, gently sloping terrains such as Askervein Hill. Because wind often has such a large impact on the behavior of a spreading wildland fire, a significant increase in the accuracy of fire spread predictions might be obtained by incorporating a wind model such as the CFD model into fire behavior prediction systems.

References

Finney, M.A. 1998. FARSITE: Fire area simulator-model development and evaluation. Research Paper RMRS-RP-4. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Forthofer, J.M. In prep. Modeling wind in complex terrain for use in fire spread prediction. Fort Collins, CO: Colorado State University. (Expected completion 2007)

Taylor, P.A.; Teunissen, H.W. 1983. Askervein '82: Report on the September/October 1982 Experiment to study boundary layer flow over Askervein, South Uist. MSRB-83-8. Downsview, Ontario, CAN: Atmospheric Environment Service.

Taylor, P.A.; Teunissen, H.W. 1985. The Askervein Hill Project: Report on the September/October 1983 Main Field Experiment. MSRB-84-6. Downsview, Ontario, CAN: Atmospheric Environment Service.

This
page is
blank
on purpose

Influence of Radiation Absorption by Environmental Water Vapor on Radiation Transfer in Wildland Fires

David Frankman[1], Brent W. Webb[1], and Bret W. Butler[2]

Abstract*—Thermal radiation emission from a simulated black flame surface to a fuel bed is analyzed by a ray-tracing technique, tracking emission from points along the flame to locations along the fuel bed while accounting for absorption by environmental water vapor in the intervening medium. The Spectral Line Weighted-sum-of-gray-gases approach was adopted for treating the spectral nature of the radiation. The flame and fuel bed for the simulations are modeled two-dimensionally with the flame being one-tenth as long as the fuel bed. Flame heights of 1 and 10 m were explored, and the angle between the flame and the fuel bed was specified to be either 60 or 90 degrees. Simulated flame temperatures of 1000 K and 1500 K were investigated. The study reveals that water vapor at 100 percent humidity will reduce the incident radiation at the base of a 1000 K flame by 9 percent for a 1 m flame and 16 percent for a 10 m flame oriented normal to the fuel bed. Radiation from an angled flame (oriented at 60 degrees from the fuel bed) experiences slightly less attenuation from water vapor than the 90-degee flame. Further, local attenuation of the hotter flame (1500 K) from environmental water vapor is higher than for the 1000 K flame. The relative effect of the water vapor attenuation is increased with distance from the flame base.*

Introduction

It is understood that thermal radiation transfer plays a significant role in wildland fire spread (De Mestre and others 1989). High temperatures in gaseous and particulate products of combustion result in significant radiation transfer to the unburned fuel ahead of advancing flames. Attenuation of flame radiation can occur from smoke and combustion products that are entrained in the intervening air between flame and fuel. This mechanism for attenuation of flame radiation is a complex function of fuel, flame, wind, and other environmental conditions. It is also recognized that environmental water vapor may be a mechanism for attenuation of flame radiation. However, the magnitude of this influence is unknown. This paper explores the attenuation of radiation from flame to fuel bed by environmental water vapor in the intervening medium.

Literature Review

Wildland fire spread has been modeled using a variety of approaches. Some models attempt to conserve energy generally without separating convection from radiation heat transfer. Still others attempt to model radiation

In: Butler, Bret W.; Cook, Wayne, comps. 2007. The fire environment—innovations, management, and policy; conference proceedings. 26-30 March 2007; Destin, FL. Proceedings RMRS-P-46CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 662 p. CD-ROM.

[1] Lead author at Department of Mechanical Engineering, Brigham Young University, Provo, UT. dave.frankman@gmail.com

[2] U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory, Missoula, MT.

and convection separately (Weber 1991). Those that do model the radiation transfer invoke varied approximations in the radiation submodels. Fons (1946) treats the radiation transfer in an approximate fashion by assuming that a fixed fraction of combustion energy comes from radiation. Emmons (1964) assumes radiation is attenuated with distance from the flame by an exponential relationship. Hottel and others (1965) were the first to model the flame shape, introducing radiation configuration factor relations that quantify the fraction of radiation emitted by one surface that is incident on another. One model considered radiation heat transfer from a planar flame to a planar fuel bed, and the other used a relation that accounted for radiation attenuation through the fuel bed using an exponential factor. Albini (1967) formulated an approach that employed the same radiation sub-model as Hottel and others, considering radiation as the dominant heat transfer mechanism. Thomas (1967) proposed that radiation from the flame was insignificant in comparison to radiation through the porous fuel bed. Other models were introduced using the same radiation configuration factor relations to track radiation transfer from flame to fuel until Cekirge (1978) introduced a formulation that could account for a circular flame front. Albini (1985) first introduced a solution to the Radiative Transfer Equation (RTE), the differential equation governing transport of radiative energy. The RTE was solved using the discrete ordinates method, but no volumetric effects in the fuel, flame, or the intervening medium were included.

To the authors' knowledge, no prior study explores the effect of attenuation of radiation between flame and fuel bed by environmental water vapor. This paper investigates this mechanism for attenuation of flame radiation.

Model

Consider a planar flame of length H and characterized by uniform temperature T_f advancing along a horizontal fuel bed, as shown in figure 1. The length of the fuel bed L is specified arbitrarily in this study to be 10 times the flame length, $L/H = 10$. The angle between flame and fuel bed is ø. Simulations were conducted with and without environmental water vapor in the air separating the flame from the fuel bed. It is assumed that the intervening

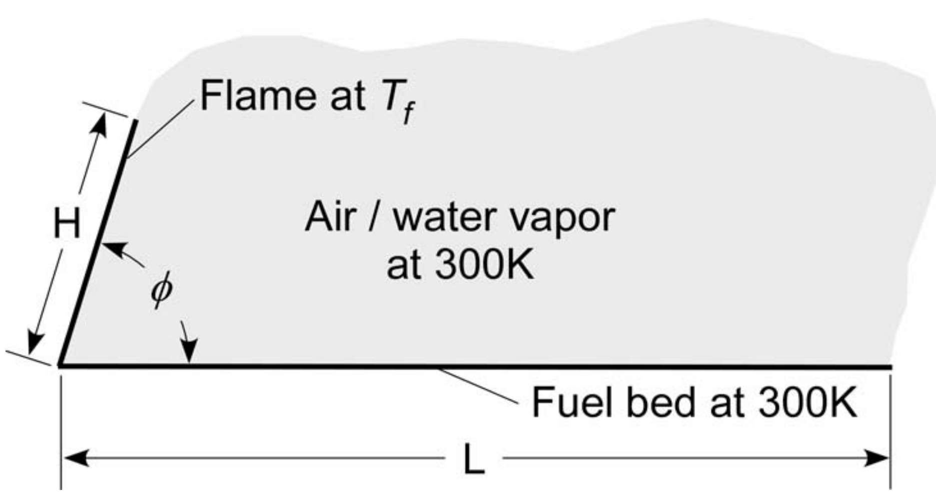


Figure 1 – Schematic illustration of configuration investigated.

medium (air/H_2O vapor) and the fuel bed are at a uniform temperature of 300 K. It should be clearly stated that attenuation by entrained combustion products (ash, H_2O, CO_2, soot, and so forth) is not considered here. Attenuation of flame radiation from such will dominate any effects by environmental water vapor. Rather, the purpose of this study is to characterize solely the effects of water vapor.

Absorption of radiation is governed by the Beer-Lambert Law (Modest 2003), which states

$$I_\eta(s) = I_{\eta o} e^{-\kappa_\eta (s - s_0)} \quad (1)$$

Equation (1) indicates that the spectral radiation intensity of magnitude $I_{\eta o}$ incident on a radiatively absorbing medium and propagating in a particular direction is attenuated exponentially with distance s from the point of incidence s_0 along this direction by the factor $e^{-\kappa_\eta (s - s_o)}$, where κ_η is the volumetric absorption coefficient (Modest 2003). As indicated by the subscript η, equation (1) is a spectral relation; the radiative intensity I_η, incident radiation intensity $I_{\eta o}$, and absorption coefficient κ_η vary with wavenumber (or wavelength). While significant absorption may occur in some regions of the spectrum, others are transparent to radiative transfer. For gases capable of volumetric absorption in the infrared spectrum, the spectral absorption coefficient is characterized by vibration-rotation bands. For water vapor, the principal absorption bands are centered at wavenumbers 3760 and 1600 cm^{-1} (wavelengths of 2.7 and 6.3 μm, respectively). Within each absorption band, thousands of narrow absorption lines exist, with strong absorption of radiation within each narrow line. Several hundred thousand absorption lines are associated with the two principal vibration-rotation bands for water vapor. The absorption strength of each line is a function of the temperature and partial pressure of water vapor. The challenges associated with rigorously modeling mathematically the attenuation of flame radiation by water vapor are significant. The spectral emission characteristics of the flame are a strong function of fuel type, humidity, water content, wind conditions, and so forth. Further, as described herein, absorption of flame radiation by the environmental water vapor occurs within the hundreds of thousands of extremely narrow spectral lines within both infrared vibration-rotation bands. In this study, the flame is characterized as a planar surface whose spectral emission of radiation can be taken to be that of a blackbody at the flame temperature T_f.

The radiative flux from black surface i incident on surface j may be expressed generally as (Modest 2003)

$$q_{i \to j} = \int_0^\infty \int_{A_i} \int_{A_j} e^{-\kappa_\eta s} \frac{\cos\theta_i \cos\theta_j}{\pi s^2} dA_i dA_j E_{bi,\eta} d\eta \quad (2)$$

Equation (2) is a triple integration over wavenumber (η), the area of the emitting surface (A_i), and the incident surface (A_j). The double integration over area is required to track the radiant emission from a location on surface i that arrives at all possible locations on surface j. This tracking must be done for all points of radiation emission on surface i. The geometric term $\cos\theta_i \cos\theta_j / \pi s^2$ accounts for the varying field of view for differential elements on surface i and surface j, separated by a distance s. $E_{bi,\eta}$ is the spectral blackbody emission from surface i, described by the Planck blackbody radiation spectral distribution at the temperature of surface i. The exponential term $e^{-\kappa_\eta s}$ in equation (2) accounts for absorption of radiation by the intervening medium of spectral absorption coefficient κ_η. Integrating over the spectrum as in the development of the classical weighted-sum-of-gray-gases model (Modest 2003), it can be shown that the radiative flux emitted by surface *i* which is incident on surface *j* is

$$q_{i\to j} = \int_0^\infty \left(s_i s_j\right)_\eta E_{bi,\eta} d\eta \tag{3}$$

where $\left(s_i s_j\right)_\eta$ is the spectral volumetric exchange factor, expressed as

$$\left(s_i s_j\right)_\eta = \int_{A_i} \int_{A_j} e^{-\kappa_\eta s} \frac{\cos\theta_i \cos\theta_j}{\pi s^2} dA_i dA_j \tag{4}$$

The dependence of both the volumetric exchange factor defined in equation (4), and the total radiant flux, equation (3), on wavenumber is evident. Because of the complex spectral variation in the absorption coefficient of water vapor, the Spectral Line Weighted-sum-of-gray-gases (SLW) model (Denison and Webb 1993a,b) was used to account for its spectral absorption characteristics. The SLW model has been shown to yield accuracy approaching that of computationally intensive line-by-line integrations for a small fraction of the computational cost. Rather than calculate the absorption of flame radiation by integrating on a line-by-line basis over the hundreds of thousands of lines using the Beer-Lambert Law, the SLW model specifies several discrete values of the absorption coefficient κ_k (called gray gas absorption coefficients), determines the total radiation source spectral content corresponding to each discrete value of κ_k (characterized by gray gas weights w_k), and sums (or integrates) the total radiation from a blackbody source over the total number K of discrete gray gas absorption coefficients specified. The integration over a few carefully chosen values of the gray gas absorption coefficient thus takes the place of spectral integration over wavelength in the traditional line-by-line method.

The integration of equation (4) is used to evaluate the radiant flux from one finite area A_i to another A_j. As shown in figure 2, $\emptyset_i$ and $\emptyset_j$ are the angles between the normal vector to each surface and the line joining the differential elements on surfaces *i* and *j*, respectively, and *s* is the distance between the two endpoints of the joining line. In order to determine the variation of local incident flux along the fuel bed, the fuel was divided into small but finite spatial strips running parallel to the shared flame/fuel edge, as shown in figure 2. The incident flux on the fuel was then calculated according to equation (4) for each strip.

Invoking the Spectral Line Weighted-sum-of-gray-gases model, the total (spectrally integrated) radiative flux leaving the planar flame surface and arriving at an arbitrary spatial strip *j* along the fuel bed may be shown to be the sum of radiative contributions from all gray gases:

$$q_{flame\to fuel,j} = E_{b,flame} \sum_k^K \left(s_{flame} s_{fuel,j}\right)_k w_k \tag{5}$$

where $q_{flame\to fuel,j}$ is the total (spectrally integrated) incident radiation flux emitted by the flame that arrives at (is incident on) strip *j* along the fuel bed, $E_{b,flame}$ is the total blackbody radiation flux emitted by the flame at temperature T_f, $\left(s_{flame} s_{fuel,j}\right)_k$ is the volumetric exchange factor for radiant transfer from the flame to spatial strip *j* corresponding to gray gas coefficient κ_k, and w_k is the gray gas weight associated with each gray gas absorption coefficient κ_k. Once the discrete gray gas absorption coefficients κ_k are specified, the corresponding gray gas weights w_k are determined by evaluating the area

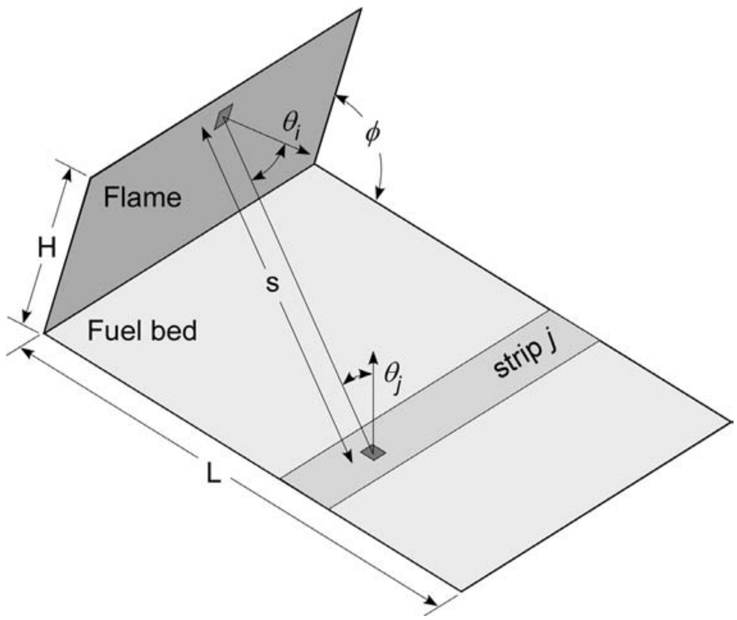


Figure 2—Detailed illustration of geometry and nomenclature for determination of volumetric exchange factor and local incident flux.

under the Planck spectral blackbody radiation distribution $E_{b,flame,\eta}$ where the gray gas absorption coefficient prevails for the gas specie in question (water vapor in this case) (Denison and Webb 1993a). The gray gas weights sum to unity, $\sum_{k}^{K} w_k = 1$. Increasing the number of gray gases employed improves the accuracy of the predictions. In this study, $K = 20$ gray gases were used in equation (5). Further increases in the number of gray gases yielded no appreciable change in the solution.

Because the closed-form integration of equation (4) to evaluate the volumetric exchange factor for each gray gas, $\left(s_{flame}s_{fuel,j}\right)_k$, is generally not possible for general cases involving radiation attenuation in the intervening medium, the expression was evaluated using numerical integration. Referring again to figure 2, the approach followed here tracks radiation emitted from specified locations along the planar flame to destination strip *j* along the fuel bed. A reduction of two-dimensional flame and fuel surfaces (shown in fig. 2) to the one-dimensional variation in incident flux along the fuel suggested in figure 1 is not forthcoming in the integration of equation (4). Consequently, two-dimensional flame and fuel bed surfaces were used in the numerical integration as shown. The lateral extent of the flame and fuel surfaces as then sequentially increased in exploratory simulations to determine the dimension large enough to yield the one-dimensional variation in radiative flux along the fuel bed illustrated in figure 1. The lateral dimension required to achieve predictions independent of end effects was 20 times the flame height for all configurations. The surfaces of both flame and fuel were discretized in two directions for numerical evaluation of the integrals in equation (4). The multiple spatial strips along the fuel bed were clustered near the base of the flame in order to accurately resolve the steep gradient of incident radiant flux with position along the fuel. Each strip *j* was subsequently discretized into smaller differential elements used to evaluate the integrals in equation (4). The numerical integration procedure sweeps through differential area elements on the fuel bed and on each strip of the flame, evaluating the local angles θ_i and θ_j for each of the elements and the corresponding distance s separating the two differential elements in question. The solution thus determines the fraction of radiation emitted by a given element on the flame that is incident on its destination element along the fuel after attenuation by the water vapor in the intervening medium. This accounting must be done for all elements on the flame. The double integration must be performed for the volumetric exchange factor corresponding to each gray gas. Thereafter, the summation over all K gray gases in equation (4) is carried out to determine the total radiative flux.

The volumetric exchange factor $\left(s_{flame}s_{fuel,j}\right)_k$ presented above is identical to the classical configuration factor $F_{i,j}$ (used for predicting radiative exchange between diffuse surfaces in the absence of a radiatively participating intervening medium), with the exception of the exponential absorption term, $e^{-\kappa_k s}$. Analytical expressions for the radiative configuration factor $F_{i,j}$ for commonly encountered surface-to-surface exchange configurations are tabulated in the literature (Siegel and Howell 2002). The accuracy of the evaluation of the volumetric exchange factor can therefore be verified by comparing the numerical integration of equation (4) for the transparent intervening medium case ($\kappa_k \to 0$) to published analytical expressions for the radiation configuration factor between surfaces with adjoining edges and included angle ø. Figure 3a illustrates the error between the numerically evaluated volumetric exchange factor $\left(s_{flame}s_{fuel,j}\right)_k$ for $\kappa_k \to 0$ and the corresponding classical radiation configuration factor $F_{i,j}$ (Siegel and Howell 2002) for radiative transport from the entire flame surface to a 10-cm long element at the base of the fuel bed as a function of number of points used in the numerical integration. Both $\phi = 60$ and 90 degree flame configurations for a flame length $H = 1$ m are shown. Radiative exchange between the flame and the small segment at the base was selected for this validation exercise because it is the most rigorous accuracy

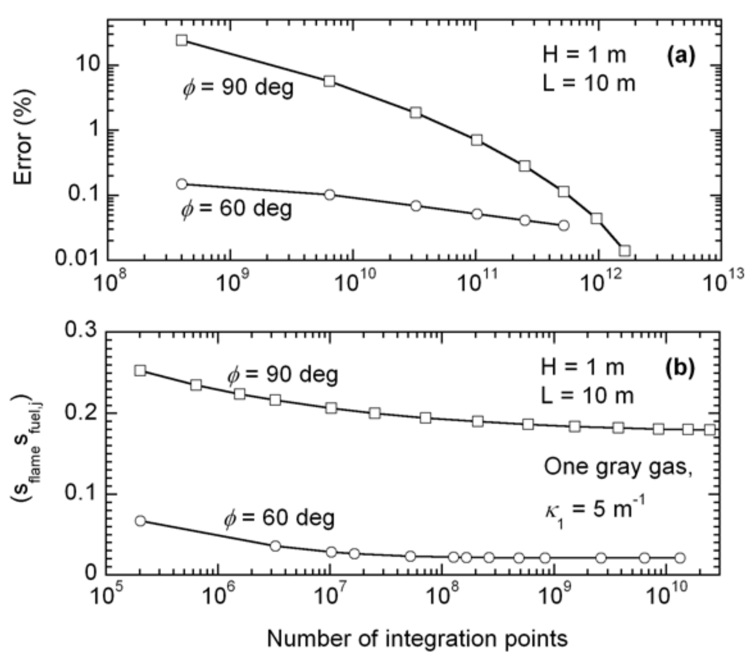


Figure 3—(a) Error between the volumetric exchange factor for $\kappa_k \to 0$ (for $K = 1$) and the corresponding classical radiation configuration factor, and (b) variation in calculated volumetric exchange factor with number of integration points.

test of the numerical integration. It is for this configuration that the numerical evaluation of the exchange and configuration factors incurs the greatest error. As expected, figure 3a shows that the error decreases as the number of integration points increases. The difference between numerical integration and analytical result is less than 1 percent for a surface discretization employing more than 10^{11} integration points for both flame angle configurations. This favorable comparison for the limiting case $\kappa_k \to 0$ demonstrates the accuracy of the numerical integration of equation (4), if only for the transparent intervening medium case.

While the data of figure 3a constitute evidence that the numerical integration is accurate for the transparent-medium scenario, there is still some uncertainty that with the inclusion of the transmission term $e^{-\kappa_k s}$, the solution may not be convergent. Therefore, a study was undertaken to demonstrate that a convergent solution, independent of the number of points in the numerical integration, was achieved for the case of finite attenuation ($\kappa_k \neq 0$). Figure 3b illustrates the variation in calculated volumetric exchange factor $\left(s_{flame}s_{fuel,j}\right)_k$ between the flame and a fuel bed surface strip near the base of the flame for a single gray gas (K = 1) of gray gas absorption coefficient κ_1 = 5 m^{-1}, with the number of points in the numerical integration for both the normally oriented and angled flame configurations. This value of the gray gas absorption coefficient used in the exercise is in the mid-range of the coefficients used in the simulations reported hereafter in the results. The figure reveals that the value of $\left(s_{flame}s_{fuel,j}\right)_k$ returned by the numerical integration is unchanging beyond 10^{10} integration points for both flame angles studied. Further, to ensure that this choice produced a solution free of round-off error in addition to a solution independent of the number of integration points, all variables associated with the numerical integration were increased in computer precision to confirm that the answer remained the same. It was found that increasing the computer precision (to the so-called "long double" precision) yielded no change in eight significant figures over the double precision results used in all predictions shown hereafter. The results suggest a convergent solution, lending confidence in the accuracy of the volumetric exchange factor for finite gray gas absorption coefficient.

Based on the results of the validation exercise illustrated in figure 3, 10^{11} integration points were used in all simulations reported here. The prediction of incident flux variation along the fuel bed for a given set of conditions was computationally intensive. The calculation of the volumetric exchange factor for each gray gas for all strips on the fuel bed required approximately 12 hours of computation time. This computation was performed for each of the 20 gray gases. In practice, $\left(s_{flame}s_{fuel,j}\right)_k$ was evaluated for all gray gases simultaneously using parallel computing, after which the summation of equation (5) was performed to determine the local radiant flux incident on the fuel.

Results And Discussion

Simulations were conducted for two flame heights, H = 1 and 10 m, with corresponding fuel bed lengths of L = 10 and 100 m, respectively. Included flame angles ϕ of 60 and 90 degrees were explored. Two flame temperatures were investigated, T_f = 1000 and 1500 K, bounding the reasonable nominal range of flame temperatures in wildland fires (Butler and others 2004). All simulations were conducted with and without environmental water vapor in the intervening medium between flame and fuel bed. For those predictions including water vapor, a uniform mole fraction of 3.5 percent H_2O was imposed, corresponding approximately to a relative humidity of 100 percent at a temperature of 300 K. This represents the upper bound on the influence of environmental water vapor on radiation attenuation in wildland fires.

Figure 4 illustrates the variation in predicted local incident radiant flux with position along the fuel bed for a 1 m long flame (H = 1 m) under normal flame conditions (ϕ = 90 deg) for a flame temperature T_f = 1000 K. Two cases are shown, with and without the effect of radiation attenuation by 3.5 percent environmental water vapor. The trends for both cases are qualitatively similar. As expected, the highest flux incident on the fuel bed is at the base

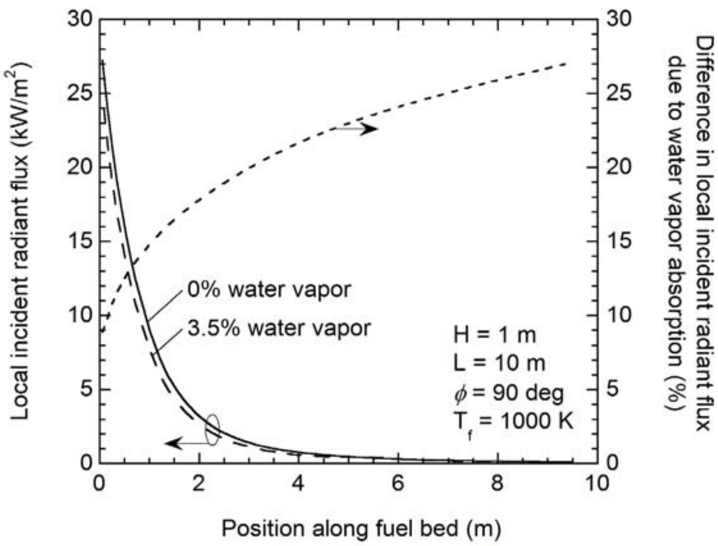


Figure 4—Predicted local incident radiant flux along the fuel bed for the cases with and without water vapor absorption, H = 1 m, L = 10 m, ϕ = 90 deg, and T_f = 1000 K.

of the flame, where the flame is viewed most intensely by the fuel bed. The local radiant flux drops dramatically with increasing distance along the fuel bed. As expected, the influence of water vapor is to attenuate the radiation incident on the fuel bed. At the base of the flame where the radiant flux is the highest, the environmental water vapor reduces the flux incident on the fuel bed by approximately 9 percent. Also plotted in figure 4 is the difference in local incident radiant flux due to water vapor, expressed as a local percentage difference relative to the otherwise identical case with no absorption. The fractional influence of water vapor is lowest near the base of the flame (9 percent), and increases with increasing distance along the fuel bed. This may be explained by the increasing absorbing path length through which emission from the flame must pass for fuel bed locations farther from the flame base. It should be recognized that although the fractional influence is higher farther from the flame, the incident flux decreases rapidly in this direction. Thus, the incident flux is lowest in regions where the percentage influence is highest. The data of figure 4 are used as benchmark against which the parametric effect of varying flame temperature, flame height, and flame angle will be explored in sections to follow.

The effect of varying flame temperature is illustrated in figure 5 for the 1 m, normal flame configuration (ϕ = 90 deg). Predictions for two flame temperatures are presented, T_f = 1000 and 1500 K. As expected, the magnitude of

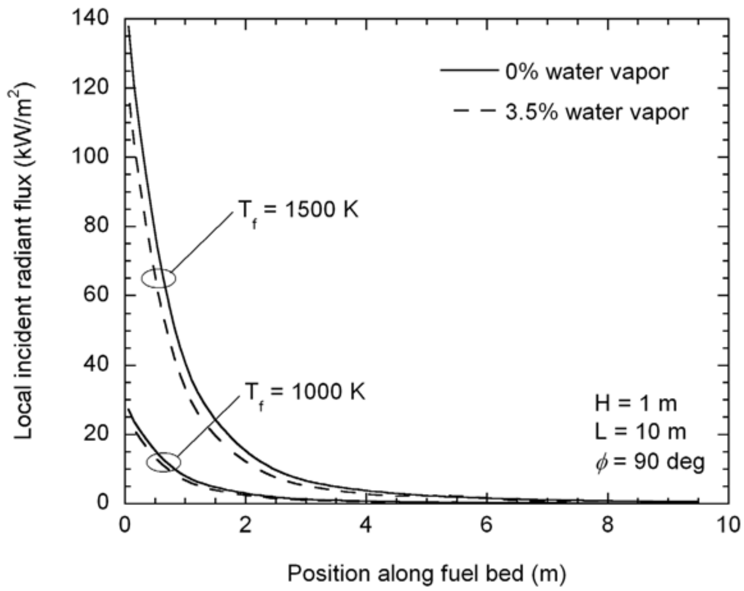


Figure 5—Effect of flame temperature on local incident radiant flux along the fuel bed for H = 1 m, L = 10 m, and ϕ = 90 deg.

the incident flux is considerably higher for the hotter flame. The predictions reveal that the incident radiation at the base of the 1500 K flame is attenuated by water vapor an amount 13 percent relative to the case with no H_2O, compared to 9 percent for the 1000 K flame. The greater influence of water vapor at higher T_f is due to the fact that the spectral emission from the hotter flame is concentrated more heavily in the spectral regions corresponding to the two primary infrared absorption bands of water vapor. It may be concluded that a hotter flame scenario results in greater attenuation by environmental water vapor than is experienced by a relatively cooler flame.

The effect of flame length is shown in figure 6, where local incident flux predictions for H = 1 and 10 m (with L = 10 and 100 m, respectively) are plotted for the normal flame configuration with T_f = 1000 K. The differences

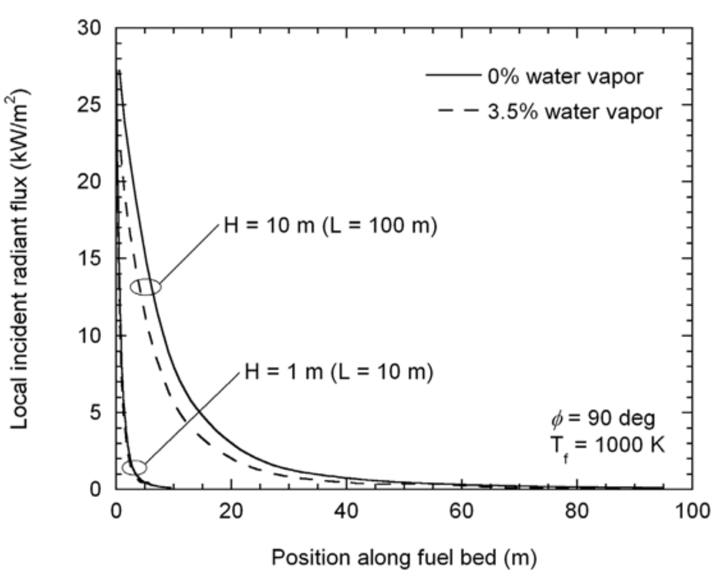


Figure 6—Effect of flame length on local incident radiant flux along the fuel bed for ϕ = 90 deg and T_f = 1000 K.

in flux magnitude near the base of the flame are not significant for the two flame length simulations. This is not surprising, since the region near the flame base "sees" little of the flame beyond the 1 m length, and is therefore exposed to nearly the same radiative environment in both cases. Farther from the flame base along the fuel bed, however, the longer flame yields higher incident flux magnitudes produced by the effect of the additional flame length for H = 10 m. It appears that attenuation of radiation by water vapor is more significant for the longer flame. This may be explained by the fact that radiation from the longer flame must, on average, traverse greater distance of absorbing medium before reaching the fuel bed.

Figure 7 illustrates the influence of flame angle on the incident radiant flux for the 1 m flame, T_f = 1000 K. Relative to the normal flame configuration (ϕ = 90 deg), the radiative flux is substantially higher for the angled flame. As the flame angle decreases from ϕ = 90 degees, it occupies a greater field of view for all locations along the fuel bed. In other words, the fuel bed "sees" the flame more prominently for angled flame conditions, resulting in high incident radiant flux. While not evident in the figure, the fractional decrease in incident flux due to absorption by water vapor is reduced for the angled flame. Whereas the reduction in incident flux at the base of the flame for the ϕ = 90 degee case was 9 percent, the flux is reduced there by only 5 percent for the ϕ = 60 degee case. Again, this may be explained by the fact that the average path length for radiation between flame and fuel bed is smaller for ϕ < 90 degees. Consequently, there is less attenuation by water vapor.

The local influence of flame radiation absorption by water vapor for the cases presented in the foregoing sections is summarized in figure 8. As was done in figure 4, the effect of absorption by water vapor is expressed in figure 8 as a local percentage difference relative to the otherwise identical case with no absorption. To facilitate the presentation of data for both flame lengths studied, the data are plotted as a function of normalized position along the fuel bed, x/L, where x is the coordinate along the fuel bed measured from the base of the flame. For all cases the fractional influence is lowest near the

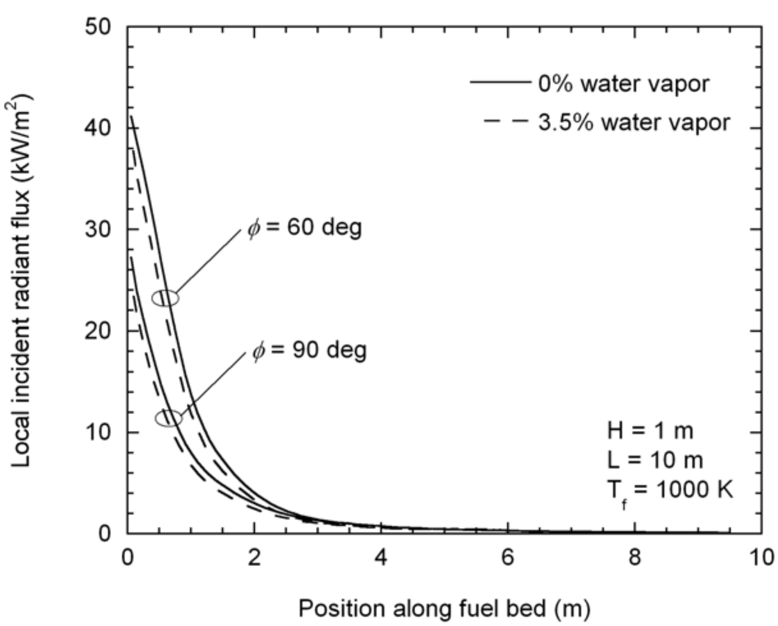


Figure 7—Effect of flame angle on local incident radiant flux along the fuel bed for H = 1 m, L = 10 m, and T_f = 1000 K.

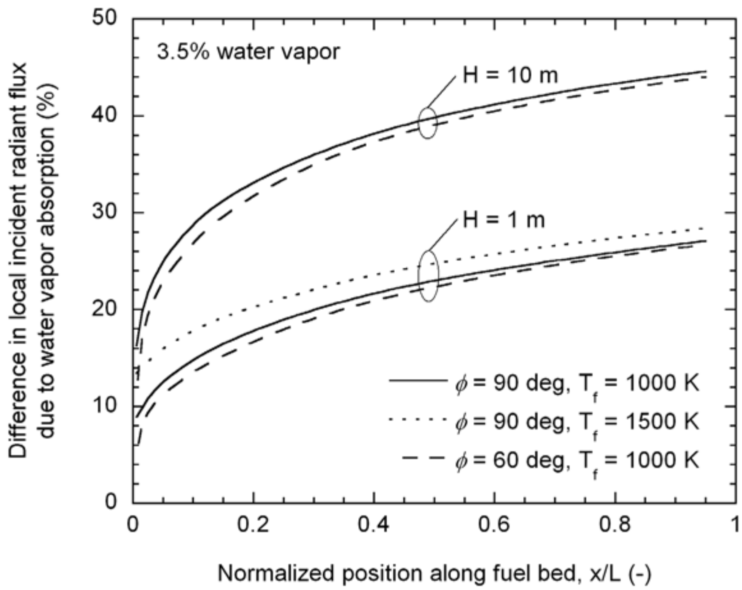


Figure 8—Difference in local incident radiant flux due to water vapor absorption as a function of normalized position along the fuel bed for all cases studied.

base of the flame, and increases with increasing distance along the fuel bed. It should be recognized, however, that although the fractional influence is higher farther from the flame, figures 4 through 7 indicate that the local incident flux decreases rapidly in this direction. Thus, the flux is lowest in regions where the percentage influence is highest. It is again observed that the relative effect of water vapor absorption is greater for increasing flame temperature, flame length, and inclination angle. As outlined previously, this is explained by the greater average path-length through which the flame radiation must pass before arriving at the fuel bed for these scenarios.

The foregoing sections have presented the effect of absorption by environmental water vapor on the *local* radiative flux incident on the fuel bed. Of interest is the aggregate effect of radiation absorption by water vapor on the overall heat transfer to the fuel, found by summing the local incident flux spatially over the entire fuel bed area:

$$Q_{flame \to fuel} = \sum_j q_{flame \to fuel, j} A_j \qquad (6)$$

Here, $Q_{flame \to fuel}$ is the total radiant heat transfer (as opposed to local heat *flux*) emitted by the flame that is incident on the entire fuel bed. The results of the calculation of equation (6) are found in table 1 for all of the cases explored, again expressed as a percentage difference relative to an otherwise identical case with no H_2O absorption. The general trends illustrated by figure 8 are confirmed by the tabulated results. For the range of parameters investigated here, the attenuation of flame radiation by environmental water vapor affects the total heat transfer to the fuel bed by an amount ranging from 11.9 to 26.7 percent. As observed and explained previously, the overall influence of environmental water vapor is less important for lower-temperature flames and for angled flames. While its effect is modest (but perhaps nonnegligible) for small flames, it can become quite significant for larger flames.

Table 1—Overall reduction in total radiative heat transfer incident on the fuel bed due to absorption by environmental water vapor.

Flame length	$\phi = 90$ deg $T_f = 1000$ K	$\phi = 90$ deg $T_f = 1500$ K	$\phi = 60$ deg $T_f = 1000$ K
$H = 1$ m ($L = 10$ m):	13.5 percent	16.7 percent	11.9 percent
$H = 10$ m ($L = 100$ m):	26.7 percent		25.1 percent

Conclusions

Predictions have been made for radiative transfer from black, isothermal, planar flame to a black fuel bed maintained at 300 K. The effect of flame inclination, flame temperature, and flame length were explored for cases with and without absorption by environmental water vapor in the intervening air (at 300 K). From these simulations one can see that, depending on the conditions, water vapor has a modest but nonnegligible effect on the radiative transfer from flame to fuel. The effect is more pronounced for larger flames at higher flame temperatures. The influence of water vapor on attenuation of radiation is reduced for angled flames.

References

Albini, F.A. 1967. A physical model for fire spread in brush. Pittsburg, PA: Eleventh Symposium (Int.) on Combustion, The Combustion Institute: 533-560.

Albini, F.A. 1985. A model for fire spread in wildland fuels by radiation. Combustion Science and Technology. 22:229-258.

Butler, B.W.; Cohen, J.; Lathan, D.J.; Schuette, R.D.; Sopko, P.; Shannon, K.S.; Jimenez, D.; Bradshaw, L.S. 2004. Measurements of radiant emissive power and temperatures in crown fires. Canadian Journal of Forest Research. 34:1577-1587.

Catchpole, W.R.; Catchpole, E.A.; Tate, A.G.; Butler, B.W.; Rothermel, R.C. 2002. A model for the steady spread of fire through a homogeneous fuel bed. Forest Fire Research and Wildland Fire Safety. Rotterdam: Millpress. ISBN 90-77017-72-0.

Cekirge, H.M. 1978. Propagation of fire fronts in forests. Computers and Mathematical Applications. 4:325-332.

De Mestre, N.J.; Catchpole, E.A.; Anderson, D.H.; Rothermel, R.C. 1989. Uniform propagation of a planar fire front without wind. Combustion Science and Technology. 65: 231-244.

Denison, M.K.; Webb, B.W. 1993a. A spectral line-based weighted-sum-of-gray-gases model for arbitrary RTE solvers. ASME Journal of Heat Transfer. 115:1004-1012.

Denison, M.K.; Webb, B.W. 1993b. An absorption-line blackbody distribution function for efficient calculation of gas radiative transfer. Journal of Quantitative Spectroscopy and Radiative Transfer. 50:499-510.

Emmons, H. 1964. Fire in the forest. Fire Research Abs. Rev. 5:163-178

Fons, W.L. 1946. Analysis of fire spread in light forest fuels. Journal of Agricultural Research. 72:93-121.

Hottel, H.C.; Williams, G.C.; Steward, R.R. 1965. The modeling of firespread through a fuel bed. Tenth Symposium (Int.) on Combustion. Pittsburg, PA: The Combustion Institute: 997-1007.

Modest, M.F. 2003. Radiative Heat Transfer, 2nd Edition. New York: Academic Press.

Siegel, R.; Howell, J.R. 2002. Thermal Radiation Heat Transfer, 4th Edition. New York: Taylor and Francis.

Thomas, P. H. 1967. Some aspects of the growth and spread of fire in the open. Forestry. 40:139-164

Weber, R.O. 1989. Analytical models for fire spread due to radiation. Combustion and Flame. 78:398-408.

Weber, R.O. 1991. Modelling fire spread through fuel beds. Progress in Energy and Combustion Science. 17:67-82.

This page is blank on purpose

Fire Behavior Modeling to Assess Net Benefits of Forest Treatments on Fire Hazard Mitigation and Bioenergy Production in Northeastern California

David J. Ganz[1], David S. Saah[2], Klaus Barber[3], and Mark Nechodom[4]

Abstract—*The fire behavior modeling described here, conducted as part of the Biomass to Energy (B2E) life cycle assessment, is funded by the California Energy Commission to evaluate the potential net benefits associated with treating and utilizing forest biomass. The B2E project facilitates economic, environmental, energy, and effectiveness assessments of the potential public benefits associated with: (1) various options for treatment, disposition, and utilization of forest biomass and (2) energy production from biomass produced by forest remediation activities. The study models forest conditions, fire behavior and fuel changes over a 40-year period, under three fuel treatment scenarios: no treatment; harvest and thinning on industrial private lands; and a range of prescriptions on industrial private and public multiple use ownerships. Effects of three fuel treatment scenarios are evaluated on fuel treatment effectiveness, economic feasibility, energy production supported, ecosystem impacts, and the location and capacity of modeled biomass facilities. The B2E project is novel in its scale of analysis, modeling the landscape effects of fire and treatments on 2.7 million acres of forest and brushland in the northern Sierra Nevada. This landscape represents high-hazard fuel areas, a broad range of ownerships, diverse habitats, complex infrastructure, and other values at risk. With 50 percent public multiple use and 17 percent industrial private lands, this landscape provides a unique opportunity to evaluate the effectiveness of Strategically Placed Area Treatments (SPLATs) and compare them with industrial private thinning and harvest. With average pretreatment biomass levels of 79 bone-dry tons (bdts) per acre, the private treatments removed an average of 31 bdts/acre while SPLATs removed an average of 24 bdts/acre. Wildfire modeling of these treatments showed a 6 percent reduction in the number of acres burned from private treatments and a 22 percent reduction from both private and SPLATs on public lands. While the ownerships, forest type, density, and slope dictated the type of treatment prescriptions, the spatial arrangement of treatments has a greater impact on their ability to change fire intensity and extent than the prescription applied.*

Introduction

California's wildlands and forests have accumulated an excess of small diameter woody material, or biomass. Fire suppression over the past century, combined with intensive forest management and a generally warmer and wetter climate, have led to increasingly dense vegetation. When wildfires occur, the heavy accumulation of biomass often makes those fires larger and more severe. The increase in forest biomass threatens public health and safety, watersheds, and wildlife habitat with unacceptable losses to wildfire. Public land management agencies and local landowners are focusing their efforts on thinning forests to reduce wildfire risks and to make them more resilient

In: Butler, Bret W.; Cook, Wayne, comps. 2007. The fire environment—innovations, management, and policy; conference proceedings. 26-30 March 2007; Destin, FL. Proceedings RMRS-P-46CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 662 p. CD-ROM.

[1] TSS Consultants, Oakland, CA. Dganz@tssconsultants.com

[2] Landscape Ecologist, Spatial Informatics Group, LLC, San Leandro, CA.

[3] Regional Analyst, U.S. Department of Agriculture, Forest Service, Region 5, Ecosystem Planning, McClellan, CA.

[4] Social Scientist, U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, Davis, CA.

to insects and diseases. These forest thinnings produce significant volumes of biomass as a waste product. Because this material currently has little commercial value, most agencies and landowners are faced with the expense of disposal by burning, chipping, and spreading, or hauling to a remote disposal site. Using forest biomass to generate electrical power is another disposal option. However, at this time, the costs of removing forest biomass to generate electrical power are generally higher than the costs of generating electricity from traditional sources, such as natural gas.

The social and environmental benefits of using forest biomass to generate electrical power are potentially substantial. In 1999, a major study conservatively placed the value of environmental benefits associated with biomass energy production in the United States at 11.4 cents per kilowatt-hour over and above the retail value of the energy generated (Morris 1999). In this study, the use of biomass from in-forest treatments is the least developed analysis, due in large measure to a lack of data and other analytical studies. While many studies have concluded that overall benefits of biomass energy production substantially outweigh costs, researchers face considerable challenges in quantifying the relevant economic values, particularly the benefits. A more accurate accounting of costs and benefits for forest biomass-to-energy strategies is needed to develop coherent policies that link forest health management, fuel loading reduction, and energy production.

Current inventory information indicates that in-forest fuels reduction may provide one of the largest sources of biomass fuel for power production in California. Removal of excess biomass from California's wildland areas to achieve public safety and environmental benefits could theoretically produce more than 30 million bone-dry tons (bdt) of biomass annually, of which approximately 18 million bdt would come from commercial and noncommercial forest management (CEC 1992; Shelly and others 1998; Kadam and others 1999). Assuming that this volume of biomass could be environmentally and economically available, it would comprise nearly eight times the biomass volume from all sources currently consumed for biomass power production in California (Morris 2002). The potential for power production would be substantial: 30 million bdt could produce more than 3,000 megawatts of power. Current biomass power production in California stands at about 650 megawatts annually, with a total capacity of approximately 750 megawatts. Biomass energy contributes 15 percent of the renewable power currently produced in the State, but has the potential to provide many times more (Morris 2002).

Life Cycle Assessment Approach

One approach used to identify and quantify the costs and benefits of biomass energy production is through a life cycle assessment. A life cycle assessment, or LCA, models the environmental impacts and related economic values associated with a product, process, or activity by identifying energy and materials used and wastes released to the environment. Decisionmakers can use LCA models to evaluate opportunities to reduce negative environmental impacts and achieve economic efficiencies. LCA is a systematic analytical method used to quantify the benefits and drawbacks associated with the entire life cycle of a product. In LCA, all stages of a product's life are analyzed, from the extraction of raw materials needed to make the product through final product distribution. An LCA is ideal for comparing new technologies with existing technologies to identify overall costs and benefits in terms of economic, environmental, and energy effects.

The Pacific Southwest Research Station of the U.S. Department of Agriculture, Forest Service is working with the California Energy Commission's Public Interest Energy Research Program; the University of California at Davis; energy, forestry, and environmental consultants; and several State and Federal agencies to construct a cradle-to-grave forest biomass LCA model. The model, called the Biomass to Energy (B2E) LCA model, will be used to identify and analyze social, economic, and environmental costs and benefits of using forest biomass to generate electrical power.

Study Objectives

The objective for the Biomass LCA Project is to develop a comprehensive economic, environmental, and energy LCA model that can be used to evaluate the potential net public benefits associated with treating and utilizing forest biomass. This computer-based model will be designed to facilitate economic, environmental, energy, and effectiveness assessments for the potential public benefits associated with (1) various options for treating, disposing, and utilizing forest biomass, and (2) electricity production from forest remediation biomass

The model will require synthesis of existing studies and additional research to populate individual modules. A wide range of research and peer-reviewed data will be incorporated into the model, such as wildlife habitat impacts; costs of vegetation management, collection, processing, and transport of biomass materials; air and water quality impacts and benefits; changes in wildland fire behavior and impacts; and so forth. Model users will be able to game out different options (or scenarios) within the various modules, and to change modeling assumptions such as forest remediation prescriptions, transportation distances, types of equipment used, biomass generating technologies, and so forth. Ultimately, the model will be used to explore opportunities for converting forest biomass to electricity, based on economic viability, environmental impacts, and energy efficiency. It will also allow policymakers to evaluate the effectiveness of alternative forest biomass management policies in meeting public goals, stakeholder needs, and government regulations.

Study Site Selection

One important risk in complex environmental modeling concerns the degree of generality one assumes about the impacts of the unit processes within the model. To increase the accuracy of the modeling assumptions and impacts, the LCA project team will select specific geographic locations that correspond to the kinds of forest remediation needs in California. Each location will represent a different landscape archetype. The team will draw data from these selected areas to resolve fuzziness in the model, test assumptions, and provide opportunities to "ground truth" the model. Selection of the number and kinds of landscape archetypes was a key challenge early on in the project. Possible criteria for selecting areas include the following: (1) vegetation condition, (2) human population density, (3) sensitive ecological systems (habitats), and (4) existing infrastructure-related opportunities (for example, roads to provide access to treatment areas and transport materials from treatment sites) (table 1).

Table 1—B2E landscape archetype selection criteria.

Criterion	Specifics
High-hazard Fuel	FRCC3 fuel loading over a substantial portion of the landscape
Ownership Mix	Must have a reasonable mix of Public Multiple Use (PMU), Public Conservation and Recreation (PCR), Industrial Private Forestry (IPF), Non-industrial Private Forests (NIPF)
Human Settlement & Assets Capital Assets	Must have substantial areas of WUI A reasonable number of key infrstructure assets, such as dams, power line corridors, etc.
TES/SSC habitat	Habitat at risk of wildfire for several species of concern
Data Quality	Data available in several categories required by the model (e.g., private land use, WUI described, habitat (WHR) mapped, Fuel loading mapped, etc.)
Landowner/Agency Interest	Demonstrated interest in working with the B2E Project from public agencies, communities, environmental NGOs and private sector industries
Current Management	Baseline conditions, fire histories and current vegetation management prescriptions must be described and ideally mapped
Geographic Scope	Must be of sufficient size to measure changes in large-scale impacts, such as carbon cycling, habitat change across populations of T&E species or cumulative watershed effects
Representative Ecoregion	Must represent landscape characteristics of diverse forest/chaparral dominated ecoregions in California

The B2E LCA Beta model, selected as a landscape archetype using the criteria described above, is novel in its scale of analysis, modeling the landscape effects of fire and treatments on 2.7 million acres of forest and brushland in the northern Sierra Nevada (fig. 1). The Beta landscape was originally chosen to represent high-hazard fuel areas with a reasonable mix of ownerships encompassing a broad range of infrastructure and other values at risk. This landscape represents high-hazard fuel areas, a broad range of ownerships, diverse habitats, complex infrastructure, and other values at risk. With 50 percent public multiple use and 17 percent industrial private lands, this landscape provides a unique opportunity to evaluate the effectiveness of Strategically Placed Area Treatments (SPLATs) and compare them with industrial private thinning and harvest.

The Beta landscape has more than 240 vegetation strata, or types of vegetative assemblages, ranging from lower elevation scrub and manzanita (for example, around Oroville Dam on the lower west side), to midelevation mixed conifer, to eastside pine and western juniper. Many of these vegetation types are in overstocked condition, with a Fire Regime Condition Class (FRCC) rating of 2 and 3.

Figure 1—Location and features of B2E Beta landscape.

Fire Modeling Strategy and Assumptions

The Biomass to Energy (B2E) Team has constructed a comprehensive forest biomass-to-electricity model, which has identified and analyzed the economic and environmental costs and benefits of using forest biomass to generate electrical power while changing fire behavior at the landscape level. Recognizing the urgent need for reducing "catastrophic" fires at a landscape level, the B2E Team identified a modeling strategy for depicting fire behavior changes on the landscape as a result of emerging forest remediation treatment opportunities. This modeling strategy depends on a series of assumptions, which will be described in the following section.

Fundamental to the assumptions of the B2E treatments is the concept of SPLATs as described by the research and fire behavior modeling of Mark Finney of the Missoula Fire Lab in the Rocky Mountain Research Station, USDA Forest Service (Finney 2001). Finney's research on optimized treatments reveals that how you spatially arrange fuel treatments across the landscape is much more important than how much of the area is treated. Using the fire behavior modeling software FARSITE and FlamMap, Finney and his colleagues at the Missoula Fire Lab have shown that treatments on only 20 to 30 percent of the landscape can be effective in reducing the threat of crown fires and other severe fire behavior if the spatial arrangement of the treatments interrupts the fire's rate of spread (fig. 2).

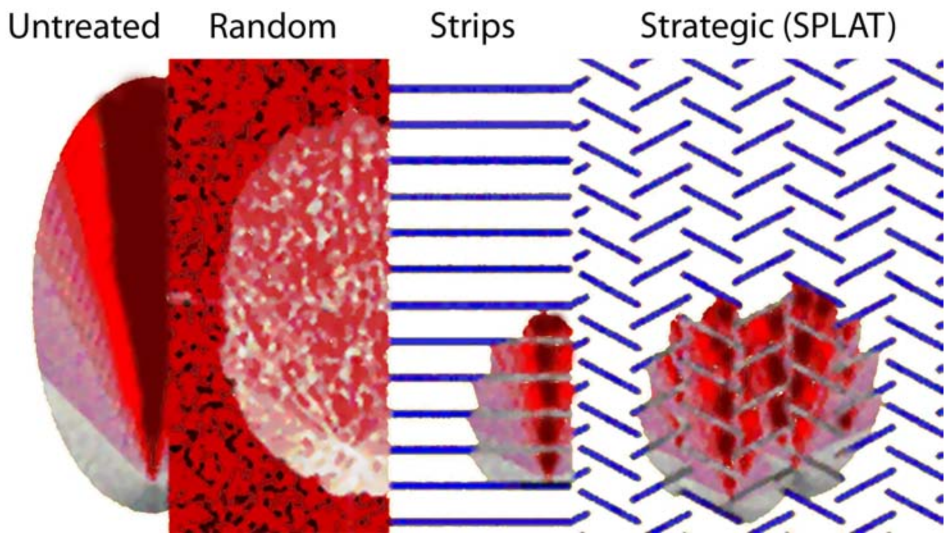


Figure 2—The effects of various fuel treatment patterns on fire size (adapted from Finney 2001). Left to right: homogenous fuel conditions (untreated), random treatments, complete overlap of parallel strip treatments, and strategic, slanted overlapped treatments.

For this study, fire behavior was summarized into three classes of severity to distinguish and report changes in wildfire effects across the B2E landscape (fig. 3). Burned areas were classified based on spatially explicit FlamMap (Finney and others 2006) model results of fireline intensity and the crowning behavior of the fires. The effects of wildland fire behavior on vegetation were tracked in the vegetation portion of the larger B2E-LCA project (domain), and overseen by the USDA Forest Service Region 5's Stewardship and Fireshed Assessment (SFA) Team. The severity of wildfire was assigned to three classes (nonlethal, mixed lethal, or lethal effects) depending on its flame length and fire type (ground fire, passive crowing fire, or active crowing fire). Fire severity determines the numbers of trees killed and the quantity of vegetation consumed by fire. Simulations were performed on a 10-year temporal sequence for 40 years with a series of fires taking place immediately at the beginning of each decade in each fireshed.

Fire Severity Classes		Fire Type (Crown Fire Activity)		
		Ground	Passive Crowning	Active Crowning
Flame Length (feet)	0.00-3.99	N	X	L
	4.00-7.99	X	X	L
	8.00-11.99	X	L	L
	12.00+	L	L	L

Figure 3—Classes of fire severity used in B2E fire modeling (Stewardship and Fireshed Assessment Team): (N) – Nonlethal, (X) – Mixed-lethal, (L) – Lethal.

The modeling strategy was to measure and treat changes in wildfire effects as expected value outcomes, reflecting average outcomes over long periods of 10 years or more. The team averaged probabilities of wildfire occurrence across space and time. The 10-year intervals over a 40-year timeframe for the fire modeling effort have been selected because this timeframe fits well with the economics that drive timber harvest (single entry at 20-year intervals for uneven aged management) as well as the life cycle of the technology being evaluated (biomass conversion plants are likely to become obsolete and depreciate after 20 years).

Modifying landscape-scale fire behavior when only a portion of the landscape can be realistically treated requires attention to layout. Mark Finney's research indicates that fire spread rates can be reduced, even outside of treated area, if a fire is forced to flank treated areas where fuels have been reduced. However, two criteria must be met for the strategy to be effective: (1) the pattern of treatments must be laid out in a manner that interrupts fire spread, and (2) prescriptions within the treatments must be designed to modify fire behavior.

Of course, forest management has to be conducted with multiple objectives in mind. The impact of fuel treatments on wildlife habitat, threatened and endangered species, and recreational opportunities are essential considerations. In addition, forest managers often have an opportunity to generate revenue through timber sales to cover or offset the costs of management activities. This means that optimal pattern for preventing wildfires is not a realistic option. The treatments are adjusted to protect sensitive wildlife habitat, reduce negative watershed effects, shape recreational opportunities, and capture timber volume to help pay for treating more areas.

Methods

This study was able to track the contribution of private and public land treatments toward modifying large-scale fire behavior by comparing the difference in fire behavior between three management scenarios:

- *Scenario 1* – No treatment: This scenario assumes no treatments on private or public lands, thereby providing a reference for the interaction of the environment and fire. Vegetation is grown across the beta landscape over the 40-year period, and the resulting fire effects are modeled. The scenario assumes no salvage harvest or reforestation after wildfires. When compared to scenario 2 (below), the no treatment scenario allows the team to track the contribution of private land treatments (including salvage) toward modifying large-scale fire behavior.
- *Scenario 2* – Industrial Private Forests (IPF) only: This scenario assumes treatments on private lands only; no treatments are assumed for public lands. On public lands, vegetation is grown from the current date and only fire effects are tracked, much as in scenario 1. It is assumed that the mix of IPF ownership managed under even aged and uneven aged management is 50-50 percent.
- *Scenario 3* – IPF and Public Multiple Use (PMU) combined: This scenario assumes the overriding goal is to achieve fire behavior modification at a landscape scale. Private lands are treated as under the same prescriptions as scenario 1 (IPF only), and PMU lands are treated using a variety of strategic approaches (defensible fuels profile zones and SPLATS).

Fire modeling outputs included the number of acres in three classes of fire severity, the number of burned acres with crown fire behavior, and flame lengths less than and greater than 4 feet. Historical fire occurrence was used to locate ignitions. Discrete ignition points at locations across the landscape were chosen recognizing that demographics, human activities, and climatic conditions will vary with time (fig. 4). This study used predetermined ignitions per decade instead of a random generator. Randomization of ignition locations did not yield the "catastrophic" events needed to measure differences between the three main treatment scenarios. While purely a means to the end, the rule sets generated for performing these three treatments across 2.7 million acres (table 2) have received attention for similar modeling ventures in California.

Results

With a no treatment weighted average biomass levels of 79 bone-dry tons (bdts) per acre, the private treatments removed an average of 31 bdts/acre while SPLATs removed an average of 24 bdts/acre (table 3). Downstream models are evaluating the effects of these three fuel treatment scenarios on economic feasibility, energy production supported, ecosystem impacts and the location and capacity of modeled biomass facilities. For the purposes of

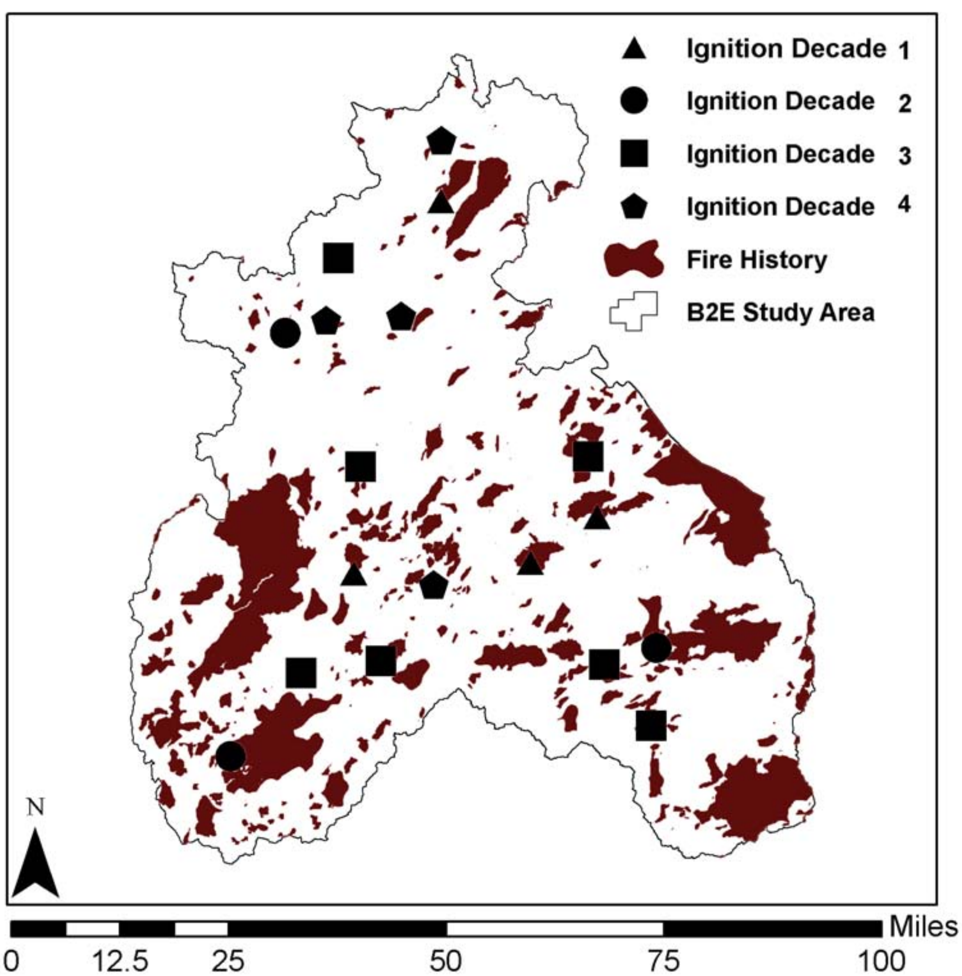


Figure 4—B2E Beta landscape fire history and ignition placement by decade.

Table 2—Treatment allocation rule base and logic.

Mgnt. Regime	Lands Applied to:	Treatment Cycle	Treatment Unit Size	Regime Code or ID	Per-1	Per-2	Per-3	Per-4	Rx Desc	Salvage
Wildland Fire Use	Public Conservation	n/a	n/a	n/a	n/a	n/a	n/a	n/a		no
Rx Fire [initial	Public-MU >50%	20-yrs	140-acres	31	Rx Fire		Rx Fire			no
				32		Rx Fire		Rx Fire		
Restricted Thin	Public-MU <50%	20-yrs	150-acre ave. SPLAT [Finney Herring Bone Psattern]	21	Initial Integ.Fuel s Treat		Maint - Integ.Fuels Treat		thin for fuels- retain 40% cc	yes
				22		Initial Integ.Fuels Treat		Maint - Integ.Fuels Treat		
			DFPZs as mapped under QLG [1/4mi fb]	23	Initial Integ.Fuel s Treat		Maint - Integ.Fuels Treat		thin for fuels- retain 40% cc	
	SMZ-IFL[1]	treated along with interesect unit	300-ft perin.	n/a	Initial Integ.Fuel s Treat		Maint - Integ.Fuels Treat		thin for fuels- retain 40% cc	yes
				n/a		Initial Integ.Fuels Treat		Maint - Integ.Fuels Treat		
Unevn-aged	IFL [1] all Slopes and IFL[2] w/SLp >50% only	20-yrs	140-acres	11	Selective Harvest		Selective Harvest		Thin for product [~5mbf/ac] & stand vigor	yes
				12		Selective Harvest		Selective Harvest		
	All NIFL Slp <50%	20-yrs	20-acres	11	Selective Harvest		Selective Harvest			no
				12		Selective Harvest		Selective Harvest		
Even-aged	IFL[2] slp <50%, mature	70-years	20-acres	1	Regen Harvest	PCT		ComThin	Regn Harvest-Clearcut	yes
				2,7		Regen Harvest	PCT			
				3,6	ComThin		Regen Harvest	PCT	comthin to a Ave. BA	
				4,5		ComThin		Regen Harvest		
	IFL[2] Plantations , <15yrs	70-years	as mapped	8	PCT		ComThin		percom thin to 150-160 tr/ac	no
No Treatment	all others	n/a	n/a	1-4	n/a	n/a	n/a	n/a		no

PMU Public Multiple Use
PCR Public Conservation-Recreation
IFL_U Industrial Forest Lands [1, 2]
NIFL Non Industrial Forested Lands
NON Others, Non Forested Lands, Urban
SMZ Streamside Management Zone.

this study, by comparing the difference in fire behavior between three management scenarios over the 40-year management trajectory, we can evaluate the contribution of private and public land treatments toward modifying large-scale fire behavior.

While the ownerships, forest type, density, and slope dictated the type of treatment prescriptions, we found that the spatial arrangement of treatments has a greater impact on their ability to change fire intensity and extent than the prescription applied. While we recognize that the optimal pattern for preventing catastrophic wildfires (or reducing their impacts) is not always a realistic option, we have modeled scenarios 2 and 3 with the necessary adjustments to protect sensitive wildlife habitat, reduce negative watershed effects, shape recreational opportunities, and capture timber volume under industrial private forest ownerships (that are both realistic in turns of net revenues and

Table 3—B2E pretreatment inventory and amounts of biomass removed by scenario and year (in BDTs/acre)

Scenario	Year	Inventory	Treatment
1: No treatment	2006	64	
	2016	73	
	2026	80	
	2036	86	
	2046	91	
	Average	**79**	
2: Industrial Private Forests (IPF) only	2006	64	30
	2016	69	35
	2026	73	28
	2036	76	31
	2046	79	
	Average	**72**	**31**
3: (IPF) & Public Multiple Use (PMU)	2006	64	28
	2016	67	34
	2026	70	23
	2036	73	26
	2046	75	
	Average	**70**	**28**
3b: (PMU) - SPLATS	2006	64	26
	2016	66	34
	2026	67	17
	2036	70	20
	2046	72	
	Average	**68**	**24**

yet protects their proprietary information). Many of these assumptions are depicted in the treatment allocation rule sets and logic described above.

Quantifying effectiveness of fire mitigation treatments is a challenge as there is no accepted system of measurement. Evaluations of fire hazard mitigation programs tend to focus primarily on the number of acres treated and treatment costs associated with mitigation without adequately assessing the benefits of these treatments. These programs also tend to focus on monitoring the total number of acres burned from 1 year to the next to determine efficacy of certain fire mitigation strategies (for instance, comparing DFPZs and/or SPLATs with traditional fuel break systems). Wildfire behavior modeling, especially with FlamMap, lends itself well to landscape comparisons (for example, pre- and posttreatment effectiveness) and for identifying hazardous fuel and topographic combinations, thus aiding in treatment prioritization and landscape-level assessments such as the B2E Beta model. The B2E Beta wildfire behavior modeling of these three treatment scenarios showed a 6 percent reduction in the number of acres burned from private treatments and a 16 percent reduction from SPLATs on public lands (table 4). Scenario 3 had the overall greatest effect on the number of acres burned (that is, fire perimeters) with a 22 percent reduction from the no treatment scenario. For scenario 2, decade 2 had the greatest impact on reducing the fire perimeter with a 19 percent reduction in total acres (table 4). We expected to see a similar trend for reducing fire perimeters across all four decades but recognize

Table 4—Summary of B2E Beta Model burned acres by scenario and year.

Year	1: No treatment	2: Industrial Private Forests (IPF)	3b: (PMU)	3: (IPF) & (PMU)
2006	92,684	92,168	81,004	80,487
2016	60,153	48,616	51,383	39,846
2026	69,953	65,241	49,097	44,385
2036	76,543	75,758	68,582	67,796
Total Acreage	299,334	281,782	250,066	232,514
% Change from No TMT	0%	–6%	–16%	–22%

that differences existed due to modeling assumption and fire placements. These heightened effects for decade 2 were attributed to the location of the ignitions, higher proportion of private industrial ownership, and the topography within the fire perimeters.

As expected, scenario 1 generated the most acres burned with an average of 74,833 acres. While not all fires will achieve the same size, the burned acreage per decade averaged 67,802 acres for all three scenarios. Ignoring the small fires, the B2E Beta landscape's fire history on record (past 80 years) averaged around 65,000 burned acres per decade. The wildfire behavior modeling efforts for this B2E LCA Beta model have tried to mimic the fire history on record burning 65,000 acres in a variety of fire size and intensities with acres in each severity class approaching 30 percent based on work by Miller and Fittes (2006).

Evaluations of fire hazard mitigation programs tend to focus primarily on changes in the number of acres burned (since those are easiest to monitor). A modeling venture such as the B2E LCA Beta model allows us to evaluate the contribution of private and public land treatments toward modifying large-scale fire behavior using intensity as the change metric. Across all scenarios, 30.8 percent of the acres burned were characterized as nonlethal; that is, surface fires with flame lengths between 1 and 4 feet (table 5). The percentages of fire severity classes from the B2E wildfire modeling effort correspond well with Forest Service severity monitoring for the Sierra Nevada (Miller and Fites 2006).

These fire severity classes are important to the B2E LCA Beta modeling project because many of the downstream models are evaluating the effects of these three fuel treatment scenarios based upon these three classes. For

Table 5—Summary of B2E Beta Model severity class acres by scenario.

	Scenario			Summary	
Fire Severity Class	**1**	**2**	**3**	**Total**	**%**
N - nonlethal	81,471	82,160	86,586	250,216	31%
X - mixed lethal	136,887	125,156	98,560	360,603	44%
L - lethal	80,976	74,465	47,368	202,809	25%
Grand Total	**299,334**	**281,782**	**232,514**	**813,629**	**100%**

instance, fire consumption rates for canopy fuels and resultant wildfire emissions for green house gases are all modeled and calibrated to these fire severity classes.

As expected with the higher total number of acres burned, the percentages of acres with lethal and mixed-lethal fire severity classes were also highest in decade 2 (table 6). All three fire severity classes were favorably affected by applying both the private and public treatments over the four decades. Only decade 3 showed a decrease in the number of acres in the nonlethal severity class (3,880 acres) but that is due to the dramatic drop in total acres burned from implementing both public and private treatments in this particular decade with a positive change of 25,568 acres or 36.5 percent from the non-treated scenario 1 (table 4).

Table 6—B2E Beta Model severity class acres by scenario by year.

		Fire Severity Classes		
Scenario	**Decade**	**N**	**X**	**L**
1	1	36,579	33,176	22,929
	2	19,447	20,947	19,759
	3	19,296	31,691	18,965
	4	6,148	51,072	19,324
2	1	37,953	30,592	23,623
	2	21,491	13,208	13,917
	3	14,312	32,791	18,138
	4	8,404	48,566	18,787
3	1	37,889	24,740	17,858
	2	19,914	15,452	4,480
	3	15,417	18,496	10,472
	4	13,366	39,873	14,557

Despite a 6 percent positive effect on the number of acres burned, applying private treatments alone does not always result in a favorable effect on changing the fire severity. Decade 1's lethal severity class increased by 694 acres and decade 3's mixed lethal increased by 1,100 acres (albeit 827 acres of these can be attributed to a decrease in severity from lethal to mixed-lethal classes). Crown fire behavior in even-aged managed stand, especially during early stages of plantation development, can explain for these two increases in fire severity classes (out of 12 represented in table 6). Overall, the majority of the acres modeled in this effort demonstrated favorable impacts of implementing industrial private forest treatments with a decrease of 7 percent in the lethal severity class across the entire B2E Beta landscape.

Conclusions

Assuming that collection, processing, and transportation are economically viable, the conversion of forest biomass to useful energy becomes a critical economic and environmental issue. The B2E LCA Team has constructed a comprehensive forest biomass-to-electricity model, which has identified and analyzed the economic and environmental costs and benefits of using forest biomass to generate electrical power while changing fire behavior at the landscape level. The B2E wildfire behavior modeling of three treatment scenarios showed reductions in the number of acres burned and changes in intensity classes. Whether compared for the entire B2E Beta landscape or within perimeters of the 67,800 acres burned per decade, treatments applied to both public and private lands changed fire behavior and growth. The B2E wildfire modeling venture has demonstrated that treating public multiple use lands with SPLATs, albeit not nearly as strategically applied as originally intended by its designers, contributes more (percentage wise) than private sector treatments for modifying landscape-scale fire behavior. The goal of such modeling efforts is not to differentiate between public and private sector treatments, but rather, to improve our understanding of implementing forest treatments across ownerships to prevent catastrophic wildfires (or at least reduce their impacts). The next steps for improving the B2E wildfire modeling component of this B2E project will be to move to another landscape archetype using the criteria described in this paper and design a growth model for brush types that will complement the vegetation growth simulations over a 40-year timeframe.

The California Biomass to Energy project and other similar projects will help provide information about potential economic, energy, and environmental tradeoffs associated with various options for managing forest biomass and using forest biomass material to produce renewable energy. The results, findings, and conclusions of these efforts will help government organizations establish policies, legislation, incentives, and funding initiatives relative to biomass power, as well as assist private, academic, and government organizations in setting priorities and establishing plans for forest research and development programs.

Discussion

A primary assumption of the B2E fire behavior modeling approach is that SPLATs, as both a theoretical and an applied approach, will indeed fragment the fire-prone environment of the Beta landscape for the desired effect of reducing fire behavior, growth and/or severity. The modeled outcomes demonstrated in our results show a favorable effect from the spatial arrangement of treatments, but it is obvious that policymakers will need more empirical data to justify greater application of SPLATs on public lands. Recognizing this need, the USDA Forest Service and the Joint Fire Science Program have funded several empirical studies that are designed to demonstrate landscapes that have been treated for fuels with SPLATs, DFPZs, and other strategic approaches that can effectively change the behavior of wildfires. One such study currently producing empirical results is being performed at the Sagehen Experimental Forest by Dr. Scott Stephens and Dr. John Battles from the University of California at Berkeley (Saah and others 2006). Other studies have begun to report the efficacy of earlier treatments in reducing the effects of wildfires (for example, see Fulé and others 2001a,b; Finney and others 2005). In 2002, the Cone Fire on the Blacks Mountain Experimental Forest and funding from the Joint Fire Science Program provided Skinner and others (2004) with the opportunity to document changes in fire behavior on a landscape where fuels treatments had been conducted. Skinner and others (2004) stated, "In the case of both treatments the fire dropped quickly out of the crowns to become either a surface fire or die out upon entering the treated areas. The rapidity of apparent change from a high-intensity crown fire to a much lower-intensity surface fire may have significant implications for management of wildland/urban interface zones as well as wildlands in general."

As Mark Finney's research indicates, modifying landscape-scale fire behavior when only a portion of the landscape can be realistically treated requires attention to layout. We agree that the spatial arrangement of treatments is critical. On the B2E Beta landscape we noticed that strategic placement had a greater impact on fire intensity and extent compared to treatments themselves (dictated by ownership, forest type, density, and slope). Fire severity, as defined by the three classes, decreased by both private and public forest remediation treatments with a greater effect on public multiple-use lands. We were not surprised to find that the mass SPLAT implementation on public lands had a greater effect on fire behavior than the treating of private lands for commercial timber values. The downstream models utilizing these modeling outputs for further analysis are undoubtedly going to question the large-scale implementation and lack of strategic direction when SPLATs were applied to the B2E landscape. In our B2E LCA model, all stages of a product's life are analyzed, from the extraction of raw materials needed to make the product through final product distribution. In this LCA, biomass is the raw material (considered here as a waste product) and energy is the desired final product. The mass application of SPLATs on public lands to generate this raw material while positively reducing fire behavior, growth and/or severity (and subsequently reducing the emissions that would have been emitted by these fires), will either tip the balance for generating renewable energy from this waste product or drive up the costs of removing forest biomass due to the need for strategic planning and treatment implementation.

References

CEC. 1992. [The] 1991 biomass resources assessment report for California - draft report. Sacramento, CA: California Energy Commission.

Finney, M.A. 2001. Design of regular landscape fuel treatment patterns for modifying fire behavior and growth. Forest Science 47: 219-228.

Finney, M.A.; Britten, S; and others. 2006. Flammap. Missoula, MT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fire Sciences Lab; and Systems for Environmental Management.

Finney, M.A.; McHugh, C.W.; and others. 2005. Stand- and landscape-level effects of prescribed burning on two Arizona wildfires. Canadian Journal of Forest Research 35(7): 1714-22.

Fulé, P.Z.; McHugh, C.W.; and others. 2001a. Potential fire behavior is reduced following forest restoration treatments. Ponderosa pine ecosystems restoration and conservation: Steps toward stewardship. Ogden, UT: U.S. Department of Agriculture, Forest Service.

Fulé, P.Z.; Waltz, E.M.; and others. 2001b. Measuring forest restoration effectiveness in reducing hazardous fuels. Journal of Forestry 99: 24-29.

Kadam, K.L.; Camobreco, V.J.; and others. 1999. Environmental life cycle implications of fuel oxygenate production from California biomass - technical report. Golden, CO: U.S. Department of Energy, National Renewable Energy Laboratory.

Miller, J.D.; Fites, J. 2006. Sierra Nevada fire severity monitoring: Internal report. Nevada City, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Region, Adaptive Management Services Enterprise Team: 62.

Morris, G. 1999. The value of the benefits of U.S. biomass power. Golden, CO: U.S. Department of Energy, National Renewable Energy Laboratory.

Morris, G. 2002. Biomass energy production in California 2002: Update of the California biomass database. Golden, CO: U.S. Department of Energy, National Renewable Energy Laboratories.

Saah, D.S.; Battles, J.J.; and others. 2006. Translating SPLATs from a theoretical to a real world landscape. http://sagehen.ucnrs.org/research.htm.

Shelly, J. R.; Weiant, P.; and others. 1998. Assessment of urban/wildland biomass utilization and disposal options. Sacramento, CA: California Department of Forestry and Fire Protection.

Skinner, C.; Ritchie, M.; and others. 2004. Effects of prescribed fire and thinning on wildfire severity: The cone fire, Blacks Mountain Experimental Forest. Proceedings 25th Vegetation Management Conference, Redding, CA.

This page is blank on purpose

Combining Turbulent Kinetic Energy and Haines Index Predictions for Fire-Weather Assessments

Warren E. Heilman[1] **and Xindi Bian**[1]

Abstract*—The 24- to 72-hour fire-weather predictions for different regions of the United States are now readily available from the regional Fire Consortia for Advanced Modeling of Meteorology and Smoke (FCAMMS) that were established as part of the U.S. National Fire Plan. These predictions are based on daily real-time MM5 model simulations of atmospheric conditions and fire-weather indices over specific modeling domains. Included in the suite of fire-weather indices provided by the FCAMMS is the well-known Haines Index (HI), an operational "mesoscale-type" index that characterizes the atmospheric risk of extreme fire behavior based solely on stability and moisture conditions in the lower to middle troposphere. However, there are other atmospheric variables that also influence the risk of extreme fire behavior, especially those that characterize conditions in the atmospheric boundary layer where small-scale fire-atmosphere interactions are so important. One of those variables is atmospheric turbulence (that is, wind gustiness), as measured by turbulent kinetic energy (TKE). TKE can be classified as a "boundary-layer-type" index, with its generation and dissipation dependent on wind shear and buoyancy conditions near the surface. Like the HI, predictions of TKE are available from the daily FCAMMS MM5 model simulations. This study examines the utility of combining the HI with TKE to assess potential atmospheric risk of extreme fire behavior. Output from the FCAMMS - Eastern Area Modeling Consortium (EAMC) MM5 simulations of fire-weather conditions over the western Great Lakes region is used to identify regional patterns of HI and TKE on a daily basis. A comparison of the patterns of the two indices allows for an assessment of whether large HI values typically occur with large near-surface TKE values, a potentially dangerous fire-weather condition.*

Introduction

The regional Fire Consortia for Advanced Modeling of Meteorology and Smoke (FCAMMS) (http://www.fs.fed.us/fcamms), established by the U.S. National Fire Plan (USDA Forest Service 2002), are providing daily 24- to 72-hour real-time fire-weather predictions for different regions of the United States as part of their research programs focused on developing new and improved tools for predicting fire-fuel-atmosphere interactions. These predictions are based on simulations performed with the Fifth Generation Penn State University (PSU)/National Center for Atmospheric Research (NCAR) Mesoscale Model (MM5) over specific modeling domains set up to cover the conterminous United States. The well-known Haines Index (HI) (Haines 1988) is one of many fire-weather indices routinely provided by the FCAMMS as part of their fire-weather predictions. As an operational index for fire-weather forecasting, the HI can be considered a mesoscale-type index that characterizes the stability and moisture conditions in the lower to middle troposphere. Its value is meant to provide an indication of the atmospheric risk of extreme fire behavior due solely to these atmospheric conditions.

In: Butler, Bret W.; Cook, Wayne, comps. 2007. The fire environment—innovations, management, and policy; conference proceedings. 26-30 March 2007; Destin, FL. Proceedings RMRS-P-46CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 662 p. CD-ROM.

[1] Research Meteorologist and Meteorologist, respectively, U.S. Department of Agriculture, Forest Service, Northern Research Station, East Lansing, MI. Lead author wheilman@fs.fed.us

While the HI has proven to be a valuable tool for fire-weather forecasters in some regions of the United States, there are other atmospheric properties and processes that can affect the severity of fires, especially those properties and processes that characterize the atmospheric boundary layer where small-scale fire-atmosphere interactions are so important. Atmospheric turbulence, or wind gustiness, is one of those properties. Wind gusts are a reflection of turbulent eddies imbedded within the general circulation of air flow, with the energy associated with these eddies defined as turbulent kinetic energy (TKE). The generation and dissipation of turbulent eddies and TKE in the atmosphere are dependent on wind shear and buoyancy conditions. Strong vertical wind shears and unstable temperature lapse rates tend to increase atmospheric turbulence, while stable temperature lapse rates tend to dissipate turbulence. Predictions of TKE in the atmospheric boundary layer using the higher order level 2.5 closure from the Mellor-Yamada turbulence hierarchy (Mellor and Yamada 1974, 1982; Gerrity and others 1994) are available from the daily FCAMMS MM5 model simulations. However, unlike the HI predictions from the FCAMMS, TKE predictions have not been used in the past for characterizing atmospheric risk of extreme fire behavior.

The FCAMMS—Eastern Area Modeling Consortium (EAMC) has been investigating the utility of combining the mesoscale-type HI with TKE, a boundary-layer type index, for assessing the atmospheric potential for extreme fire behavior. For example, Heilman and others (2003) reported some initial results from an analysis of regional patterns of HI and TKE over the Northeastern United States based on daily EAMC MM5 fire-weather simulations covering the period 1 March 2003 to 18 July 2003. While the analyses were limited to the Northeast and covered a short period of time, they provided some important insight into where high HI and high TKE values typically occur in this region of the nation. The analyses also demonstrated that combining the HI and TKE via a simple product of the two indices may have some utility in predicting where both lower to middle tropospheric conditions and boundary layer conditions are especially conducive to extreme fire behavior, as shown by an application of this "combined" index to the Double Trouble State Park wildfire in New Jersey on 2 June 2002.

As a follow-up to the Heilman and others (2003) investigation, this paper describes a more comprehensive analysis of seasonal HI and TKE patterns over the western Great Lakes region of the United States derived from EAMC MM5 daily fire-weather simulations for year 2006. Comparisons of seasonal patterns of HI and TKE patterns along with analyses of the relative significance of wind shear and buoyancy effects in the atmospheric boundary layer in contributing to high TKE values when high HI values are also present provide new insight into the atmospheric dynamics that contribute to extreme fire behavior.

Haines Index Description

The well-known HI (Haines 1988) is a simple index that provides a measure of the lower to middle tropospheric instability and dryness. The index characterizes the stability and moisture content of specific atmospheric layers, depending on the elevation above sea level of the underlying terrain. The index is defined as

$$HI = \overbrace{(T_{p1} - T_{p2})}^{A} + \overbrace{(T_p - T_{dp})}^{B} \qquad (1)$$

where T_{p1} is the temperature (°C) at pressure level p1, T_{p2} is the temperature (°C) at pressure level p2, and T_p and T_{dp} are the temperature (°C) and dew-point temperature (°C), respectively, at one of the pressure levels. The pressure levels, p1 and p2, are set at 950 mb and 850 mb, respectively, for low terrain elevations; 850 mb and 700 mb, respectively, for mid terrain elevations; and 700 mb and 500 mb, respectively, for high terrain elevations. The defined low, mid, and high terrain elevation regions for the United States can be found in Haines (1988). For the HI calculations performed in this study, both the low and mid terrain elevation designations are used.

Haines (1988) defined specific temperature lapse rate and dew-point depression thresholds for the low, mid, and high terrain elevation designations. Integer values of 1, 2, or 3 are assigned to the lapse rate (A) and dew-point depression (B) components of the HI, as shown in equation 1, depending on the actual values of the lapse rates and dew-point depressions in comparison to the defined thresholds. The two integers are added to create an index varying from 2 to 6, with the following adjective definitions for the potential for large plume dominated fires:

(A + B) = 2 or 3	[very low]
(A + B) = 4	[low]
(A + B) = 5	[moderate]
(A + B) = 6	[high].

The lower to middle tropospheric temperature and dew-point temperature data required for calculating the HI typically come from radiosonde observations at 0000 UTC and 1200 UTC or from numerical weather prediction models that can provide output data specific to any time of the day. Haines Index observations or predictions are often presented in the form of maps that allow for a spatial analysis of regional patterns of the index. The HI can be classified as a mesoscale-type index because it attempts to capture the stability and moisture conditions of atmospheric layers that extend above the atmospheric boundary layer. As a mesoscale-type index, it can be useful for describing the atmospheric risk for extreme fire behavior over relatively large spatial areas. When fire plumes penetrate atmospheric layers characterized by high HI values, the potential exists for increased lofting of the plume and the downward transport of high-momentum, dry air from these layers to the surface, a potentially dangerous wildfire scenario.

Turbulent Kinetic Energy Description

While stability and moisture conditions in atmospheric layers above the boundary layer can influence fire behavior, turbulent atmospheric circulations (that is, wind gusts) within the boundary layer can also create an environment conducive to extreme fire behavior. Wind gusts are manifestations of turbulent eddies generated by wind shear and buoyancy effects, which can be large in the boundary layer. The amount of energy in these turbulent eddies is defined as turbulent kinetic energy, and is given by $0.5q^2$ where

$$q^2 = \overline{u'^2} + \overline{v'^2} + \overline{w'^2} \tag{2}$$

and $\overline{u'^2}$, $\overline{v'^2}$, and $\overline{w'^2}$ are the variances of the departure (turbulent) velocities in the horizontal x, horizontal y, and vertical z directions, respectively. Large vertical wind shears under thermally unstable (convective) conditions lead to a highly energetic turbulence regime (that is, large TKE values), whereas a thermally stable environment will tend to suppress any turbulence generated through mechanical wind shears and produce more laminar-type flows (low TKE values). Irrespective of the enhanced atmospheric turbulence generated by buoyancy and wind shears associated with a fire, an already highly turbulent atmospheric boundary layer can contribute to even more erratic fire behavior through interactions between the fire-induced and ambient boundary-layer turbulence regimes.

Simulations and predictions of TKE are possible in many of the current research and operational atmospheric mesoscale and boundary layer numerical models, including MM5. Turbulent kinetic energy can be simulated and predicted using the level 2.5 closure scheme from Mellor and Yamada (1974, 1982) given by

$$\frac{\partial}{\partial t}\left(\frac{q^2}{2}\right)+V\bullet\nabla\frac{q^2}{2}-\frac{\partial}{\partial z}\left[K_q\frac{\partial}{\partial z}\left(\frac{q^2}{2}\right)\right]=P_s+P_b-\varepsilon \qquad (3)$$

where the terms on the left side of the equation represent the local time rate of change of TKE, the advection of TKE by the three-dimensional mean wind V, and the vertical diffusion of TKE (parameterized in terms of diffusion coefficient K_q). The terms on the right side of the equation represent the production of TKE through vertical wind shear effects (P_s), the production or dissipation of TKE through buoyancy effects (P_b), and the nonbuoyant dissipation of TKE (ε) via the breakdown of turbulent eddies into smaller and smaller sizes. The production (P_s) of TKE through vertical wind shear effects is given by

$$P_s=-\overline{u'w'}\frac{\partial\overline{u}}{\partial z}-\overline{v'w'}\frac{\partial\overline{v}}{\partial z} \qquad (4)$$

and the buoyant production or dissipation (P_b) of TKE is given by

$$P_b=\frac{g}{\theta_v}\overline{\theta_v'w'} \qquad (5)$$

where g is the acceleration due to gravity, $\overline{u}$ and $\overline{v}$ are the horizontal components of the mean wind, θ_v is the virtual potential temperature, and $\overline{u'w'}$, $\overline{v'w'}$, and $\overline{\theta_v'w'}$ are the vertical turbulent fluxes of momentum and heat. The MM5 mesoscale model used in this study includes the Mellor and Yamada (1974, 1982) TKE formulation and is described in more detail by Gerrity and others (1994).

Unlike the HI, which can be easily computed from radiosonde observations or numerical model output, TKE as a potential fire-weather index has not been used extensively because it is fairly complex and is rarely, if ever, included in the suite of fire-weather variables made available to fire managers. However, the increasing availability and delivery of TKE predictions from research and development groups such as the FCAMMS have now made it possible to assess the feasibility of using TKE in some fashion as a potential fire-weather index.

Analyses of HI and TKE Patterns

The analyses presented here are built upon daily 48-hour real-time EAMC MM5 simulations (0000 UTC initialization) over a 4-km grid spacing domain covering the western Great Lakes region for the period of 1 January 2006 through 31 December 2006. Simulated patterns of the mid-afternoon frequency of occurrence of different HI and near-surface TKE values were analyzed as a first step in determining: (1) how frequently high HI values (5 or 6) occur concurrently with significant near-surface atmospheric turbulence in this region; (2) whether there are preferred locations where high HI and high near-surface turbulence tend to occur in this region; and (3) whether there is a seasonal dependence on those occurrence patterns.

Figure 1 shows the simulated frequency of occurrence of HI values equal to 5 or 6 (moderate or high atmospheric risk of large plume dominated fires) at 2000 UTC during the January-February-March (JFM), April-May-June (AMJ), July-August-September (JAS), and October-November-December (OND) periods in 2006. During the JFM period, mid-afternoon high HI values were most common over northern Iowa, southern Minnesota, western and southern Wisconsin, and central Michigan. The highest frequencies occurred over northeastern Iowa, with 25 to 30 percent of the days during this 3-month period characterized by HI values equal to 5 or 6 at 2000 UTC. During the spring and summer periods (AMJ and JAS), high HI values at 2000 UTC were more frequent and widespread in this region. HI values of 5 or 6 occurred more than 20 percent of the time at 2000 UTC over most of Minnesota, Iowa, southern Wisconsin, northern Illinois, and northern, western, and eastern Michigan. The autumn period (OND) was characterized

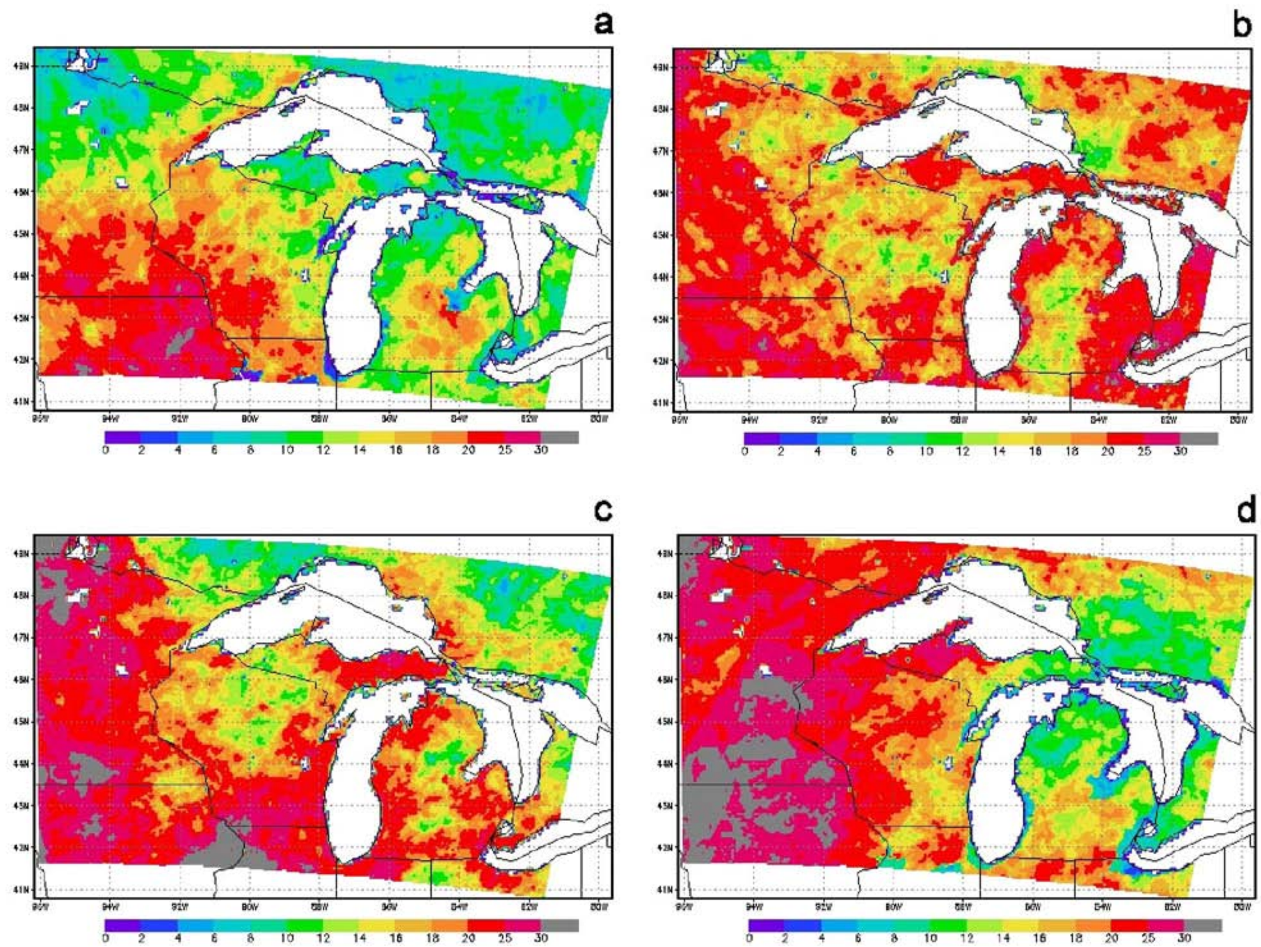


Figure 1—Simulated frequency (percent) of HI values equal to 5 or 6 at 2000 UTC for the periods (a) JFM, (b) AMJ, (c) JAS, and (d) OND in 2006.

by maximum frequencies of high HI occurrence at 2000 UTC exceeding 30 percent over large parts of Minnesota and Iowa, and minimum frequencies over much of northern Michigan. Overall, the simulated patterns of high HI occurrence over the western Great Lakes region in 2006 suggest that mid-afternoon lower to middle tropospheric stability and moisture conditions were more frequently conducive to extreme fire behavior over the western sections of the region than elsewhere during all seasons.

The simulated frequencies of occurrence of near-surface TKE values exceeding 3 m^2s^{-2} (significant turbulence) at 2000 UTC over the same four 3-month periods in 2006 are shown in figure 2. The percentage of days when near-surface turbulence was significant during the winter months (JFM) in 2006 was low over the western sections of the Great Lakes region. Only the upper peninsula and northern part of the lower peninsula of Michigan and along the shores of Lake Superior had relatively frequent occurrences of significant near-surface turbulence, generated primarily by mechanical wind shear effects. The increased stability of the atmospheric boundary layer during the winter months reduces the buoyancy contribution to TKE production. The spring months (AMJ) were characterized by increases in occurrence of high near-surface turbulence over the upper peninsula and northern sections of the lower peninsula of Michigan, northern Wisconsin, and large areas of Minnesota and Iowa. More than 30 percent of the days in some of these areas had near-surface TKE values exceeding 3 m^2s^{-2} at 2000 UTC. Overall frequencies of occurrence of high near-surface

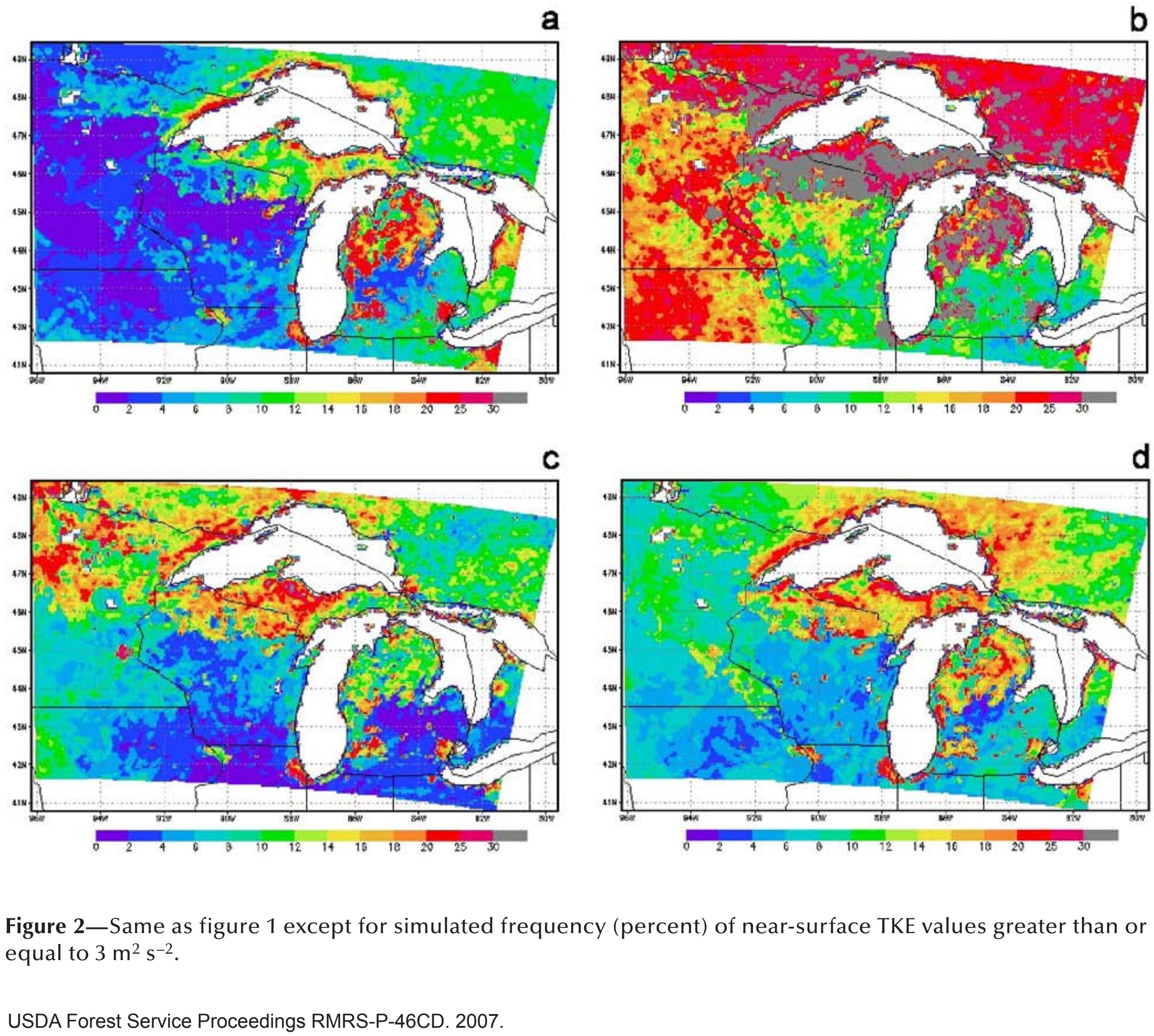


Figure 2—Same as figure 1 except for simulated frequency (percent) of near-surface TKE values greater than or equal to 3 m^2 s^{-2}.

turbulence were lower during the summer (JAS) and autumn (OND) periods over the western Great Lakes region in comparison to the maximum frequencies observed during the spring months.

A comparison of the HI and TKE frequency of occurrence maps in figures 1 and 2, respectively, reveals that large HI values in 2006 often did not occur in the same areas where large near-surface TKE values occurred. In fact, episodes of concurrent high HI and near-surface TKE values were infrequent. This suggests that combining the HI and near-surface TKE in some fashion could produce a highly discriminatory index that captures those relatively rare events when both the atmospheric mesoscale environment, as quantified by the HI, and the atmospheric boundary-layer environment, as quantified by near-surface TKE, are highly conducive to extreme fire behavior. One possible way of combining the indices is to simply take the product of the two indices. Figure 3 shows the simulated frequency of occurrence at 2000 UTC of episodes where HI x TKE > 15, a threshold meant to roughly capture those cases when the HI and TKE values are greater than or equal to 5 and 3 m^2s^{-2}, respectively. Over much of the western Great Lakes region, the occurrence of concurrent high values of HI and near-surface TKE in 2006 was relatively rare. It was only during the spring season (AMJ) that frequencies of occurrence above about 10 percent were common over large sections of Minnesota, Wisconsin, and Michigan. Frequencies above 20 percent also

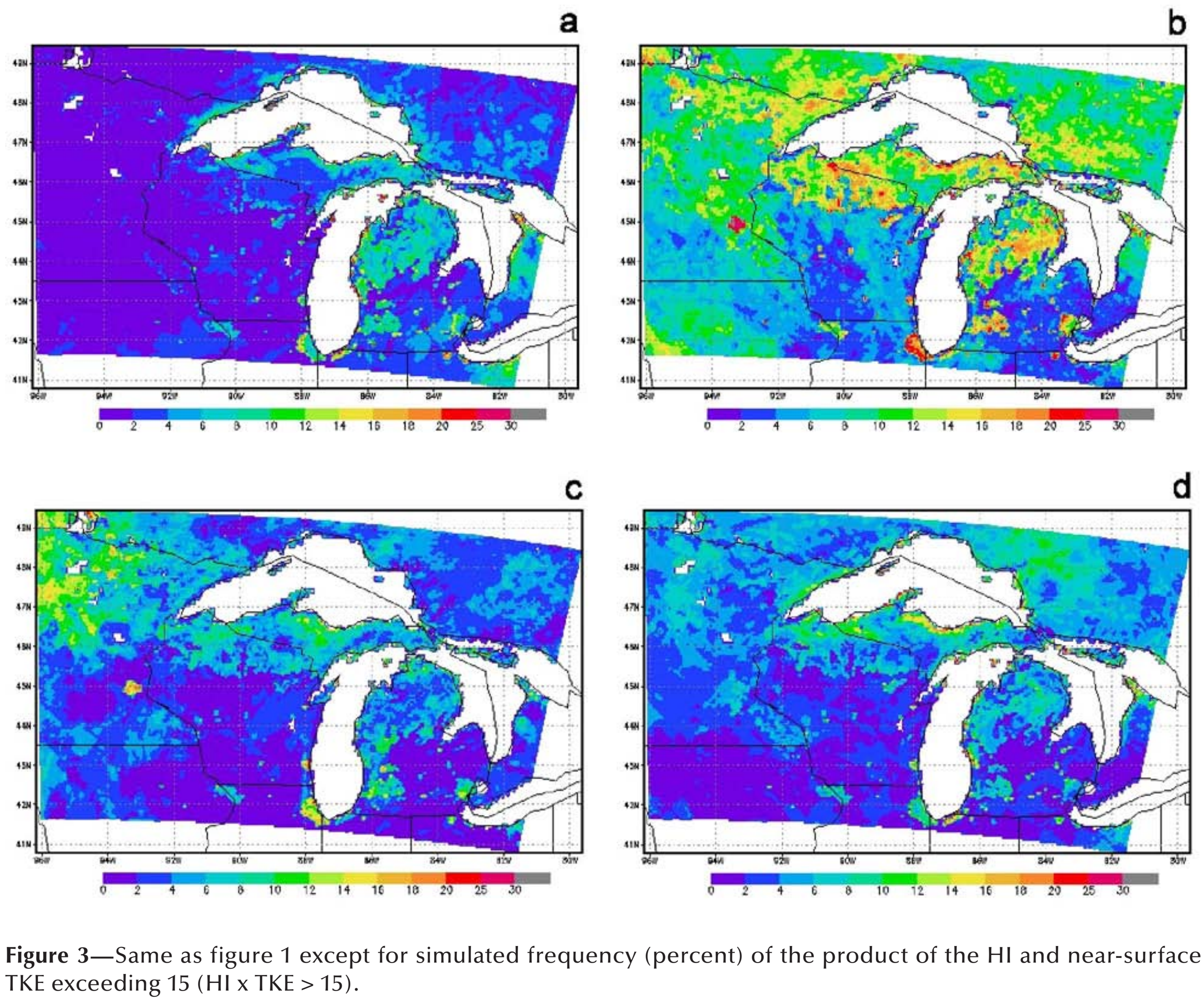


Figure 3—Same as figure 1 except for simulated frequency (percent) of the product of the HI and near-surface TKE exceeding 15 (HI x TKE > 15).

characterized the local urban areas of Minneapolis, Chicago, Milwaukee, and Detroit during the spring. During the summer months (JAS), the highest frequencies (~10 to 15 percent) occurred over northern Minnesota and these same urban areas. Frequencies in the fall were generally less than 10 percent everywhere except along the southern shore of Lake Superior.

Fire Case Studies

In order to test the feasibility of combining the Haines Index and TKE for assessing the atmospheric mesoscale and boundary layer risk of extreme fire behavior, preliminary analyses were carried out to determine the behavior of the product of HI and near-surface TKE values during actual wildland fire events in the western Great Lakes region in 2006. Twenty-one wildland fire cases in the western Great Lakes region were identified in 2006, ranging from 100 to nearly 32,000 acres in size. For each wildland fire case, the HI, near-surface TKE, and the product of the HI and TKE were computed each hour for the entire duration of the fire at locations corresponding to each wildland fire event (based on archived, real-time hourly output from the EAMC MM5 daily fire-weather simulations over the western Great Lakes region). Results from those simulations are shown in table 1. The five largest fires all had occurrences of maximum HI x TKE values greater than 15, with the largest value (32.196) observed during the Cavity Lake Fire in the Boundary Waters Canoe Area of northern Minnesota. Significant near-surface turbulence (TKE > 3 m^2s^{-2}) was simulated during these fires, with HI values ranging from 4 to 6 at the time

Table 1—Maximum values of the product of the Haines Index (HI) and near surface turbulent kinetic energy (TKE), and the dates, times, and Richardson number (Ri) values when the HI x TKE maximum values occurred during selected wildland fire episodes in the western Great Lakes region in 2006. Values of maximum HI x TKE exceeding the threshold of 15 are shown in bold.

Fire name	Start date	End date	HI	TKE	Max. HI*TKE	Date:time (UTC) of max HI x TKE	Ri	Acres burned
Cavity Lake	7/14	9/1	6	5.366	**32.196**	07/17: 0200	-0.314	31,830
Peatland	10/6	10/8	4	8.214	**32.856**	10/08: 1900	-0.018	6,625
East Zone Cmp.	9/8	10/1	5	6.282	**31.410**	09/22: 2300	-0.005	5,898
Red Lake 16	4/6	4/7	4	5.253	**21.012**	04/06: 2300	-0.028	3,650
Turtle Lake	7/13	8/3	4	4.651	**18.604**	07/16: 0300	-0.012	2,085
Grain Bin	4/26	4/27	5	2.519	12.595	04/26: 2000	-0.280	1,496
20 Mile	4/26	4/27	5	2.519	12.595	04/26: 2000	-0.280	1,456
Cederbend	11/21	11/22	5	1.232	6.160	11/23: 0600	0.036	727
Trail	4/10	4/11	6	3.068	**18.408**	04/11: 2300	-0.012	676
Richardville	4/22	4/23	5	2.214	11.070	04/24: 0000	-0.124	640
Red Lake 197	4/16	4/16	5	1.815	9.075	04/16: 1900	-0.281	550
Black River	4/16	4/17	5	0.620	3.100	04/17: 0300	-0.140	500
Easter Sunday	4/16	4/17	6	1.565	9.390	04/16: 2000	-0.026	348
Parkers Prairie	4/9	4/11	4	1.798	7.192	04/09: 2000	-0.028	326
Sharptail Burn	4/17	4/18	4	3.222	12.888	04/17: 2000	-0.280	317
219	7/19	7/24	5	5.735	**28.675**	07/19: 1900	-0.078	240
Shack	4/6	4/7	3	4.655	13.965	04/07: 0000	-0.012	200
Clementson	9/4	9/12	5	1.817	9.085	09/05: 1900	-6.807	149
Hammer	11/9	11/10	5	2.131	10.655	11/09: 0700	-0.002	115
Keystone	8/3	8/5	4	0.565	2.260	08/05: 0700	-0.184	106
Wobble Grade	7/12	7/13	6	1.418	8.508	07/12: 2000	-2.992	100

when maximum HI x TKE values were simulated. Fourteen of the 21 fire cases included in this study had simulated maximum HI x TKE values less than 15. Most of the maximum HI x TKE values during the analyzed fires occurred in the local afternoon or evening hours.

The application of a combined HI and near-surface TKE for spatially pinpointing where atmospheric mesoscale and boundary layer conditions are both highly conducive to extreme fire behavior was tested for the Cavity Lake Fire that burned nearly 32,000 acres from 14 July to 1 September 2006. Figure 4 shows the simulated patterns of HI, near-surface TKE, and HI x TKE values at 0200 UTC on 17 July 2006 (9:00 pm CDT on 16 July 2006). Most of the western Great Lakes region had HI values of 5 or 6 at this time, with large areas of HI = 6 covering parts of Minnesota, Wisconsin, and Michigan (fig. 4a), including the Boundary Waters Canoe Area of northern Minnesota. Significant near-surface turbulence (TKE > 3 m^2s^{-2}) also occurred in the region at this time, but was confined to much smaller areas located over northern Minnesota, southwestern Minnesota, northern Wisconsin, and parts of northern and western Michigan (fig. 4b). Figure 4c shows the spatial pattern of the product of the HI and near-surface TKE across the region, and clearly indicates that the mesoscale and boundary-layer conditions were highly conducive to extreme fire behavior in the BWCA of Minnesota where the Cavity Lake Fire was spreading rapidly at the time (McDaniel 2006). Values of HI x TKE exceeded 20 over much of the arrowhead region of northern Minnesota.

The product of the HI and near-surface TKE presented here represents a simple means of combining the two indices for capturing the concurrent atmospheric mesoscale and boundary layer risk of extreme fire behavior. The preliminary analyses of case studies carried out in this study suggest that computing the product may provide a useful tool for predicting when and where the stability/moisture conditions in the lower and middle troposphere and atmospheric boundary-layer turbulence could all contribute to extreme fire behavior at the same time, a relatively rare but dangerous situation.

Haines Index and Turbulence Dynamics

Beyond the spatial and temporal variability patterns of the HI and near-surface TKE in the western Great Lakes region, the atmospheric dynamics associated with concurrent lower tropospheric instability and dryness (as measured by the HI) and near-surface turbulence (as measured by TKE) are also of interest. As part of our analyses, we examined how the mid-afternoon production of near-surface turbulence through wind shear and buoyancy processes (equations 3 through 6) varied with changing HI values during each season in 2006 across the western Great Lakes region. Figure 5 shows the frequency distribution of simulated near-surface TKE values at 2000 UTC for all HI classes for the JAM, AMJ, JAS, and OND periods in 2006. Considering all HI classes (2 through 5), mid-afternoon TKE values between 0 and 1 m^2s^{-2} were most common across the western Great Lakes region during the winter (2,530,087 occurrences – 53.9 percent; fig. 5a), summer (2,191,371 occurrences – 39.0 percent; fig. 5e), and fall (2,781,916 occurrences – 49.0 percent; fig. 5g) seasons. During the spring season, mid-afternoon TKE values between 1 and 2 m^2s^{-2} were most common in the region (1,887,489 occurrences – 34.4 percent; fig. 5c). The occurrence of mid-afternoon TKE values greater than 3 m^2s^{-2} for all HI classes was a relatively rare event. The percentages of all model grid points having TKE

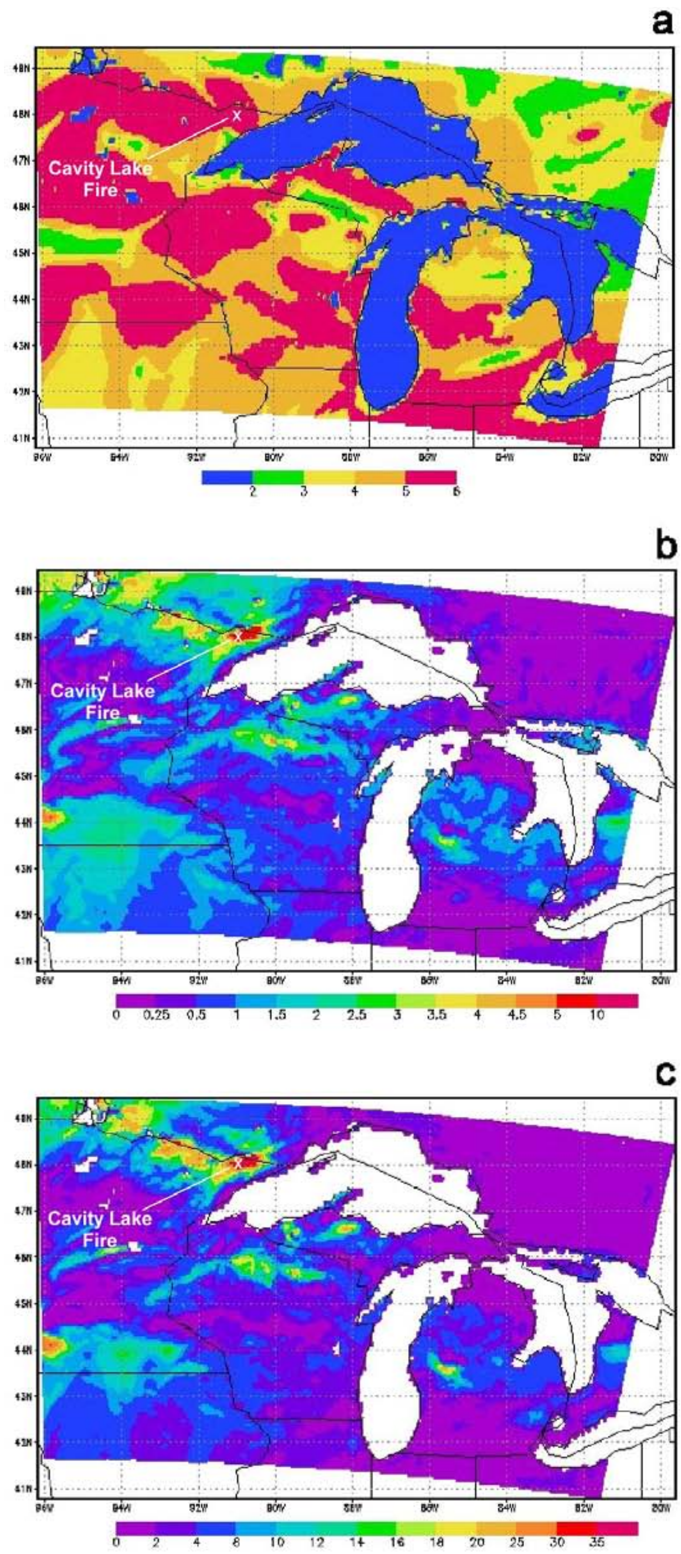


Figure 4—Simulated patterns of (a) HI, (b) near-surface TKE (m^2s^{-2}), and (c) HI x TKE at 0200 UTC on 17 July 2006. The location of the Cavity Lake Fire in northern Minnesota is highlighted with an "x" in each figure.

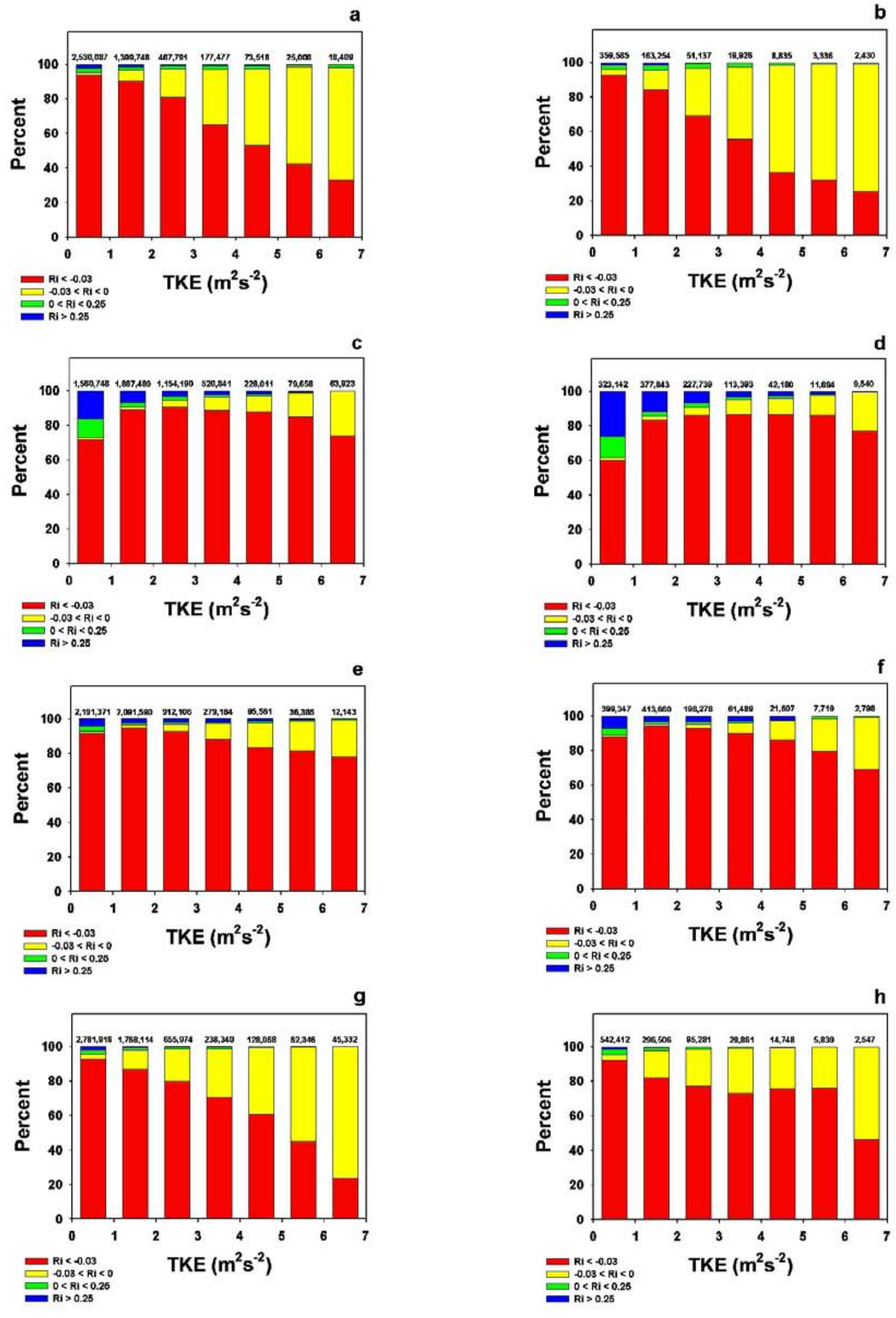


Figure 5—Frequency of occurrence (percent) of simulated near-surface TKE values in bins 0-1, 1-2, 2-3, 3-4, 4-5, 5-6, and > 6 m^2s^{-2} for all HI classes (2-6) (a, c, e, g) and for the high HI classes (5-6) (b, d, f, h) during the JFM (a and b), AMJ (c and d), JAS (e and f), and OND (g and h) periods in 2006 over the western Great Lakes region. The numbers at the top of each stacked bar indicate the total number of occurrences of TKE values within each bin, while the different colors indicate relative TKE occurrence percentages under different Richardson number (Ri) categories.

values greater than 3 m^2s^{-2} at 2000 UTC in the winter, spring, summer, and fall seasons were 6.3, 16.2, 7.5, and 8.4 percent, respectively.

When only the high HI classes are considered (HI = 5 or 6), mid-afternoon TKE values between 0 and 1 m^2s^{-2} were most common during the winter (JFM) (359,585 occurrences – 59.1 percent; fig. 5b) and autumn (OND) (542,412 occurrences – 54.9 percent; fig. 5h) seasons in 2006. The spring (AMJ) (377,843 occurrences – 34.2 percent; fig. 5d) and summer (JAS) (413,660 occurrences – 37.4 percent; fig. 5f) seasons had more occurrences of mid-afternoon TKE values in the 1-2 m^2s^{-2} range than any other range. The occurrence of mid-afternoon TKE values greater than 3 m^2s^{-2} was still a relatively rare event even when HI values reached 5 or 6 in 2006. The percentages of all model grid points having TKE values at 2000 UTC greater than 3 m^2s^{-2} were 5.7, 16.1, 8.6, and 5.4 percent for the winter, spring, summer, and fall seasons, respectively.

Figure 5 also provides insight into the relative significance of vertical wind shear and buoyancy in the production and/or dissipation of near-surface turbulence under low or high HI conditions, as measured by the gradient Richardson number (Ri):

$$Ri = \frac{g}{\theta}\frac{\partial\theta / \partial z}{\left(\partial U / \partial z\right)^2 + \left(\partial V / \partial z\right)^2} \qquad (6)$$

where g is the gravitational constant and θ is the potential temperature. As Ri becomes more negative, the production of turbulence through vertical wind shears becomes less and less important compared to the production of turbulence through buoyancy. When Ri is less than about –0.03, buoyancy completely dominates the production of turbulence. For $-0.03 < Ri < 0$, both shear and buoyancy effects play a role in the production of turbulence. Positive values of Ri indicate that buoyancy is acting to suppress turbulence generated by vertical wind shears, with complete suppression of turbulence occurring when $Ri \geq 0.25$. As shown in figure 5, buoyancy effects dominated the production of TKE ($Ri \leq -0.03$) at 2000 UTC during the spring (fig. 5c,d) and summer (fig. 5e,f) periods regardless of the amount of turbulence (that is, TKE) present or the values of the mesoscale HI. However, for the winter (fig. 5a,b) and fall (fig. 5g,h) periods, there was a significant drop-off (increase) in the frequency of occurrence of buoyancy-dominated (shear-dominated) turbulence regimes as TKE increased. Unlike the other seasons in 2006, the spring months were characterized by numerous occurrences of $Ri \geq 0.25$ and $0 \leq Ri < 0.25$ when near surface turbulence was weak (TKE < 2 m^2s^{-2}) (fig. 5c,d).

Summary

We have followed up our initial study of HI and TKE behavior in the Northeastern United States region (Heilman and others 2003) with a new study that is examining the utility of combining the HI, a mesoscale-type fire weather index, with near-surface TKE, a boundary-layer-type index, for assessing the potential atmospheric risk of extreme fire behavior in the western Great Lakes region. Using the daily, MM5-based fire-weather predictions now readily available from the EAMC, we identified the 2006 seasonal patterns of occurrence of high HI, high near-surface TKE, and concurrently high HI and TKE, expressed as the product of the two indices. Broad areas of the western Great Lakes region experienced high mid-afternoon (2000 UTC) HI values (5 or 6) on more than 20 percent of the days during each season, with the highest frequencies of occurrence happening in the summer (JAS) and fall (OND) seasons over Iowa and Minnesota. The high HI occurrence patterns differ significantly from the frequency of occurrence patterns of high near-surface TKE (> 3 m^2s^{-2}). Episodes of significant, mid-afternoon near-surface turbulence were most common over the northern sections of Michigan, Wisconsin, and/or Minnesota, with the highest frequencies of occurrence (>30 percent of the days) associated with the spring (AMJ) period in these areas. The contrasting patterns of occurrence for these two indices during all seasons suggest that episodes of high HI and high near-surface turbulence at the same time, a potentially dangerous fire-weather condition, are relatively infrequent in this region of the United States. However, this infrequency does provide an opportunity for combining the Haines and TKE indices in some fashion so that the timing and location of these rare but important events can be anticipated.

In this study, the HI and near-surface TKE values were combined via a simple product of the two, and seasonal patterns of occurrence of HI x TKE exceeding 15 across the western Great Lakes region during 2006 were examined. Like the high near-surface TKE patterns of occurrence, mid-afternoon (2000 UTC) occurrences of HI x TKE exceeding 15 were most frequent in the spring over the northern sections of Michigan, Wisconsin, and Minnesota. The urban areas of Minneapolis, Milwaukee, Chicago, and Detroit also had occurrence maxima during the spring. Although the occurrence of high HI and high near-surface TKE at the same time may be relatively rare in this region, the simulation results from 2006 suggest that when it does happen, it tends to occur in those areas of the region that are most prone to wildfires (that is, northern Michigan, northern Wisconsin, and northern Minnesota) and during the springtime when wildfires in the region are most common.

The application of a new index based on the simple product of predicted HI and near-surface TKE values to actual western Great Lakes wildland fire episodes in 2006 suggests that this type of index may be a useful tool for pinpointing when and where atmospheric stability, moisture, and boundary-layer turbulence may collectively contribute to creating an ambient local atmospheric environment highly conducive to extreme fire behavior. The five largest wildlfires in the western Great Lakes region in 2006 occurred in locations where and during periods when the product of the HI and near-surface TKE exceeded a threshold (15) indicative of dry, unstable middle tropospheric layers above a highly turbulent boundary layer. Further testing of this type of combined index is planned for the western Great Lakes region and other regions of the United States via the regional modeling activities in the EAMC and other modeling consortia in the FCAMMS.

The primary mechanism responsible for mid-afternoon turbulence generation in atmospheric boundary layers over the western Great Lakes region during the spring and summer seasons in 2006 was buoyancy, regardless of the level of turbulence present or the value of the mesoscale HI. During the winter and fall seasons, large TKE values were more frequently associated with shear-dominated turbulence regimes than buoyancy-dominated regimes. This suggests that during the springtime wildfire season in the western Great Lakes region, atmospheric instability within the atmospheric boundary layer and above is more often than not the primary factor in generating near-surface turbulence that can interact with wildland fires. However, significant near-surface turbulence generated by ambient vertical wind shears can certainly create atmospheric environments conducive to erratic fire behavior, as shown by the Ri values ($-0.03 < Ri < 0$) for four of the five largest analyzed fires in this study and for five of the seven analyzed fires that had maximum HI x TKE values exceeding the 15 threshold (table 1).

The analyses described here represent the first step in assessing the feasibility of combining the HI with near-surface TKE for fire-weather predictions in different regions of the United States. Additional analyses of HI and TKE behavior for the Northeast and for years prior to 2006 will be carried out using the historical MM5 output data archive developed by the EAMC as part of its fire-weather prediction program. With these analyses and our further examinations of the dynamic behavior of the HI and near-surface TKE before and during actual wildland fire events, we hope to not only improve our understanding of atmospheric mesoscale and boundary-layer interactions during fire-weather events, but also to determine the potential for combining these indices in some fashion for enhancing operational forecasts of extreme fire weather and fire behavior.

References

Gerrity, J.P.; Black, T.L.; Treadon, R.E. 1994. The numerical solution of the Mellor-Yamada level 2.5 turbulent kinetic energy equation in the ETA model. Monthly Weather Review. 122:1640-1646.

Haines, D.A. 1988. A lower atmospheric severity index for wildland fires. National Weather Digest. 13:23-27.

Heilman, W.E.; Bian, X.; Charney, J.; Potter, B. 2003. Combining the Haines Index and turbulent kinetic energy for fire-weather predictions. 5th Symposium on Fire and Forest Meteorology, 16-20 November 2003, Orlando, FL. American Meteorological Society, Boston, MA. [On CD-ROM]

McDaniel, J. 2006. That thing was rolling: the Cavity Lake Fire in the Boundary Waters Canoe Area Wilderness. Wildland Fire Lessons Learned Center, National Wildfire Coordinating Group. [On line]. Available: <http://www.wildfirelessons.net/Additional.aspx?Page=74>

Mellor, G.L.; Yamada, T. 1974. A hierarchy of turbulence closure models for planetary boundary layers. Journal of the Atmospheric Sciences. 31:1791-1806.

Mellor, G.L.; Yamada, T. 1982. Development of a turbulence closure model for geophysical fluid problems. Reviews of Geophysics and Space Physics. 20:851-875.

USDA Forest Service. 2002. National Fire Plan research and development – 2001 business summary. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Research Station. 29 p.

Moisture Dynamics in Masticated Fuelbeds: A Preliminary Analysis

Jesse Kreye[1] and J. Morgan Varner[1]

Abstract*—Mastication has become a popular fuels treatment in the Western United States, but predicting subsequent fire behavior and effects has proven difficult. Fire behavior and effects in masticated fuelbeds have been more intense and erratic in comparison with model predictions. While various particle or fuelbed characteristics in these fuels may contribute to the inaccuracy of model predictions, an increase in particle surface area to volume ratio by the mastication process may affect moisture dynamics. The prediction of fuel moisture is critical to predicting fire behavior and effects in prescribed fire or wildfire scenarios. Moisture dynamics in masticated fuels is characterized here by analyzing desorption rates in masticated and intact manzanita and compared with pine and maple dowels under laboratory experiments. Preliminary analysis shows that desorption rates are similar in masticated and intact manzanita as well as pine dowels by comparing relative moisture contents throughout desorption as well as by calculating response times using the timelag concept. These results held true both at the particle and fuelbed level, although masticated manzanita and pine dowels were both found to desorb moisture more quickly as individual particles compared to within fuelbeds. Particle density was strongly linked to desorption although it is not fully explored in terms of its significance as compared with other physical properties. Physical and chemical differences due to particle weathering and species differences may play significant roles as well. While this may be some of the first work to address the effects of mastication on moisture dynamics in forest fuels, future work should focus on other aspects where fuelbed or particle characteristics in masticated fuels may influence fire behavior and effects.*

Introduction

Mechanical mastication of forest fuels has become a popular method of reducing fire risk by disrupting the vertical continuity of shrub and small-tree fuels. While mastication projects are being conducted over large areas in the Western United States, little is known about the effects of mastication on subsequent fire behavior. Prescribed fires have occurred within masticated sites resulting in unexpected fire behavior and effects (Knapp and others 2006). Currently, fire modeling systems are poor at predicting fire behavior parameters in these types of treatments. Changes in moisture dynamics due to increases in surface area:volume ratios associated with the fractured nature of masticated fuels may be a primary reason for inaccurate fire behavior predictions.

Fuel moisture is a primary predictor of fire behavior. Understanding the response of fuel moisture to changes in environmental conditions is required to predict daily or seasonal fuel moisture. The adsorption and desorption of moisture in fuels during a change in environmental conditions occur differently (Blackmarr 1971) and are referred to as sorption hysteresis. The resulting

In: Butler, Bret W.; Cook, Wayne, comps. 2007. The fire environment—innovations, management, and policy; conference proceedings. 26-30 March 2007; Destin, FL. Proceedings RMRS-P-46CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 662 p. CD-ROM.

[1] Graduate Student and Assistant Professor, respectively, Department of Forestry and Watershed Management, Humboldt State University, Arcata, CA. Lead author jkreye@suddenlink.net

equilibrium moisture content following desorption is higher than the equilibrium moisture content resulting from the adsorption process across various environmental conditions (relative humidity and temperature). Desorption of moisture is critical because it occurs when fuels are drying in response to decreases in relative humidity and/or increases in ambient air temperature. The irregular shape of masticated fuel particles, resulting in a higher surface area to volume ratio, may affect the way in which fuel moisture responds to diurnal or seasonal changes in environmental conditions. Fuel moisture values that are input into fire behavior/effects models and fire danger rating systems (for example, BehavePlus and NFDRS) are often estimated from the weighing of standard ½ inch ponderosa pine dowels.

To address the deficiencies in prediction of fire behavior in masticated fuelbeds we evaluated fuel moisture during desorption in mechanically masticated fuels (*Arctostaphylos manzanita ssp. wieslanderi*) at the particle and fuelbed scale and compared them to standard fuels (*Pinus ponderosa*) as well as similar density fuels (*Acer* sp.). Two experiments were conducted addressing: (1) desorption at the individual particle level and (2) desorption at the fuelbed level. The results presented here are a preliminary analysis, and ongoing research is currently investigating site, species, and time since treatment level differences.

Methods

Mechanically masticated fuels were collected from a fuelbreak in the Six Rivers National Forest near the community of Mad River, CA, approximately 50 miles east of the Pacific Ocean. The site was dominated by dense common manzanita (*Arctostaphylos manzanita ssp. wieslanderi*) greater than 6 ft tall prior to treatment. The elevation of the study site is 940 ft with a 6 percent slope and a NW aspect. Mastication was conducted in December 2004. Within the site, all woody fuels were collected from the surface down to mineral soil at four 2 x 2 m plots. Collected fuel was transported to the laboratory for desorption experiments under controlled conditions. Desorption experiments were conducted on individual fuel particles (experiment 1) as well as constructed fuelbeds (experiment 2). Desorption rates were analyzed in two ways: (1) by comparing relative moisture contents over time using analysis of variance and (2) by estimating response times in terms of the original timelag concept as developed by Byram (1963).

Experiment 1

Masticated manzanita particles with an average diameter between 6.35 mm (¼ inch) and 25.4 mm (1 inch) were selected (n=19) for analysis of moisture desorption along with 1.27 x 12.7 cm (½ inch x 5 inch) standard ponderosa pine dowels (n=10) for comparison. Masticated particles were measured for minimum and maximum diameter at two equidistant locations along the longitudinal axis of the particle. The arithmetic mean of the four measurements was used as average diameter. Specific gravity of masticated fuels and pine dowels was measured by submersion of individual particles in water and measuring the resulting buoyant force as recorded on a balance whereby

$$specific\ gravity = oven\ dry\ weight\ (g)\ /\ buoyant\ force\ (g)$$

Masticated manzanita particles and pine dowels were oven dried at 60 °C for 72 hours, weighed, and submerged in a water bath for 7 days. Following the water bath all particles were weighed and subsequently placed in a temperature and humidity controlled room (4.5 x 3.2 m). Temperature and humidity were controlled at 28 percent relative humidity (± 2.7 percent) and 23 °C (± 1.6 °C) by sealing off all ventilation and the use of a Comfort-Aire® BHD-301 electronic dehumidifier. All particles were placed on racks to allow desorption of moisture until equilibrium moisture content was reached. Fuel particles were weighed periodically for 384 hours during the desorption process. Temperature and relative humidity data were recorded hourly throughout the experiment.

Moisture content (*m*) of fuel particles at time *t* was calculated by

$$m_t = (\text{fuel weight}_t - \text{oven dry weight}) / \text{oven-dry weight}$$

Fuel moisture content was converted to relative moisture content (Fosberg 1970) for comparing desorption rates and to estimate time lag response times by

$$E = (m_t - m_f) / (m_i - m_f)$$

where:

E = relative moisture content
m_t = moisture content at time t
mf = final moisture content
mi = initial moisture content

Relative moisture was compared across time periods (t = 0, 10, 24, 50, 100, and 288 hours) between masticated manzanita and pine dowels using GLM analysis of variance. Relative moisture contents were regressed with specific gravity as well as average diameter for both fuel types at time periods (t = 10, 24, 50, 100, 288 hours). Specific gravity was regressed with average diameter as a predictor for both fuel types as well.

The timelag concept developed by Byram (1963) is a common method of describing moisture responses in fuels resulting from changes in environmental conditions. Relative moisture content (*E*) is the remaining fraction of moisture that is evaporable at a specific time during desorption from initial moisture content to an equilibrium moisture content following a change in temperate and/or relative humidity. Nelson (1969) described the timelag parameter as characteristic of physical and chemical processes that follow an exponential decay function and that *E* could be described in terms of response time (τ) by

$$\frac{m_t - m_f}{m_i - m_f} = E = Ke^{-\frac{t}{\tau}}$$

where

K = 1 when at t = 0, $m_t = m_i$
e = base of natural logarithm
t = time (hours)
τ = response time (hours) for which 1/e (.368) of the change between two steps remains

The logarithmic form of this equation (below) can be differentiated to calculate the rate of change in relative moisture content and the resulting slope defined in terms of τ since the logarithmic form will be linear under the theoretical negative exponential function. Response time can then be calculated by solving this equation for τ.

$$\frac{d}{dt}(\ln E) = -\frac{1}{\tau}$$

Empirical studies (Anderson 1990; Mutch and Gastineau 1970; Nelson 1969) have shown that moisture response in forest fuels does not follow a pure negative exponential function. Different techniques have therefore been used to describe response times (τ) throughout desorption and adsorption processes. While response time may be thought of in terms of the time required for 63.2 percent (1 – 1/e) of the total change to occur as moisture is adsorbed or desorbed from an initial stable state to that of equilibrium at another stable state, this response time fluctuates throughout the process. Since moisture response does not follow a pure exponential decay function, the derivative of its true function should result in a nonlinear function where its slope will not be constant. Response time (τ) fluctuates throughout the process because the instantaneous rate of change along the differentiated logarithmic form of *E* changes across time (t). The instantaneous rate of change at a single time (t) can result in the calculation of a constant response time (τ), but may only be true at that particular time point.

It is common to plot *E* as a function of time (t) on a semilogarithmic axis and the resulting curves partitioned into separate linear portions. Response times are then calculated for the separate linear sections. Nelson (1969) described two timelags, or "response times," τ_1 and τ_2, which represent the initial stage of drying and the final stage of drying, respectively, but these were separated by a curvilinear portion in the middle. Mutch and Gastineau (1970) found two linear portions occurred in desorption and adsorption of reindeer lichen. Anderson (1990) studied more than one timelag period whereby E = 0.63, 0.86, and 0.95, respectively, for the first three timelag periods. All of these studies have used standard conditions of 80 °F and a step change from 90 percent RH to 20 percent RH for desorption and the reverse for adsorption. Qualitative analysis can be conducted by plotting *E* over time on a semilogarithmic axis and comparing different fuel types in terms of response times over various described timelag sections to show the variation in moisture response of different fuels as Anderson (1990) did with Douglas-fir needles, lodgepole pine needles, ½ inch square pine sticks, and lichen. Linton (1962) and Viney and Hatton (1989) described a different use of the term "timelag" in regard to the lag time of fuel moisture behind that of a theorized equilibrium moisture content that would occur on a diurnal cycle of changing temperature and relative humidity under field conditions. Viney and Hatton (1989) and Viney and Catchpole (1991) therefore suggested using the term "response time" as the time with which 63.2 percent of evaporable moisture content has been lost between a shift in two stable conditions, which usually occurs under laboratory experiments. Nonetheless the timelag concept and the use of "response times" are widely used in fire and fuels research and management and can be analyzed through empirical methods without having detailed information regarding specific fuel characteristics.

To address this nonlinearity in the research presented here, piecewise polynomial curve fitting was conducted to separate plots of the natural logarithm of E over desorption time (t) into two linear portions for both fuel types over 7 days of desorption. Linear-linear piecewise models were used to partition the curves into two (τ_1 and τ_2) timelag sections. Response times (τ) were then calculated for each timelag section. A response time for the entire desorption process (T), whereby 63.2 percent of the evaporable moisture had in fact been lost, was compared with calculated response times of timelag sections τ_1 and τ_2 for each fuel type. This response time (T) is not defined by the differential equation above, but rather by estimating the average time that 63 percent of the evaporable moisture had in fact been lost within each fuel type during desorption experiments.

Experiment 2

Twelve fuelbeds were created using masticated manzanita particles from the Mad River fuel break. Fuels were separated into traditional 1-hour (<6.35 mm diameter) and 10-hour (6.36 to 25.4 mm diameter) fuel categories. Fuels greater than 25.4 mm in diameter were excluded from experimentation because they compose a minor component of fuel loading in masticated sites in the region (Kane and others 2006). Each fuelbed was constructed of 294 g of 1-hour fuels and 435 g of 10-hour fuels, matching proportions and loading of masticated fuels on the site (Kane and others 2006). Fuelbed heights were 5 to 7 cm and were created in 26 x 38 cm aluminum baking pans.

Five manzanita particles between 6.36 and 25.4 cm average diameter (10-hour fuels) were selected within each fuelbed and marked with wire and metal tags. Two of these manzanita particles were intact while three were fractured from mastication. Intact particles did not appear to be physically altered, or fractured, by the mastication process. These five marked particles were placed at the upper layer of their respective fuelbeds whereby the upper surface of each was exposed to the atmosphere directly above the fuelbed, representing the driest portion of the fuelbed.

Pine (*Pinus ponderosa*) and maple (*Acer* sp.) dowels were also marked with wire and tags and added to all fuelbeds. Two pine dowels (12.5 x 127 mm) and two maple dowels (12.8 x 127 mm) were placed at the upper layer of each fuel bed to compare moisture dynamics with that of the manzanita particles.

All fuelbeds were submerged in a water bath for 7 days, drained and placed in the humidity-controlled environment as in experiment 1. Temperature and humidity were controlled at 31 percent relative humidity (± 3.4 percent) and 24 °C (± 1.0 °C). Holes were placed in the bottoms of each pan and pans were elevated on wooden slats to allow excess moisture to drain throughout desorption. Fuelbeds were allowed to desorb moisture for 336 hours. Fuelbeds and marked particles were weighed throughout the experiment. Average diameters of all particles (manzanita, pine dowels, and maple dowels) were then measured in the same manner as experiment 1. Fuelbeds were oven dried at 60 °C for 72 hours. Specific gravity for all marked particles was calculated using the same methods as experiment 1. Fuel moisture content and relative moisture content values were calculated for marked particles and the fuelbeds themselves. For fuelbed moisture content, weights of pine and maple dowels were subtracted at each time point to obtain fuelbed moisture values of the manzanita particles exclusively.

Specific gravity was compared across fuel types using GLM analysis of variance (see table 1 in the Results section). Relative moisture content was compared between the following fuel types: masticated manzanita, intact manzanita, pine dowels, and maple dowels, at time periods 10, 24, 50, 100, and 288 hours using GLM analysis of variance. Timelag response times were calculated using the same methods as experiment 1 for all four fuel types from individual marked particles. Response times were also calculated for the 12 fuelbeds. Results of timelag response times for both experiments 1 and 2 were combined and reported under experiment 2 results (see table 2 in the Results section).

Results

Desorption Experiment 1

Average diameters of masticated manzanita particles (n=19) ranged from 7.84 to 20.44 mm, while diameters of pine dowels (n=10) ranged from 12.34 –12.57 mm. Masticated manzanita particles were significantly higher in density with a mean specific gravity of 0.69 (±0.011) as compared with pine dowels with a mean specific gravity of 0.48 (±0.025).

Relative moisture content did not differ significantly between masticated manzanita fuels and pine dowels (fig. 1) across time periods t = 0, 10, 24, 50, 100, 288 hours (α = 0.05). Variation in relative moisture content appears to be higher in masticated manzanita than that of pine dowels (fig. 2), although the Levene's test rejected homogenous variance between fuel types at 10 hours of desorption only.

Average diameter and specific gravity were related (r^2 = 0.427) within masticated manzanita particles, but not within pine dowels (r^2 = 0.002; fig. 3). In masticated manzanita linear regression resulted in a stronger relationship between relative moisture content and diameter in early stages of desorption (fig. 4), while relative moisture content had a stronger relationship with specific gravity in later stages. Relationships of relative moisture content with both diameter and specific gravity became less strong as particles approached equilibrium moisture content. In ponderosa pine dowels relative moisture content was strongly related to specific gravity in early stages also (fig. 5), but relative moisture content and average diameter was not related at all. It of course should be noted that variation in diameters of pine dowels was minuscule and these results were expected.

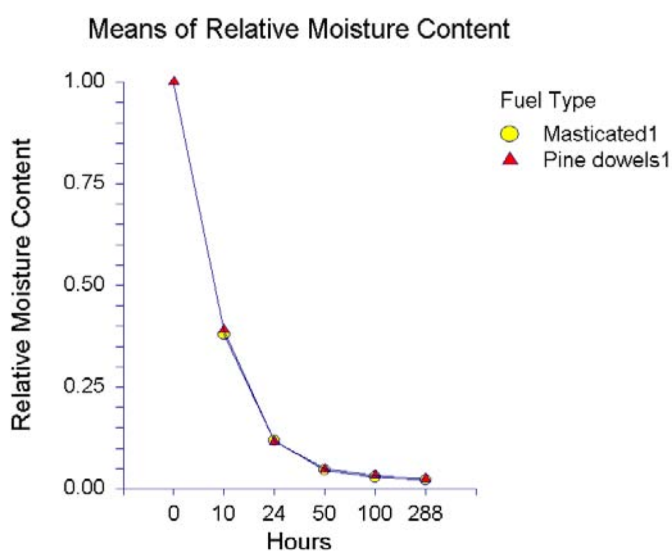


Figure 1—Relative moisture content in standard 10-hour pine dowels and masticated manzanita fuel particles at throughout desorption.

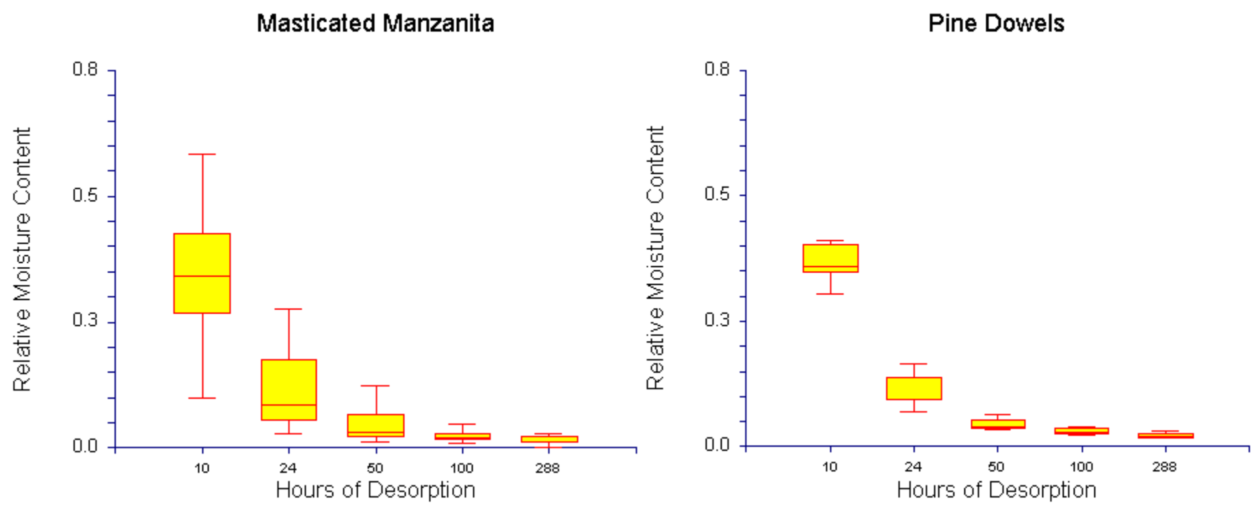


Figure 2—Variation in relative moisture content at 10, 24, 50, 100, and 288 hours of desorption in masticated manzanita fuel particles and standard 10-hour pine dowels.

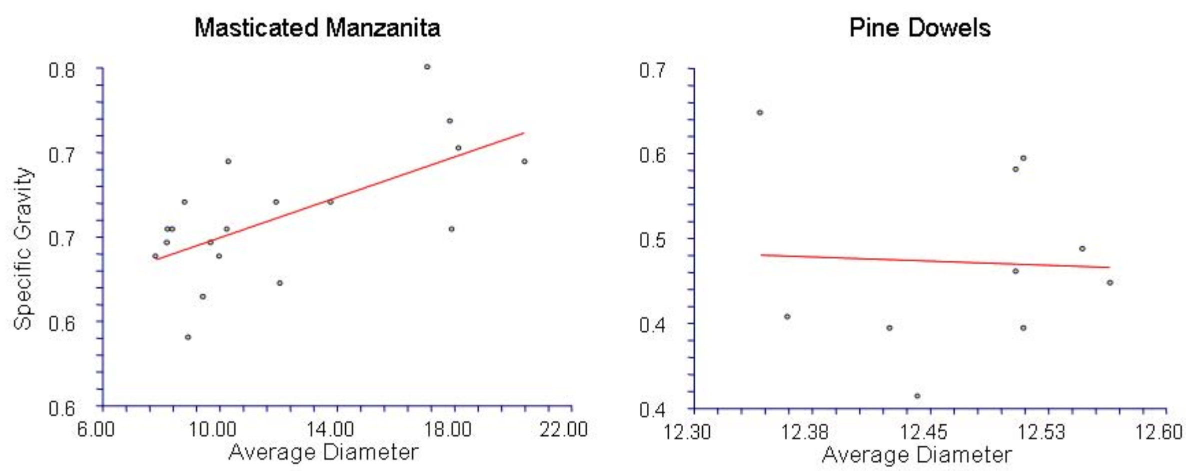


Figure 3—Relationship of specific gravity and average diameter in masticated manzanita ($r^2 = 0.472$) and ponderosa pine dowels ($r^2 = 0.002$).

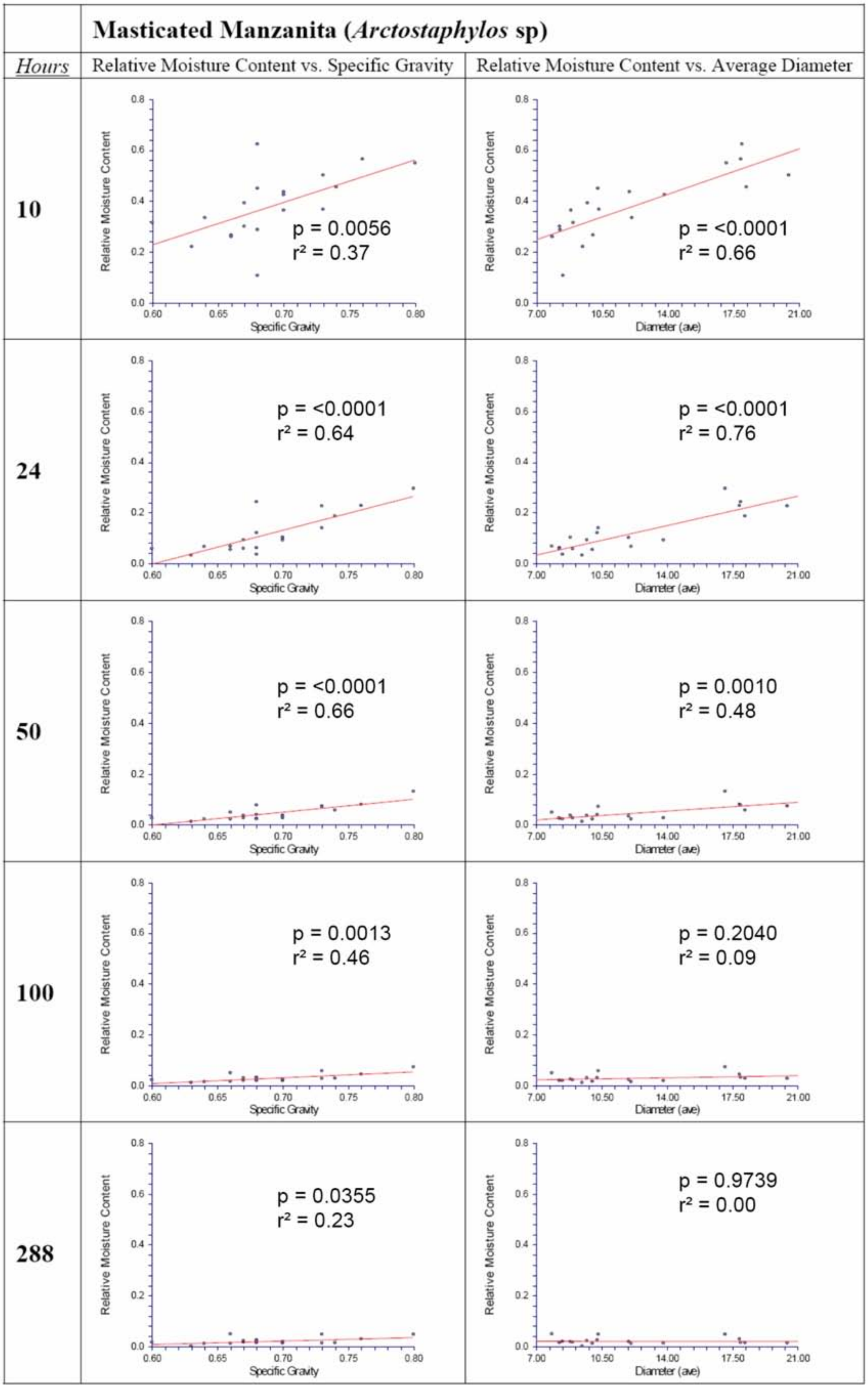


Figure 4—The relationship of relative moisture content with specific gravity and diameter at 0, 10, 24, 50, 100, and 288 hours of desorption in masticated manzanita. Results are from linear regression.

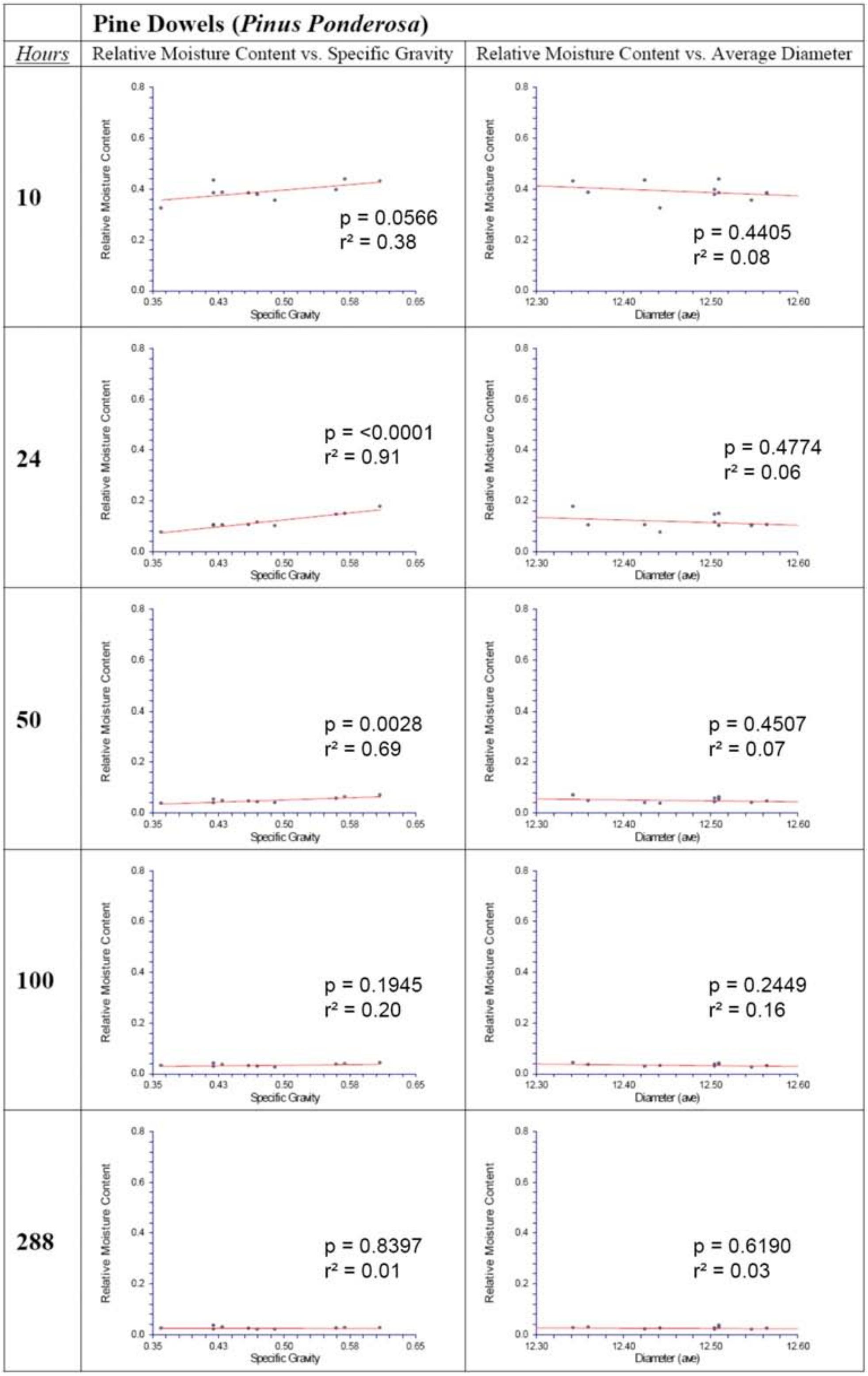


Figure 5—The relationship of relative moisture content with specific gravity and diameter at 0, 10, 24, 50, 100, and 288 hours of desorption in standard pine dowels. Results are from linear regression.

Desorption Experiment 2

Specific gravity differed significantly ($p<0.001$) between pine dowels and all other fuel types (intact masticated, masticated, and maple dowels) used in the fuelbed experiments. Masticated manzanita was higher in specific gravity (0.70) than maple dowels (0.65), although the difference was not substantial. Intact manzanita did not differ from either masticated manzanita or maple dowels (table 1).

Table 1—Specific gravity of maple dowels, pine dowels, intact manzanita, and masticated manzanita used in desorption experiment 2.

Fuel type	Specific gravity	Std Error
Maple dowel[a]	0.65	0.011
Pine dowel[c]	0.47	0.011
Intact manzanita[ab]	0.68	0.012
Masticated manzanita[b]	0.70	0.0009

[abc] No significant difference ($p<0.001$) between fuel types with like notation.

Fuelbed relative moisture content differed significantly from all fuel types marked individually across time periods 10, 24, 50, 100, and 288 hours using the Tukey-Kramer multiple-comparison test $\alpha = 0.05$ (fig. 6). Relative moisture content of maple dowels was significantly different from all other fuel types. Pine dowels and intact manzanita did not differ in regards to relative moisture content. Relative moisture content of intact manzanita did not differ from masticated manzanita. It is apparent that desorption in intact manzanita, masticated manzanita, and pine dowels are fairly similar in comparison to maple dowels, which desorb more slowly at the fuelbed level.

The development of response times (τ) under the timelag concept yielded similar results as comparing relative moisture contents by fuel type. Linear portions developed for each fuel type are shown in figure 7. Results include those from experiments 1 and 2. Response times (τ) calculated from slopes (b) of linear sections, or timelag sections, are shown in table 2 by fuel type. Intact and masticated manzanita as well as pine and maple dowels all had

Table 2—Response times (τ_i) for piecewise linear portions and overall response time (T) where ~63 percent of evaporable moisture was actually lost.

Fuel type	Slope			r^2	Response time		
	J [c]	b_1	b_2		τ_1	τ_2	T
	hours	- - - - *x10*$^{-2}$- - - -			- - - -*hours* - - - -		
Fuelbed	98	–1.41	–2.32	.977	71	43	70
Maple dowel[a]	61	–2.76	–1.36	.966	36	74	40
Pine dowel[a]	36	–5.00	–1.47	.950	20	68	23
Intact manzanita[a]	39	–5.38	–1.40	.943	19	71	20
Masticated manzanita[a]	36	–5.09	–1.52	.940	20	66	20
Pine dowel[b]	51	–7.94	–0.949	.976	13	105	10
Masticated manzanita[b]	51	–8.56	–0.687	.912	12	146	10

[a] Fuel particles desorbing within fuelbeds (experiment 2).
[b] Fuel particles desorbing individually (experiment 1).
[c] J is the upper limit (hours) of the 1st piecewise linear portion of lnE vs. time (hours).

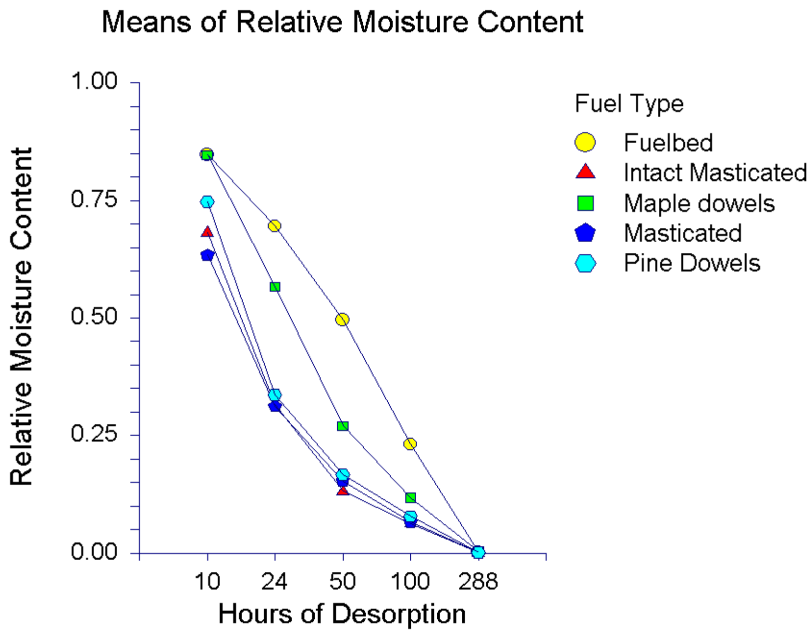


Figure 6—Relative moisture content in fuelbeds, intact manzanita ("intact masticated"), masticated manzanita, maple dowels, and pine dowels throughout desorption.

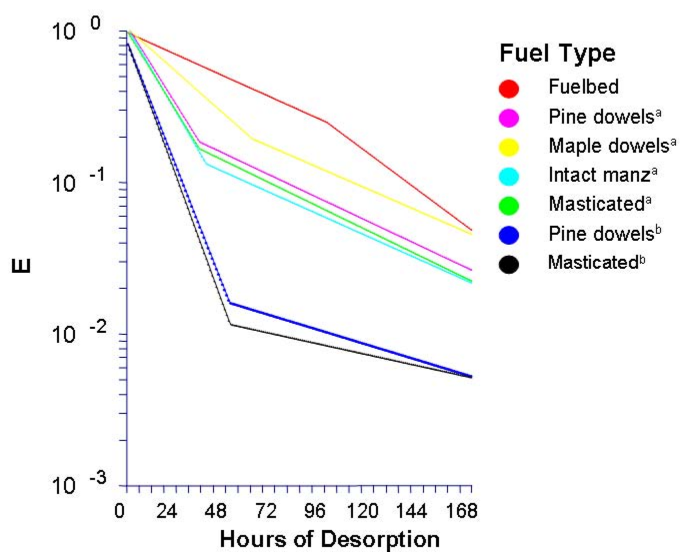


Figure 7—Fraction of evaporable moisture (*E*) throughout desorption developed from linear-linear regression using piecewise polynomial curve fitting. Response times (τ_i) are developed from the inverse of the slope of each linear portion.

initial timelag sections with shorter response times (τ_1) than that of later stages (τ_2). The transition between τ_1 and τ_2 occurred late in desorption where 80 percent or more of the evaporable moisture has been lost. The increase in response time in the later stage of desorption indicates a decrease in the rate of desorption during later stages of drying. Fuelbeds on the other hand desorbed moisture at a higher rate during the later stage of drying as indicated by the increase in response time in the second timelag section (τ_2).

Pine dowels and masticated manzanita dried faster at the individual particle level (experiment 1) as compared to any of fuels at the fuelbed level (experiment 2) during the first timelag section (τ_1). Although initial response time of masticated manzanita was shorter than pine dowels at the individual level, 12 hours versus 13 hours, respectively, they appear to have desorbed moisture fairly similarly. The transition from timelag section τ_1 to τ_2 both occur at 51 hours. Response time τ_2 of pine dowels was shorter than that of masticated manzanita at the individual level.

All fuels initially (τ_1) desorbed moisture more quickly than do fuelbeds (fig. 7). After 4 days fuelbed desorption appeared to increase, as shown by the shift of response time from 71 to 43 hours (table 2), which differs from all other fuel types. Desorption rates decreased during later stages (τ_2) in all other fuel types. Of all fuel types, maple dowels had the longest initial response time (τ_1) of 36 hours. Pine dowels, intact manzanita, and masticated manzanita had similar initial response time of 20, 19, and 20 hours, respectively. Later stages of desorption (τ_2) are fairly similar between all four fuel types (maple dowels, pine dowels, intact manzanita, masticated manzanita) with response times of 74, 68, 71, and 66 hours respectively, although the transition (J) from timelag section τ_1 to τ_2 was later in maple dowels (table 2). Transition times (J) are similar between pine dowels, intact manzanita, and masticated manzanita occurring at 36, 39, and 36 hours, respectively.

The times at which 63 percent of evaporable moisture was actually lost (T) during desorption were similar to response times calculated for the initial timelag sections τ_1 (table 2) for all fuels in both experiments including the fuelbed.

Discussion

Analyzing moisture dynamics in masticated fuels is important in attempting to understand observed fire behavior and fire effects within masticated fuels treatments. Desorption of moisture within fuels addressed here occurs differently at the individual level as compared with those fuels drying at the fuelbed level. Also while diameter affects moisture dynamics within forest fuels, the effect of particle density is shown to affect moisture dynamics.

Comparing relative moisture content over time as well as calculating response times under the timelag concept reveals no substantial differences in the way that masticated manzanita desorbs moisture as compared with intact manzanita or ponderosa pine dowels. The similarity of desorption rates between manzanita and pine dowels and the difference between manzanita and maple dowels suggests density and species differences having a role in moisture dynamics. Because intact manzanita and masticated manzanita do not appear to differ in desorption rates, the similarity of masticated manzanita in experiment 1 with that of pine dowels may not necessarily be explained by the idea that surface area to volume ratio and density are working against each other. Although it may be that physical and chemical properties of manzanita versus ponderosa pine at the species level may be significant in moisture dynamics, the fact that the manzanita had weathered for 2 years on site before moisture experiments had been conducted may be a factor in these results. Discrepancies in modeling fire behavior in masticated fuels do not lie in an inability of predicting fuel moisture based on surface area to volume ratios being altered by the mastication process. It should be noted though that the effect of surface area to volume (SA:V) ratio in fire danger rating systems has been in regard to the effect on the heating of fuels ahead of the flaming front during combustion as moisture is evaporated and the interior portions of fuel particles increase in temperature to the point of combustion. The differences in SA:V ratio between masticated and intact fuels may play a role in the combustion process and should not be disregarded altogether in terms of modeling discrepancies in fire behavior prediction in masticated fuels.

The role of density, as analyzed through specific gravity here, plays a role in desorption rates in these fuels. The role of density in the timelag concept was addressed by Byram (1963), but the extent of its role might not be fully understood. While timelag categories have been developed based on fuel diameter, specific gravity appears to be positively correlated with diameter and plays a similar role in moisture dynamics. Both increases in diameter and increases in fuel density result in slower desorption rates. The degree of effect between diameter and density on moisture dynamics in fuels analyzed here appears to change temporally whereby diameter and density shift in their dominance in controlling desorption. Diameter appears to have more control in early stages of desorption while density becomes more dominant during later stages. While the preliminary analysis of these data suggests an insignificant role in the mastication of fuels in regards to moisture dynamics, these results are from a single site conducted with one species. Future analysis of experiments with masticated fuels from other sites, different species, and various times since treatment should increase our understanding of the role that mastication has on influencing moisture dynamics in these fuels.

The response times and their respective linear portions described here are from desorption of fuels from initial fuel moisture contents much higher than fiber saturation, through soaking, to that of equilibrium moisture contents in an environment of approximately 25 °C and 30 percent RH. Previous studies referenced here have conducted moisture dynamics experiments under standard conditions of 26.7 °C while shifting relative humidity from 90 to 20 percent and then from 20 to 90 percent for desorption and adsorption, respectively, allowing fuels to come to equilibrium at each stage. Differences in timelag sections developed here and that of previous studies may be a result of the scale at which desorption is being analyzed. The use of developing response times for certain portions of desorption curves by partitioning may be useful in attempting to describe desorption or adsorption rates in general, but these curves appear to be curvilinear following logarithmic transformation and more precise modeling may be useful in further understanding how various factors affect moisture dynamics in forest fuels. Further research regarding other particle and fuelbed characteristics of masticated fuels is needed to explore the questions regarding the inability of current fire modeling systems to accurately predict fire behavior and fire effects in these types of treatments.

References

Anderson, H.E. 1990. Moisture diffusivity and response time in fine forest fuels. Canadian Journal of Forest Research 20: 315-325.

Blackmarr, W.H. 1971. Equilibrium moisture content of common fine fuels found in southeastern forests. Research Paper SE-74. Asheville, NC: U.S. Department of Agriculture, Southeastern Forest Experiment Station.

Byram, G.M. 1963. An analysis of the drying process in forest fuel material. Unpublished report. Missoula, MT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory.

Fosberg, M.A. 1970. Drying rates of heartwood below fiber saturation. Forest Science 16: 57-63.

Kane J.M.; Knapp, E.E.; Varner, J.M. 2006. Variability in loading of mechanically masticated fuel beds in northern California and southwestern Oregon. In: Andrews, P.L., Butler, B.W. comps. Fuel Management – How to Measure Success: Conference Proceedings. Mar. 27-30, 2006. Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 341-350.

Knapp, E.E.; Busse, M.D.; Varner, J.M.; Skinner, C.N.; Powers, R.F. 2006. Behavior and short-term effects of fire in masticated fuel beds. Proceedings of the Third International Fire Ecology and Manageme4nt Congress, Nov 13-17, 2006, San Diego, CA.

Linton, M. 1962. Report on moisture variation in forest fuels-prediction of moisture content. Melbourne, Autralia: Commonwealth Scientific and Industrial Research Organization, Division of Physical Chemistry.

Mutch, R.W.; Gastineau, O.W. 1970. Timelag and equilibrium moisture content of reindeer lichen. Research Paper INT-76. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station.

Nelson, R.M., Jr. 1969. Some factors affecting the moisture timelags of woody materials. Research Paper SE-44. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station.

Viney N.R.; Catchpole, E.A. 1991. Estimating fuel moisture response times from field observations. International Journal of Wildland Fire 1: 211-214.

Viney, N.R.; Hatton, T.J. 1989. Assessment of existing fine fuel moisture models applied to *Eucalyptus* litter. Australian Forestry 52: 82-93.

Relationships Between Prefire Composition, Fire Impact, and Postfire Legacies in the Boreal Forest of Eastern Canada

Alain Leduc[1], Yves Bergeron[2], and Sylvie Gauthier[3]

Abstract—*Canadian mixedwood forests have a high compositional and structural diversity. It includes both hardwood (aspen, balsam poplar, and white birch) and softwood (balsam fir, white spruce, black spruce, larch, and white cedar) species that can form pure stands or mixed stands. This heterogeneity results in a variety of vertical structural strata that can potentially interact with fire behaviour. Fourteen fire impact maps including information on preburn stand composition and structure were gathered in a Geographical Information System. The relative influence of prefire forest composition, stand density, and surficial deposits on postfire forest cover attributes (such as variation in proportion of green/red/charred trees) was analyzed using contingency tables. Many attributes of postfire forests (fire legacy) can be related to preburn forest composition and structure. Highest fire impact was observed in coniferous stands. At the other end of the spectrum, aspen stands and wetlands contributed to most of the fire skips. Within coniferous stands, there was a difference between species with regard to their susceptibility to windthrow following fire. Jack pine stands had less severe windthrow allowing for an abundance of snags, whereas windthrow is common in balsam fir stands. Impacts vary with regard to fire severity, suggesting that observed differences between stand types may be less important when fires are very intense. These results have consequences on the maintenance of the diversity of the forest mosaics through time as well as our capability to predict fire behaviour and impacts.*

Introduction

The Canadian boreal forest has often been described as a region where large severe crown fires control vegetation dynamics (Johnson and others 1998). These severe fires are usually recognized as leaving few surviving trees in burned areas. Many forest managers used this conventional wisdom to justify a relatively low level of retention after harvesting. In fact, there are relatively few studies that address the question of how much area is spared from fire and on how those unburned islands are spatially distributed after severe crown fire events (Schmiegelow and others 2006).

Canadian mixedwood forests have a high compositional and structural diversity. It includes both hardwood (aspen, balsam poplar, and white birch) and softwood (balsam fir, white spruce, black spruce, larch, and white cedar) species that can form pure or mixed stands. This heterogeneity results in a variety of vertical structural strata that can affect fire behaviour (Cumming 2001; van Wagner 1977).

In: Butler, Bret W.; Cook, Wayne, comps. 2007. The fire environment—innovations, management, and policy; conference proceedings. 26-30 March 2007; Destin, FL. Proceedings RMRS-P-46CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 662 p. CD-ROM.

[1] Adjunct Professor, Centre d'étude de la forêt and Département des sciences biologiques, Université du Québec à Montréal, Montréal, Québec, Canada. leduc.alain@uqam.ca

[2] Director and Professor, NSERC UQAT/UQAM Industrial Chair in Sustainable Forest Management, Université du Québec en Abitibi-Témiscamingue, Québec, Canada.

[3] Research Scientist (Ecology), Natural Resources Canada, Canadian Forest Service, Laurentian Forestry Centre, Quebec, Quebec, Canada.

In this study, we used 14 fire impact maps (fig. 1) that were overlaid on forest inventory maps to define the original forest cover before fire event. The relative influence of prefire forest composition, stand density, and surficial deposits on postfire forest cover attributes (such as variation in proportion of green/red/charred trees) was analyzed using contingency tables.

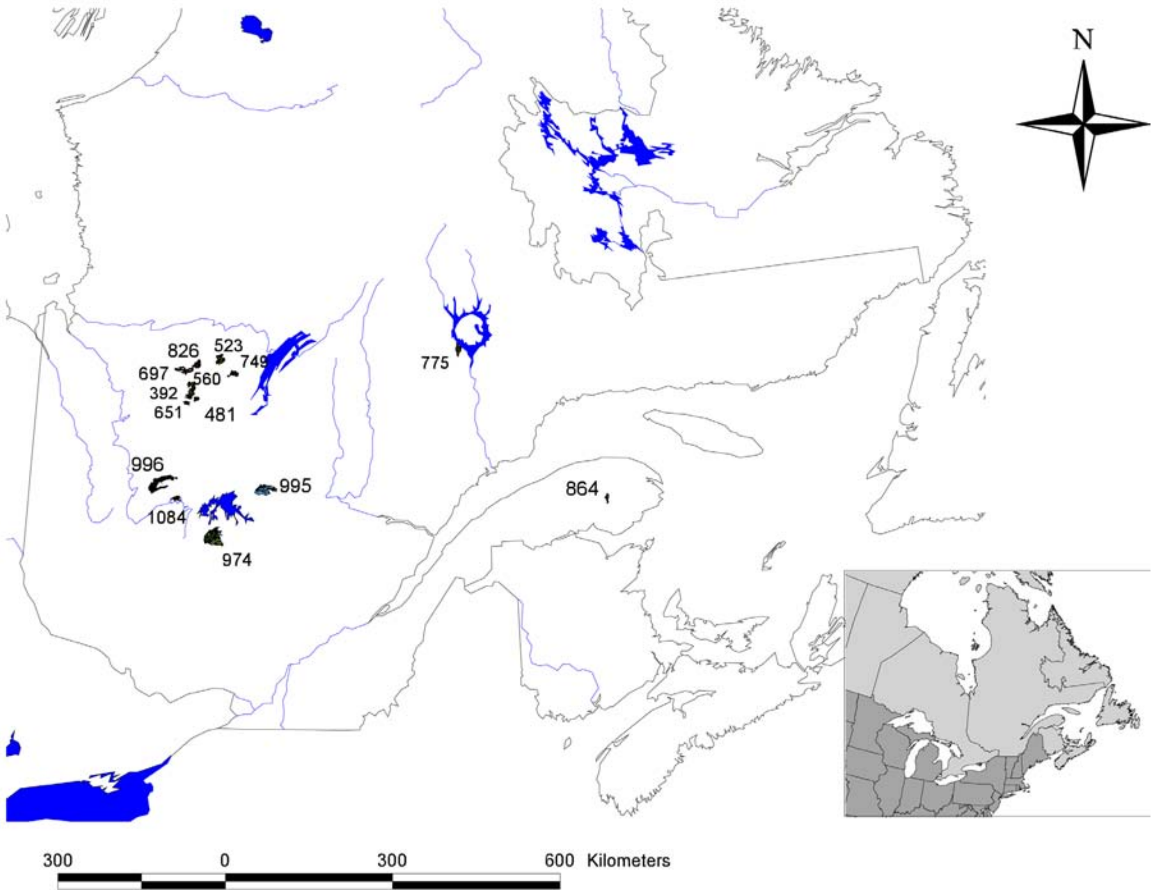


Figure 1—Map of Quebec showing the location of 14 fire events.

Methods

Fire impact maps are produced by the Quebec Ministry of Natural Resources after large wildfires in order to plan salvage logging operations. These maps describe timber damage immediately after fire in six severity classes (table 1). Forest inventory maps are available for the commercial zone as raster format at a resolution of 14 ha. These maps (inventory and fire impacts) were overlaid in ARC-GIS in order to produce a table of 15,200 records for which we obtained the prefire forest cover composition, the percentage of forest cover, the site type (a combination of surface deposit and moisture regime) and the fire severity class.

In the first step, each fire event was clustered based on the overall impact on black spruce stands (the dominant cover in all fires) defining a fire intensity index. This index corresponds to a weighted mean of area affected by fire severity classes where partially burned area in which green trees dominate was

Table 1—Relative importance (area) for fire severity class for the overall 14 fires.

Fire severity class	Relative importance (%)
5: Charred trees > 40% blowdown	8.6
4: Charred trees < 40% blowdown	51.3
3: Crown scorched < 25% blowdown	1.8
2: Mixed zones of scorched trees > green trees	7.7
1: Mixed zones of green trees > scorched trees	26.1
0: Fire skips	4.4

weighted by 1, mixed zones dominated by scorched tree was weighted by 2, and area dominated by crown scorched or charred trees was weighted by 3 (fire skips were not counted). In the second step, the relationships between six fire severity classes and prefire or site characteristics were illustrated by deviance; in other words, the relative difference between observed frequency and expected frequency reported on expected frequency, overall or taking into account the intensity index.

Results

Fires were clustered in three severity classes corresponding to weak (fire 481, 775, 826), moderate (fire 392, 523, 560, 651, 697, 749, 1084) and high overall impact (fire 864, 974, 995, 996; fig. 2). All fire events that burned more than 30,000 ha belong to the high severity class showing a good relationship between the area burned and the severity of damage registered on tree cover (fig. 3).

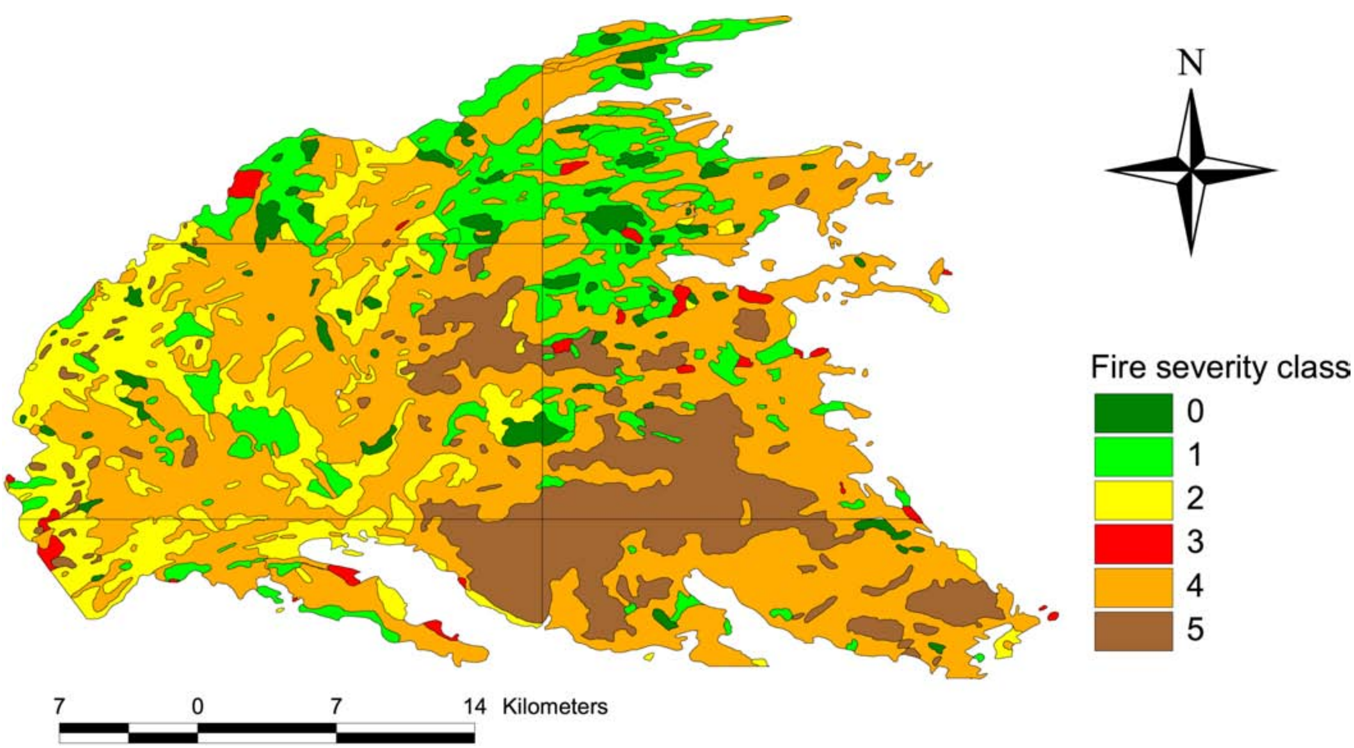


Figure 2—Impact map of fire number 974 that occurred in 1995 near Parent township.

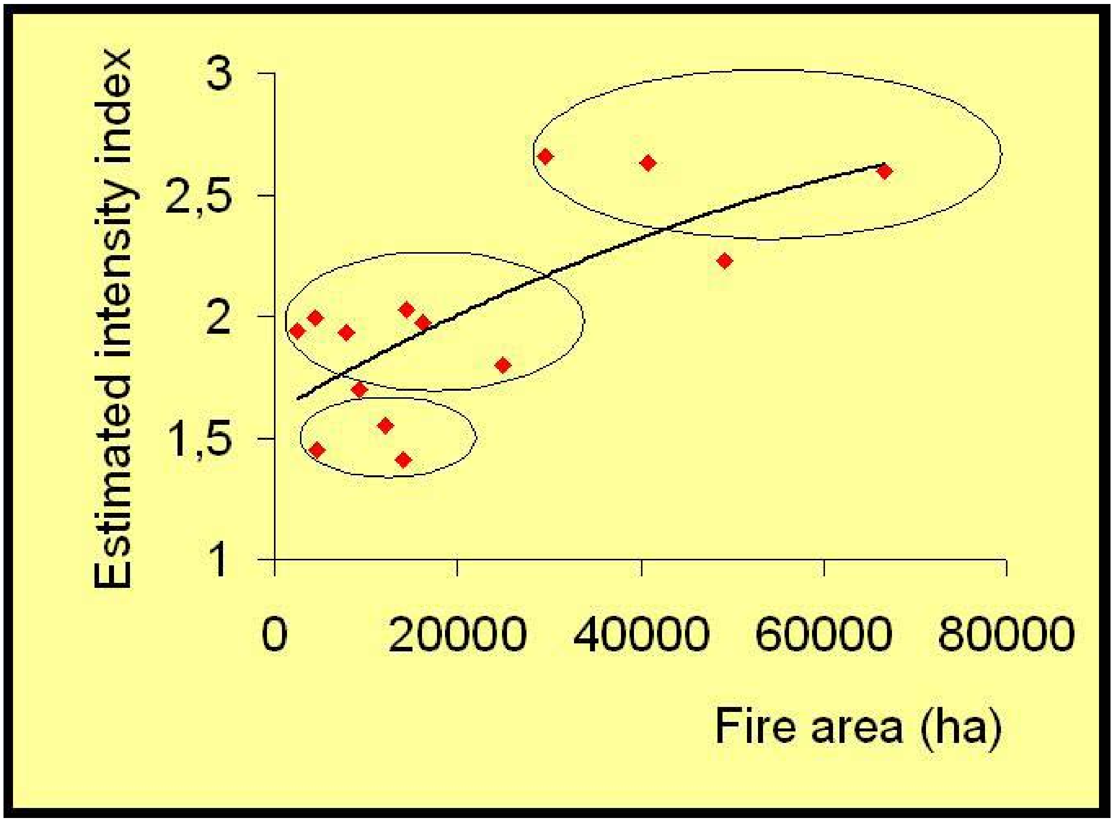


Figure 3—Relationship between fire size and fire intensity index such as estimated by proportion of black spruce stands (area) having undergone heavy impact.

Figure 4 shows how site types can interact with fire severity in black spruce forest cover type in all fire events. Deviance (percent deviation from expected value) indicates an overabundance of weak severity (classes 1 and 0) on hydric soil types such as organic soil and sub-hydric coarse sand. In contrast, rocky outcrops and xeric coarse sand show an overabundance of the highest severity (class 5).

Figure 5 shows the influence of black spruce stand density on severity class distribution. Fire skips (class 0) are overrepresented in closed black spruce stands (> 80 percent closed canopy). Note that this stand density appears also slightly overabundant in impact class 4 (charred trees with < 40 percent blowdown). Open canopies (25 to 40 percent closed canopy) generate an overabundance of weak severity class 1 with a dominance of green trees after fire.

Figure 6 shows the influence of forest cover composition for each fire intensity level. Generally, fire skips and green tree dominated zones are overrepresented in wetlands and stands with prefire forest cover dominated by deciduous cover such as trembling aspen and white birch stands. Balsam fir stands can form fire skips when fire severity is low but usually fire impact was high in these stands. Open forested lands also usually burned intensively. Among high intensity fires, jack pine stands could provide fire skips or green tree dominated zones but with less propensity than trembling aspen stands. Jack pine stands appear also more wind firm (less than 40 percent blowdown) than white birch and mixed white birch stands (fig. 6c).

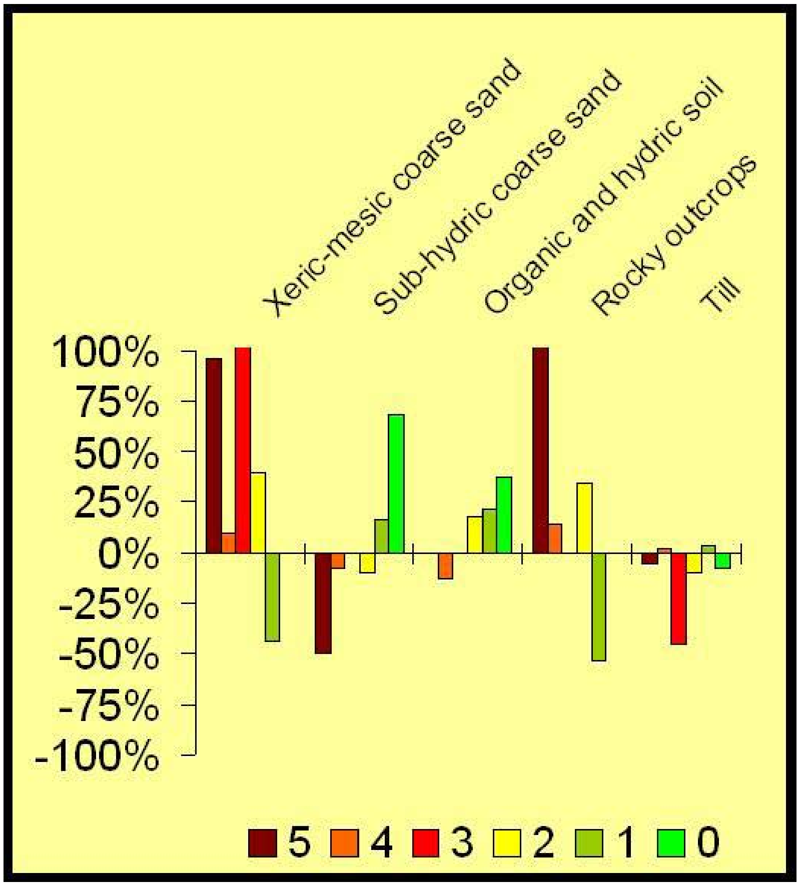


Figure 4—Influence of site types on the distribution of fire severity classes. A positive deviance indicates an overabundance of a severity class for a given site type. Conversely, a negative deviance means a under abundance.

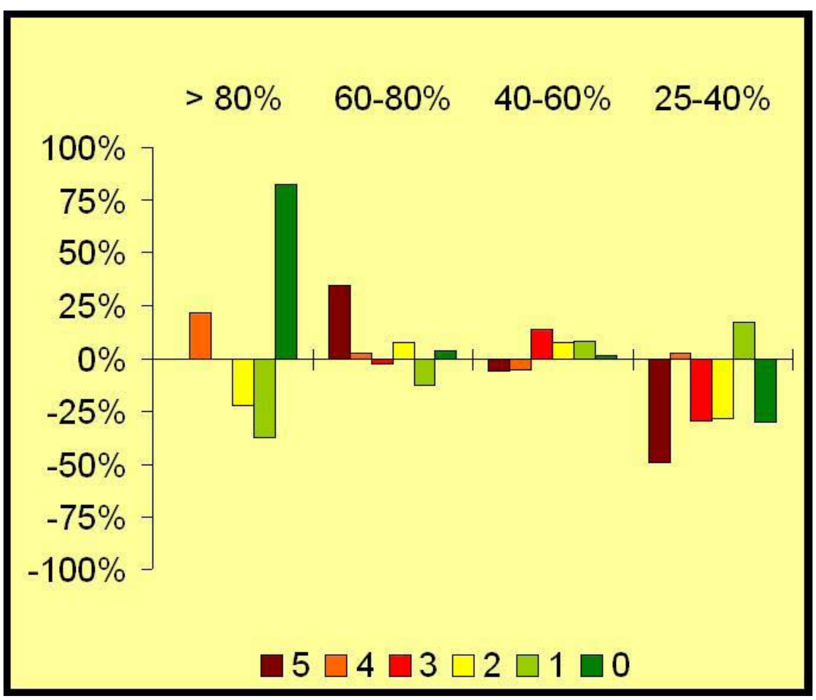


Figure 5—Influence of stand density (for black spruce forest cover only) on prevalence of fire severity classes.

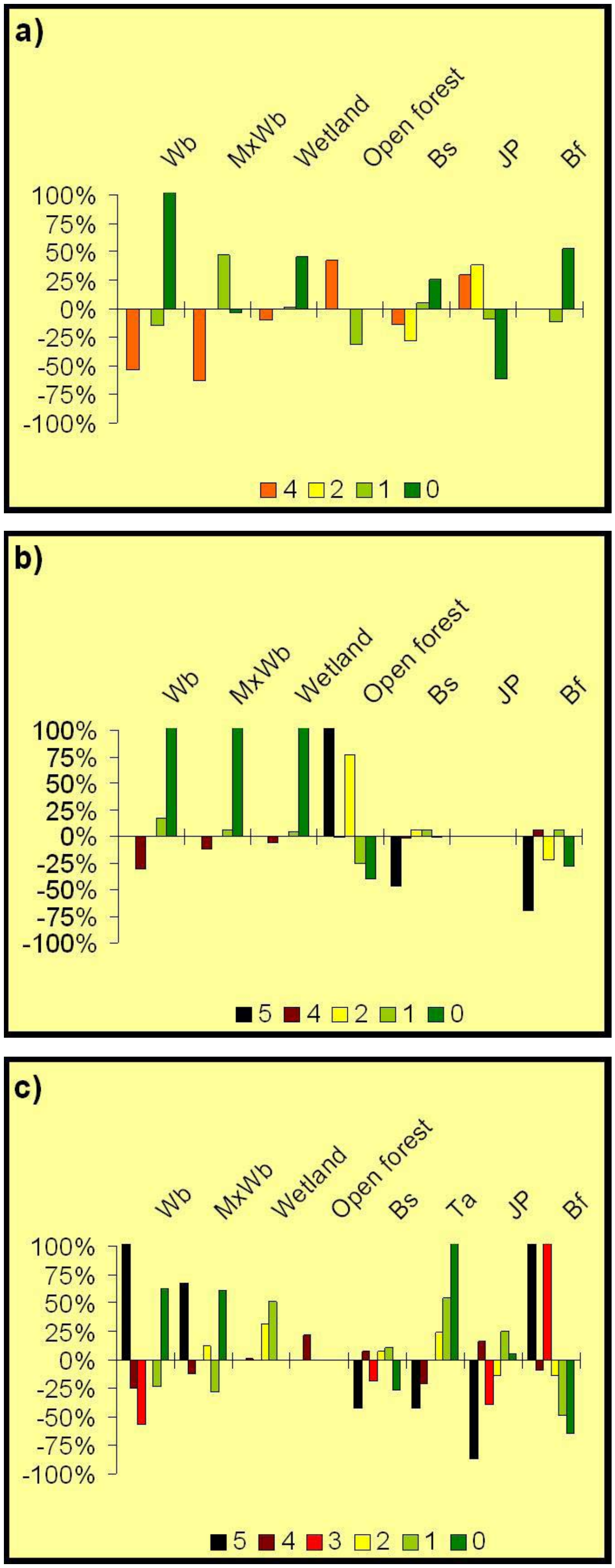


Figure 6—Influence of prefire forest cover composition on the prevalence of fire severity classes. Fires have been grouped by estimated intensity index as shown in figure 3, following they are weakly (a), moderately (b) or highly (c) intense. Some fire severity classes were absent from weakly (a) or moderately (b) intense fire groups. Stand types are coded as follows: Wb: white birch; MxWb; mixed white birch; Bs: black spruce; Ta: trembling aspen; JP: jack pine; Bf: balsam fir.

Discussion

The Canadian boreal forest is known to be characterized by severe crown fires. These fire events usually leave few residual patches (less than 5 percent of burned areas are composed of fire skips). Our results confirm this observation but also show that a relatively large portion of a fire may be occupied by partially burned zones in which green trees dominate postfire forest cover. Our results support the idea that forest cover composition and structure have an influence on fire behaviour and thus on the resulting fire severity. For instance, deciduous forest cover is more likely to generate more residual green trees (Cumming 2001; Kafka and others 2001). Moreover, our results highlight that fire behaviour may differ according to the overall fire intensity. For example, in fires with a low or moderate intensity index, partially burned stands are mainly composed of mixedwood whereas in the fires with an overall high intensity only the more fire resistant, trembling aspen stands (and to some extent jack pine stands) are partially burnt. This interaction between fire intensity and forest cover composition suggests that complex postfire outcomes, in which residual trees could survive individually or in small groups, are possible in the eastern part of Canadian boreal. This spatial pattern of postfire residual trees has implications for the spatial planning of postharvesting tree retention (Schmiegelow and others 2006). More analyses are needed, however, to characterize this spatial pattern at a finer resolution.

References

Cumming, S.G. 2001. Forest type and wildfire in the Alberta boreal mixedwood: what do fires burn? Ecological Applications 11: 97-110.

Johnson, E.A.; Miyanishi, K.; Weir, J.M.H. 1998. Wildfires in the western Canadian boreal forest: landscape patterns and ecosystem management. Journal of Vegetation Science 9: 603-610.

Kafka, V.; Gauthier, S.; Bergeron, Y. 2001. Fire impacts and crowning in the boreal forest: study of a large wildfire in western Quebec. International Journal of Wildland Fire 10: 119-127.

Schmiegelow, F.K.A.; Stepnisky, D.P.; Stambaugh, C.A.; Koivula, M. 2006. Reconciling salvage logging of boreal forests with a natural-disturbance management model. Conservation Biology 20: 971-983.

Van Wagner, C.E. 1977. Conditions for the start and spread of crown fire. Canadian Journal of Forest Research 7: 23-34.

This page is blank on purpose

Role of Buoyancy and Heat Release in Fire Modeling, Propagation, and Instability

Shahid M. Mughal[1], Yousuff M. Hussaini[2], Scott L. Goodrick[3], and Philip Cunningham[2]

Abstract*—In an investigation of the dynamics of coupled fluid-combustion-buoyancy driven problems, an idealised model formulation is used to investigate the role of buoyancy and heat release in an evolving boundary layer, with particular emphasis on examining underlying fluid dynamics to explain observed phenomena arising in forest fire propagation. The role played by the Froude number and background ambient wind in affecting various characteristics observed in propagating fires is addressed. A simplified flow situation is modeled in which controlled amounts of volumetric heat is injected into the system. By varying the strength of the heat source and the ambient winds the study examines the impact of these variables on the flow dynamics and the consequential development of instability waves that may provide insight into environmental conditions that contribute to erratic fire behaviour. Analysis suggests that there are two routes to fire behaviour and destabilisation, with Froude number playing a crucial role in the boundary layer development and consequential instability of the convecting flow. In low Froude number situations, the mechanism of fire induced local winds may arise as a product of heat release and buoyancy, which induces favourable pressure gradients accelerating local winds to above the ambient. The analysis shows that a massive destabilisation takes place and that stationary, zero streamwise and nonzero spanwise wavenumber, viscous disturbances have the highest growth rates. These stationary spanwise vortex disturbances, commonly referred to as pure vortex longitudinal "roll cell" modes, might well be linked to cross roll features that have been identified in some recent fire related numerical simulations. The simple model shows that a key requirement in breakup of the fireline, is a low enough ambient wind. In high Froude number cases, the most probable factor is the sensitivity of the boundary layer to separate and lift off the surface; this being caused by massive updrafts of buoyant air. The relatively weak nature of instabilities in this regime suggests that the convecting fireline development would otherwise be well behaved.*

In: Butler, Bret W.; Cook, Wayne, comps. 2007. The fire environment—innovations, management, and policy; conference proceedings. 26-30 March 2007; Destin, FL. Proceedings RMRS-P-46CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 662 p. CD-ROM.

[1] Research Associate, Institute for Mathematical Sciences, Imperial College, London, UK. s.mughal@imperial.ac.uk

[2] Professor of Mathematics, with School of Computational Science, and Assistant Professor with Department of Meteorology, respectively, Florida State University, Tallahassee.

[3] Research Meteorologist, U.S. Department of Agriculture, Forest Service, Southern Research Station, Athens, GA.

Introduction

Our concern is with combustion related problems, in particular forest fires, where intense volumetric heat and mass release arise during the burning process. This is a complex process whereby entrainment and mixing lead to chemical reaction, release of heat, and mass, which in turn affect the flow dynamics and hence flow entrainment, mixing and combustion; that is, the effect of one on the other is coupled and may be cyclic. It is now fairly well recognised through observations that fire propagation characteristics fall into two distinct categories. For weak wind conditions, the fire front is mainly affected by the expansion of the hot gases around the combustion zone, and in the literature this wildfire propagation regime is identified as plume dominated. For greater wind speeds the flame trajectory is affected more so by the lateral wind flow, and hot gasses are pushed toward the unburnt solid fuel, inducing additional heat source/release points.

To understand the effect of heat release on this quite complex process, we examine a simplified flow situation in which controlled amounts of volumetric heat is injected into the system. By varying the strength of our heat source and the ambient winds, we seek to examine the impact of these variables on the flow dynamics and the consequential development of instability waves that may provide insight into environmental conditions that contribute to erratic and dangerous fire behaviour.

An evolving fire is of course a complex flow, involving flow unsteadiness, turbulence, thermo-dynamics, multiple phases, chemistry, radiative effects and fluid dynamic coupling. These physical mechanisms are generally considered too complex, outside of a research environment, to be integrated on a large scale to simulate fire spread. Thus, present day fire spread models simplify the problem by representing the fire front as a curve separating the burnt area and the fresh fuel. Each point of this front is regarded as a possible ignition source (provided conditions are right), with normally empirical and experimentally derived formulae used to continue the computations to the next time and spatial level (Rothermel 1972). At the other level of sophistication, and requiring considerable computational resources, we cite the work of Morvan and Dupuy (2004), who model a wildfire propagation process by a complete multiphase formulation, though due to computational expense this work was limited to two dimensions. Typically such works model the full burning process, and thus include thermal degradation, pyrolysis, glowing combustion of solid fuel particles, convection, radiative heat transfer, effects of external wind and ground topography. Furthermore to be as realistic as possible, the solid fuel (that is, the natural vegetation) is further broken down into families of solid combustible particles, with each family (pine needles, twigs, foliage, excelsior, and so forth) characterised by a set of physical properties (density, flammability, moisture content, and so forth), which are also included in their mathematical model. A similar approach that allows for fully three-dimensional simulations of coupled atmosphere-fire behaviour, albeit employing a simplified treatment of combustion, is found in the work of Linn (1997) and Linn and Cunningham (2005).

Real fire observations and model simulations have shown that intense vortices of various strengths and sizes often occur; vortices being created either directly by the fire front or by and in conjunction with atmospheric convection. Fire vortices on the scale of metres continually occur at the fire front and are an essential component of the convection, and are hypothesised to play a fundamental role in the physics of fire spread. Heat and moisture supplied through the burning of ground, canopy, and/or crown fuel during a forest fire generate extreme levels of buoyancy. The horizontal buoyancy gradients have in certain fire conditions produced vortices of tornado strength (Banta and others1992). The presence of vertical shear in the ambient atmosphere is also an important component of fire behaviour. Vertical shear is associated with horizontal vorticity that may be converted into vertical vorticity near the ground via tilting by updrafts in the vicinity of the fire, thus leading to highly nonuniform winds near the fireline. Cunningham and others (2003) further suggest that this vertical vorticity is associated with low level horizontal winds on the downstream side of the fire that are oriented in the opposite direction to the fire spread. Simulations of Clark and others (1996a) lend support to this observation and confirm that presence of low-level wind shear can lead to particularly active fire behaviour. Moreover, the presence of low level negative shear (that is, winds decreasing with height near the ground) has been shown to be a common feature of so-called blowup fires (Byram 1954). The other feature of note is that winds at the fire scale can either be strongly modified or even solely produced by the fire, depending on the atmosphere-fire coupling. This coupling or feedback may occur over spatial scales from tens of metres at the flame front to kilometres on the scale of the total burn area. The magnitude and direction of the wind near the ground has been observed to play a crucial role in wildland fire spread.

The potential for erratic fire behaviour arising from buoyancy associated with large wildfires and horizontal flow was first theorised by Byram (1954). This theory centred upon the notion that erratic fire behaviour (instability) becomes more likely as the conversion rate of buoyant energy surpasses the flux of kinetic energy by the horizontal flow; hence, the idea of power of the fire versus the power of the wind. Byram's original theory was limited, however, by its assumptions of a neutral atmosphere and a nonentraining plume. Nelson (2003) extended the original work of Byram to remove these assumptions. A limitation of this work is that the problem is not posed as a coupled system with heat release influencing the development of the flow. Clark and others (1996a,b) make use of a numerical atmospheric model coupled to a simple fire spread model to investigate the influence of convective processes on fireline dynamics in a fully coupled system. This study provided strong evidence for a linkage between the convective Froude number F_o^2, and erratic fire behaviour, such as fingering of the fireline and the development of fire whirls of near tornado strength. Experiments were conducted for a range of wind speeds (1, 2, 3 and 5 m/s) and two fireline lengths (420 and 1500 m). These variations in wind speed accounted for a range of Froude numbers. For small values of F_o^2 they encountered strong coupling between the atmosphere and fire with erratic fireline behaviour. However, they did not delve into the nature of the instabilities. Thus, vortex tilting and unpredictability of ground winds are not only a hazard in itself to nearby firefighters, who have on occasions reported being toppled to the ground unpredictably by fire whirls, but are an important fire spread mechanism through both local dynamics and the ability to loft flaming objects into areas well removed from the fire front. The precise mechanisms of how these effects occur are still poorly understood.

This paper represents the starting point in a systematic investigation of the dynamics involved in the investigation of coupled fluid-combustion-buoyancy driven problems. In the present investigation, the basic objective of our work is to isolate the roles of the convective Froude number F_o^2 and volumetric heat release on fire dynamics and the nature of two and three dimensional unstable disturbances that arise. Most previous work is almost all based on the low temperature Boussinesq assumption, while detailed simulations use combinations of either fully unsteady compressible DNS and or large-eddy simulation (LES) models with combustion treated completely or approximated somehow. With such complex simulations, considerable difficulty arises in trying to isolate the underlying physics. Among the many reasons are the large amount of data that require processing and assimilation, and the computational expense of examining a large enough parameter space to isolate the role of key parameters. The model we use to examine the issues raised above is by way of examining the mixed forced-free convection boundary layer problem, which has been much studied in the past from the viewpoint of the heat-transfer problem. We contend and show below that this simple model can be used to elucidate some major aspects of fire propagation phenomenon too. In particular, we are interested in situations where sizable changes occur in density, temperature, and transport properties due to heating. Thus, the commonly used approximation, used in most analytic and related numerical computations, of using a Boussinesq approximation is dispensed with, and we consider the fully coupled problem where temperature variations of the order of 1200K may arise.

In this paper we define the appropriate model and discuss our numerical work for the basic nonsimilar steady field, in which we incorporate the effects of a volumetric heat source and coupled buoyancy model. Results are discussed in the context of forest fire propagation and in view of existing knowledge of fire related phenomena. Flow instability aspects of the work are discussed by the use of *linear stability theory* (LST) briefly as we believe that a proper investigation of this aspect requires the effects of nonparallelism to be included, and LST does not allow this in a straightforward manner. But the preliminary instability analysis reported here does allow and will serve as a bedrock for a future and fuller investigation using the more advanced linear and nonlinear instability analysis tools. The work we believe is an important step in elucidating the coupling of the external fluid (or wind-driven) processes and the burning process and how the two interact. Our simplification of the problem describes the two major mechanisms of importance in a coupled fluid-combustion-buoyancy dominated problem, namely the role of heat release and Froude number on atmospheric dynamics and instability. Features such as fireline length and its effect on fire spread and propagation are effectively three-dimensional in nature and left for a later investigation.

The tools currently used operationally in the wildland fire community to predict fire spread are based on empirical relationships between ambient wind speed, topography, and fuel properties (Nobel and others 1980; Rothermel 1972). The complexities of the combustion process and the intricacies of fire-atmosphere feedback processes are largely neglected. The primary focus of such tools is on predicting the spread of wind driven surface fires (Froude number >1) under homogenous, steady state conditions. These models are not typically applicable to the most intense forest fires (crown fires). The model presented in the current work, with its boundary layer approximation, is well suited to providing a simplified vision of the problem based on physics rather than empirically derived relationships. The importance of the physics based relationship is that it allows us to explore the response of the system as we move toward more buoyancy dominated conditions. While the boundary layer assumption precludes application of the model to buoyantly dominated flows, it does allow for an initial, though limited, exploration of the transition from wind to buoyancy dominated conditions and the potential for associated instabilities. Examination of the initial stages of the transition from wind to buoyancy dominated conditions (and associated flow instabilities) provides insight into the conditions that will cause current operational tools to fail.

Formulation

Basic Steady Field

We consider the fully compressible two-dimensional flat plate natural convection problem that incorporates the Boussinesq assumption, namely that density variations may be ignored in all terms apart from the gravitational term, and we use the equation of state $p^* = \rho^* R^* T^*$ to determine density. Thus, the relevant equations of mass conservation, momentum, and energy to determine the basic boundary layer state are:

$$\frac{\partial(\bar{\rho}\bar{U})}{\partial x}+\frac{\partial(\bar{\rho}\bar{V})}{\partial y}=0,$$
$$\bar{\rho}(\bar{U}\frac{\partial \bar{U}}{\partial x}+\bar{V}\frac{\partial \bar{V}}{\partial y})=-\frac{\partial \bar{P}_e^{(o)}}{\partial x}-\frac{\partial \bar{P}^{(1)}}{\partial x}+\frac{\partial}{\partial y}(\bar{\mu}\frac{\partial \bar{U}}{\partial y}),$$
$$\frac{\partial \bar{P}^{(1)}}{\partial y}=(\bar{\rho}_e-\bar{\rho})g^*, \tag{1.1}$$
$$\bar{\rho}(\bar{U}\frac{\partial \bar{T}}{\partial x}+\bar{V}\frac{\partial \bar{T}}{\partial y})=\frac{\bar{U}}{C_p}(\frac{\partial \bar{P}_e^{(o)}}{\partial x}+\frac{\partial \bar{P}^{(1)}}{\partial x})+\frac{1}{\sigma}\frac{\partial}{\partial y}(\bar{\mu}\frac{\partial \bar{T}}{\partial y})+\frac{\bar{\mu}}{C_p}(\frac{\partial \bar{U}}{\partial y})^2+\bar{Q}(x,y,z).$$

$\bar{P}_e^{(o)}(x)$ is the flow induced pressure field, and we introduce the function $\bar{Q}(x,y,z)$ to represent the volumetric heat release that arises from a burning fire. In the above x and y are streamwise and wall normal coordinates, $\bar{U},\bar{V}$ the associated velocities, $\bar{\rho}$ the density, $\bar{T}$ the temperature, $\bar{\mu}$ the viscosity, C_p the specific heat, σ the Prandtl number, and g^* the gravitational term.

To reduce the equations into a more suitable form for numerical work, we transform y using a Falkner-Skan type transformation

$$\eta=(\frac{\bar{\rho}_e\bar{U}_e}{\bar{\mu}_e x})^{1/2}\int_0^y\frac{\bar{\rho}(s)}{\bar{\rho}_e}ds, \tag{1.2}$$

and $\psi=(\bar{\rho}_e\bar{\mu}_e\bar{U}_e x)^{1/2}f$ with ψ a stream function, which satisfies mass conservation. On assuming Mach number terms of $O(M^4)$are negligible, the equations then reduce to

$$\frac{\partial(\chi f'')}{\partial\eta}+m_1(s-f'^2)+cff''-sx\frac{d\bar{P}^{(1)}}{dx}=x(f'\frac{\partial f'}{\partial x}-f''\frac{\partial f}{\partial x}),$$
$$\frac{\partial \bar{P}^{(1)}}{\partial\eta}=x^{1/2}G_o(s-1), \tag{1.3}$$
$$\frac{\partial}{\partial\eta}(\frac{\chi T'}{\sigma})+(\gamma-1)\chi M^2 f''^2+cfT'+(\gamma-1)M^2sf'x\frac{d\bar{P}^{(1)}}{dx}+sx\hat{Q}(x,\eta)=x(f'\frac{\partial T}{\partial x}-T'\frac{\partial f}{\partial x}),$$

where

$$\chi=\frac{\bar{\mu}\bar{\rho}}{\bar{\mu}_e\bar{\rho}_e};m_1=\frac{x}{\bar{U}_e}\frac{d\bar{U}_e}{dx};c=\frac{1+m_1}{2}+\frac{1}{2}\frac{x}{\bar{\mu}_e\bar{\rho}_e}\frac{d}{dx}(\bar{\mu}_e\bar{\rho}_e);M^2=\frac{\bar{U}_e^{\,2}}{\gamma R^*\bar{T}_e}.$$

Here, $f'=\bar{U}/\bar{U}_e, T=\bar{T}/\bar{T}_e$ and $\bar{\rho}_e/\bar{\rho}=s$ and are all assumed to be functions of η and x; M is the streamwise edge Mach number and the viscosity $\bar{\mu}$ is allowed to behave according to Sutherland's law. The quantities $\bar{\rho}_e,\bar{U}_e,\bar{T}_e,\bar{\mu}_e$ are functions of the surface conforming coordinate x; however, in this work we only consider the case of uniform flow over a flat surface and as such $m_1 = 0$; $c = 1/2$.

The far-field boundary conditions are the usual ones of

$$f'(\eta\to\infty,x)=T(\eta\to\infty,x)=s(\eta\to\infty,x)=1;\bar{P}^{(1)}(\eta\to\infty,x),=0$$

while at the wall $\eta = 0$,

$$f(0,x) - f_w(x); f^{'}(0,x) = 0;$$

and for temperature, either the wall temperature or adiabatic condition (of zero heat-transfer) can be satisfied, namely:

$$T(0,x) = \bar{T}_w(x) / \bar{T}_e(x) = T_m - \frac{T_b}{2}(1+\tanh(\frac{x-x_s}{x_T}))$$

or

$$T^{'}(0,x) = 0;$$

the subscript w refers to the wall value and f_w allows for wall suction or blowing (mass efflux) to be incorporated into the analysis.

In the above, the quantities of interest are the inverse of the Froude number defined

$$G_o = \frac{g^* L}{\bar{U}_e^2 R_L^{1/2}} \quad (1.4)$$

With L a length scale and $R_L = \bar{\rho}_e \bar{U}_e L / \bar{\mu}_e$ a Reynolds number, while the heat source term is dimensionalised as follows:

$$\hat{Q}(x,\eta) = \frac{L\bar{Q}(x,\eta)}{C_p \bar{U}_e \bar{T}_e}. \quad (1.5)$$

We note from (1.3) that the key parameter that controls the magnitude of the buoyancy effect is G_o, and if all other free parameters vary, it is this parameter that needs to be fixed to obtain similarity of solutions, when two apparently quite different flows are compared. Interpretation of the results and their relationship to length scales associated with real fires may be seen by associating the Sutherland viscosity model used presently with the subgrid-scale based eddy viscosity and diffusivity concepts (Deardorff 1973) used in LES based simulations. Observe that η in (1.2) involves the viscosity $\bar{\mu}_e$,as do the definitions of the inverse of the Froude number G_o (through the Reynolds number R_L). Thus, in principle by a simple association of the subgrid based eddy viscosity in these scalings, the results presented herein may be applied to the length scales associated with evolving fires, albeit rather crudely.

Source Formulation

Our ultimate objective is to consider quite general situations where the source function consists of a steady 3-D-forcing term and an unsteady component, namely

$$Q^*(x,y,z,t) = \hat{Q}(x,y,z) + \delta q(x,y,t)e^{i\beta z}$$

where $\delta << 1$. However, in this work we assume the source forcing to be steady only and of infinite extent in z (Cunningham and others 2003), having the form

$$\hat{Q}(x,y,z) = q_o \tanh(\frac{\bar{x}}{x_o})\exp(-\frac{y-y_s}{y_o})\exp(-(\frac{\bar{x}-\bar{x}_s}{x_L})^2) \quad (1.6)$$

with the parameters $q_o, x_o, y_o, y_s, \bar{x}_s, x_L$ chosen conveniently. A typical example is shown in figure 1a, while figure 1b shows a possible wall temperature distribution that may be enforced. This particular wall temperature form is used to model the fact that behind the fireline, temperatures will have been raised by the evolving fire, while ahead of the fireline surface temperatures are still presumed to be at ambient levels.

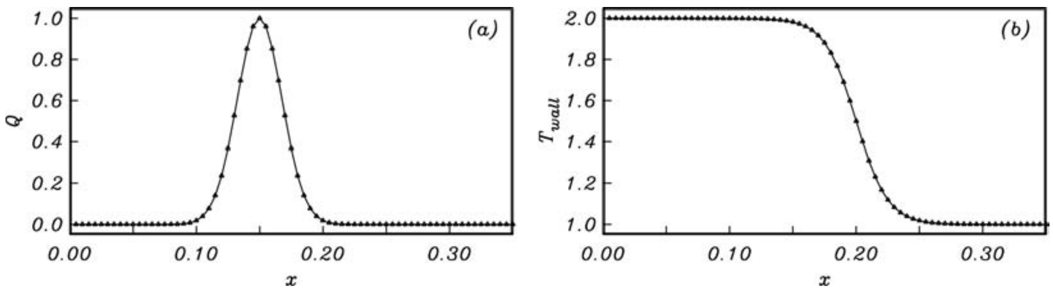


Figure 1—(a) Source strength distribution along the wall $y = 0$ for the parameters $q_o = 20$; $x_o = 0.001$; $y_o = 3$; $x_s = 0.15$; $x_L = 0.025$. (b) Wall temperature distribution for parameters $T_m = 2, T_b = 1, \bar{x}_s = 0.2, x_T = 0.025$ of equation 1.6.

Numerical Procedure

The system of equations are parabolic and thus solved by a fully implicit second-order accurate three-point backward differencing scheme, with a two point second-order accurate discretisation in the wall normal direction. The two point scheme arises by converting the second-order momentum and energy equations into a system of first-order equations. The nonlinear terms are discretised using standard Newton linearisation; thus, ultimately the inversion of a block tridiagonal matrix arises, which can be accomplished efficiently using standard methods. To initialise the computations at $x = 0$, the similarity form of (1.3) is used and thereafter a marching procedure employed.

For small magnitudes of $\hat{Q}$ the forced heat source problem will be amenable to a marching boundary layer type solution strategy. While as one should expect, and investigated by Higuera (1997), where sizable changes occur in the wall temperature, such a simple solution strategy will ultimately fail, in which case an interactive thermal layer with the pressure determined by the external inviscid adjustment of the boundary layer thickness needs to be computed or allowed for in any numerical scheme. Thus, either an interactive boundary layer type solution procedure or the fully Navier-Stokes solution procedure needs to be invoked. Flow reversal, separation, and reattachment regions do occur and are predicted by the asymptotic triple-deck analysis of Higuera (1997).

Daniels and Gargaro (1993) Boussinesq based buoyancy driven flow investigations conclude that in cases where the Froude number is too low, the boundary layer flow cannot be sustained, and the forward motion succumbs to the adverse pressure gradient induced by buoyancy. This either leads to the onset of reverse flow and the consequent failure of the numerical scheme or more generally to the occurrence of a terminal singularity. In cases where reverse flow sets in, their computations failed due to numerical instability rather than the existence of any local singular behaviour. The flow becomes subject to upstream influence, which then requires a much more sophisticated numerical treatment.

We examine the situation where both significantly raised temperatures and sizable buoyancy effects arise. Thus, at some stage where the flow parameters lead to a strong coupling between the normal pressure gradient and convective terms, either from significantly raised temperatures or buoyancy effects, we must anticipate a breakdown in the numerical solutions, since then the external inviscid field is strongly modified and straightforward boundary layer theory can then no longer be expected to be valid. We restrict our analysis to the parameter regime, where the problem is amenable to a parabolic boundary layer marching type solution procedure; namely where $G_o \sim O(1)$. Ultimately, however, as the buoyancy effects become sizable, boundary layer solution technique used here will fail, and at this point recourse to a fully Navier-Stokes solution for computation of the underlying basic state has to be made.

Basic Flow Solutions

The basic state model to be investigated is that of the forced basic steady flow, with Froude number and volume heat source $\hat{Q}$ as competing/coupled effects. We only consider zero pressure gradient, low Mach number flows, with flow parameters $T_\infty = 300K, \sigma = 0.72, R_L = 10^5, L = 1\text{m}$. The computational domain is of extent $0 \le x \le 1$, with a step length in x of $\Delta x = 0.005$. To obtain variations in Froude number we vary the free stream velocity U_e, and generally in fire related problems these flow velocities are in the range 0.5 ~ 10m/s, though as alluded to earlier the key parameter that controls the flow structure is G_o as defined by (1.4). Typical temperature variations examinable are up to 1200K; this may be varied by changing the source strength q_o.

Zero Volume Source Strength, $\hat{Q}$, and Zero Buoyancy

We begin by presenting some results for the zero source strength, zero buoyancy case. Of course this problem is the trivial flat plate incompressible Blasius problem; however, this serves as a useful guide and comparator when the more interesting parameter regime results are presented. Figure 2a shows streamwise velocity U and its derivatives, while figure 2b the streamwise normal velocity $V = V' / U_e'$ distribution at various x-intervals. Since this has a similarity structure, as would be expected, the numerical solution for U at all x-positions is identical, while that for V shows a decrease in the transpiration velocity or efflux to the external inviscid stream as the flow progresses downstream. We note two things: (1) this is of relative small order (as expected) and (2) it attains uniformly constant value sufficiently far from the wall. Furthermore, since the wall temperature is specified to be identical to the ambient, temperature variations are negligible and are thus not shown. Figure 3 shows the effect of maintaining different, above the ambient, uniform wall temperatures on solutions. The boundary layer thickens, the wall shear decreases, and the normal velocity magnitude increases; however, the near-similarity structure in the U and T profiles is still found to persist.

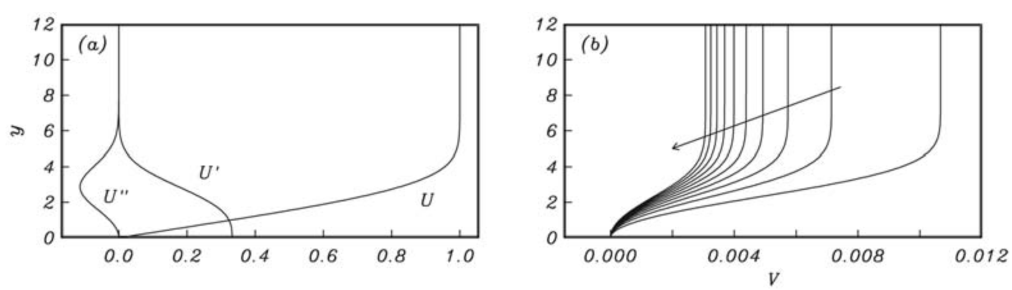


Figure 2—Blasius profiles at x = 0.065,(0.08),0.785 intervals. (a) Streamwise U velocity and derivatives U', U''. (b) Wall normal V velocity; arrow is in direction of increasing x.

To consider the effect of buoyancy on the solutions, we merely switch on the buoyancy terms in our equations and repeat the computations and the effect is shown in figure 3 by the dashed curves. We note that the differences are quite small, though they begin to increase as the wall temperature increases. The external wind speed for this particular run is approximately 3.46 m/s and the parameter $G_o = 1/386$; thus, one should not expect significant differences as the parameters selected are for a large Froude number.

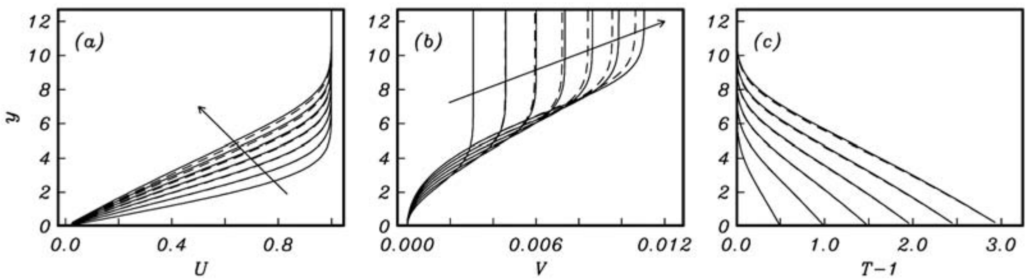


Figure 3—Compressible zero pressure gradient profiles at x = 0.785 for wall temperatures T_{wall} = (300,(150),1200),T_∞ = 300K,direction of arrows indicate increasing wall temperature. Comparison of solutions with (dashed line) and without (solid) inclusion of buoyancy terms in governing equations. (a) Streamwise U velocity; (b) Wall normal V velocity; (c) Temperature T-1.

Effects of Source Strength, $\hat{Q}$

We next consider how switching on the heat source affects results. We begin by examining the large Froude number case, corresponding to a wind speed of 10 m/s. The appropriate Q-source distribution selected is determined by trial and error; the particular source term distribution used here is that shown in figure 1a. Note from (1.6), that Y_o fixes the extent in y of the heat release, and choosing $y_o < 5$ essentially assumes that most of the heat release occurs within the boundary layer; setting $y_s > 0$ maximises the heat release off the wall boundary. The strength of the heat release (which determines the maximum temperature) is fixed by q_o. Figure 4a shows the temperature and figure 4b the wall normal (or updraft) velocity distributions achieved for varying q_o keeping y_o constant at various downstream positions. Apart from the obvious, namely increasing q_o increases boundary layer temperatures, we see that the effect is quite localised to the vicinity of the heat source (maximum heat release occurs at x=0.15). Observe that peak temperatures of about four times the ambient (~1200K) are achievable near the source, with the choice of parameters used. Downstream the overall temperatures decay in magnitude but still remain quite substantial.

We observe that changing the magnitude of the heat source has a major impact on affecting the magnitude of the vertical velocity. In the vicinity of the heat source maximum, a quite strong updraft of air arises for increasing q_o (note fig. 4b), but then immediately downstream of it a weaker though still relatively substantial downdraft also occurs. We note from figure 4b, for the choice of parameters or source forcing, the updraft velocity is almost 40 percent of the streamwise velocity, while the downdraft almost 10 percent. This downdraft diminishes, quite rapidly as we move downstream of the source, unlike the local temperature and streamwise velocity fields. We do compute

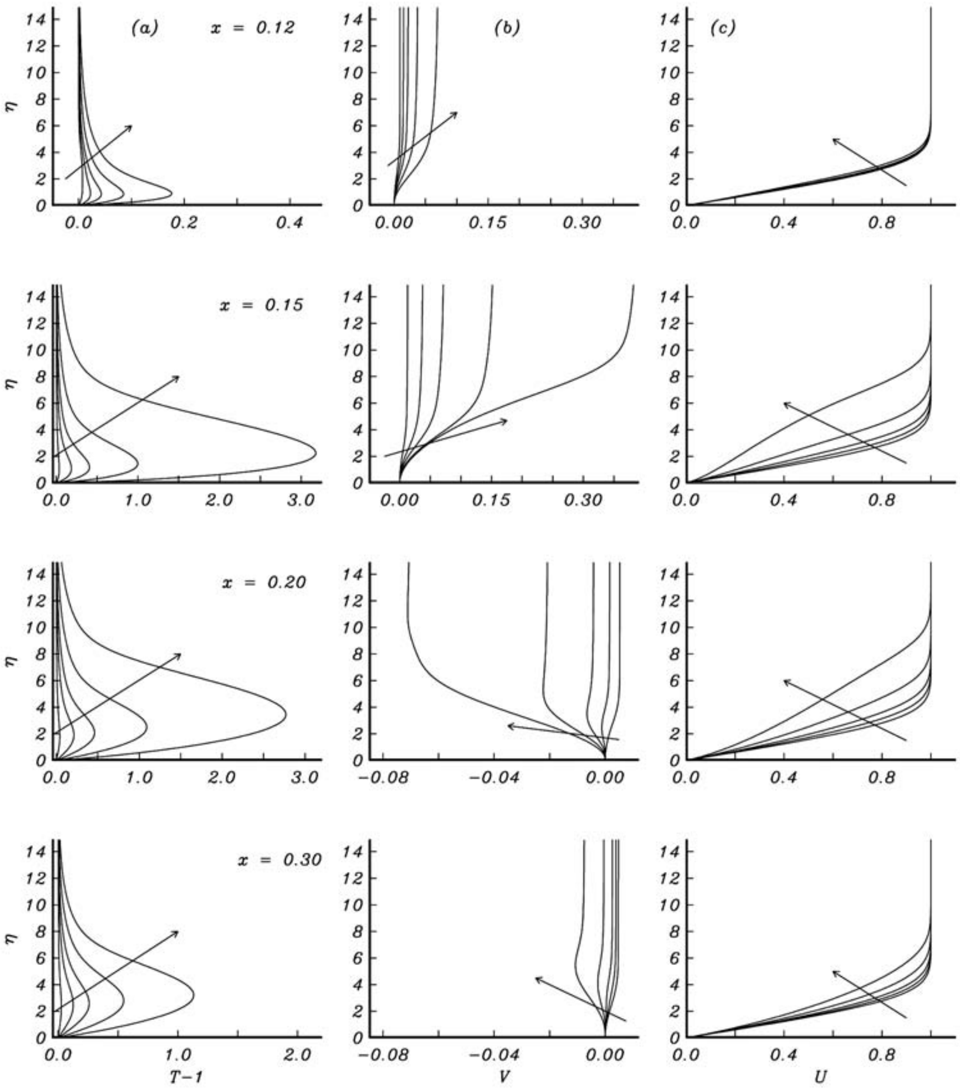


Figure 4—Effect of increasing source term magnitude q_o on nonbuoyancy driven flow at various x-locations. $U_e = 10m/s; q_o = (1,5,10,20,40); y_s = 0; y_o = 4; \bar{x}_s = 0.15; x_L = 0.025;$ $T_{wall} = T_\infty = 300K$ (*arrows point in direction of increasing* q_o). (a) Temperature profiles. (b) Wall normal velocity (*or updraft*) distributions. (c) Streamwise velocity distributions.

even greater updraft velocities for greater values of q_o which in fact exceed the value 1, with apparently no ill-effects as regards code convergence problems in this limit. We note that boundary layer theory, and the equations used presently are derived on assumption of $V \sim O(R_L^{-1/2})$, though the only terms omitted are the streamwise diffusion terms to render the equation parabolic and the assumption that the vertically convected momentum flux is of an order less than that induced by density changes. The mass conservation equation is solved exactly, so the only crucial weakness in the present model is that of assuming that the system is solvable by a parabolic marching procedure.

The effect of the heat source on the streamwise velocity, as may be deduced from figure 4c, is that heating modifies this quite drastically too, causing in general a reduction of the wall shear and a doubling of the boundary layer thickness. Ultimately if the applied heat release q_o is large enough, the boundary layer shows a tendency to separate. Our code in this limit then fails to converge. The above are computed for a ground temperature set to be the same as the ambient of $T_{wall} = T_\infty = 300K$, which is clearly impracticable; one assumes real fires have ground temperatures significantly higher. We next set the wall temperature to $T_{wall} = 600K$ and repeat the above runs. This is seen more clearly in figure 5, which also shows the downstream development of the temperature profiles. Apart from the satisfaction of the higher wall temperature condition, generally the results and trends are unchanged from those presented in figure 4.

In the context of fire propagation and sustainability we observe that well ahead of the heat source (for example, $x \sim 0.3$ in fig. 4) temperatures of the order of 600K persist. It is precisely this feature that acts as a preigniter, which readies the source material for combustion ahead of the fire line. The above is a useful indicator, since the downwind propagation distance of a fire front is usually associated with the farthest downwind location where the temperature of the solid fuel is raised to a particular threshold to initiate or continue the burning process. This is also a criterion used in determining the *rate of spread* of the fire.

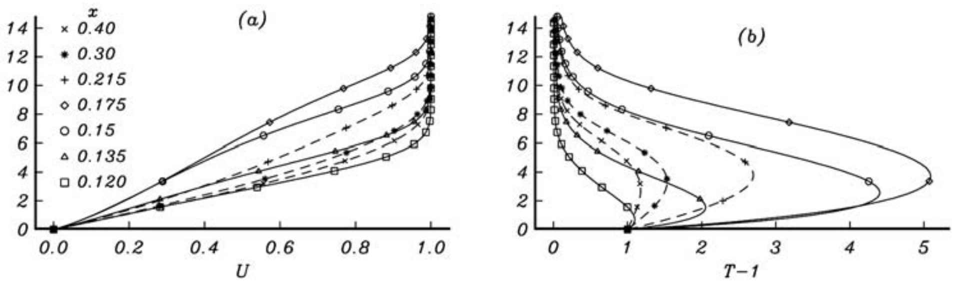


Figure 5—Streamwise velocity distributions at various x-locations. $q_o = 40$; $y_o = 4$; $y_s = 0$; $T_{wall} = 600K$; $T_\infty = 300K$. All conditions are identical to figure 4, except the wall temperature is held fixed at $600K$.

Buoyancy Effects

To examine buoyancy effects, based on evidence from the previous section, we choose values of $q_o = 25$, $y_o = 4$, $y_s = 0$ and gradually reduce the freestream velocity, thus reducing the effective Froude number F_o^2. As mentioned above it would appear to be more realistic to have sizable wall temperature and thus in all results presented we fix this at 600K. Moreover based on previous observations and numerical evidence gained presently, we note that the Froude number may be redefined to include temperature dependence, since we find numerical convergence of our fully coupled system of boundary layer equations is Froude number dependent. Thus, results are presented with the definition

$$\hat{F}_o^2 = \frac{\bar{U}_o^2 R_L^{1/2}}{Lg^* \Delta T_{\max}}, \Delta T_{\max} = \frac{T_{\max}}{T_e} - 1, \qquad (1.7)$$

with T_{max} the temperature maximum in the boundary layer. This we note also follows from (1.3), since the term $\Delta T_{\max} / \hat{F}_o^2$ is the total magnitude of the buoyancy induced pressure component at any point in the field, and quite naturally the larger this becomes, the coupling between the equations increases, until the system is no longer treatable using a parabolic based approach. Clark and others (1996a) in an attempt to characterise wind-driven fires use a similar expression, namely

$$\hat{F}_{rc}^2 = \frac{U_o^2}{W_f g^* \hat{\Delta} T_{\max}} \tag{1.8}$$

with $\hat{\Delta} T_{\max}$ a mean value of the temperature anomaly over the region of intense heating and W_f a fireline width in the mean wind direction. In the present case we observe that dynamical similarity between two different flows is assured provided the parameter G_o is identical. The cases examined and correspondence between U_e and $\hat{F}_o^2$ are given in table 1.

Table 1—Values of local Froude number $\hat{F}_o^2$ based on (1.7) for cases presented.

U_e (m/s)	$\hat{F}_o^2$	$1 / G_o$
10.00	1080	3224
7.50	610.5	1813
5.00	274.3	805.9
2.50	71.91	210.5
1.00	13.41	32.24
0.75	8.101	18.13
0.50	4.044	8.059
0.375	2.490	4.533
0.25	1.267	2.015
0.10	0.270	0.322
0.05	0.078	0.081

Profile distributions at a fixed Froude number (corresponding to $U_e = 0.05$ m/s) and varying the source strength q_o are shown in figure 6, while that of keeping q_o fixed and varying the Froude number are shown in figure 7. A number of important features may be deduced. The streamwise velocity develops distinct maxima; that is, inflectional profiles that exceed the freestream value of unity, before ultimately reducing back to unity for $y \to \infty$, and wind shear at the wall increases for decreasing $\hat{F}_o^2$. Normal velocity distributions near the heat source release are now downward directed (of order of about 30 percent), unlike the earlier high Froude number situation, followed by a much weaker updraft downstream of the heat source. This is almost the reverse of the situation depicted in figure 4. Temperature profiles show a reduction in magnitude for increasing buoyancy. Note a reduction in peak temperature of approximately 600K as the Froude number $\hat{F}_o^2$ reduces from 1080 to 0.078.

The generation of inflectional profiles is of course related to density (temperature) gradients and the high value of G_o that results in sizable buoyancy induced pressure gradients, which feed into accelerating the streamwise velocities by way of a strongly induced streamwise pressure gradient. In the earlier high Froude number situation this mechanism was suppressed, and thus the extra energy supplied in the form of the volumetric heat release could only be quickly dissipated by increasing the updraft velocity. Furthermore, we observe that inflectional profiles result from the temperature difference and that our inclusion of a heat release source term in the equations, simply

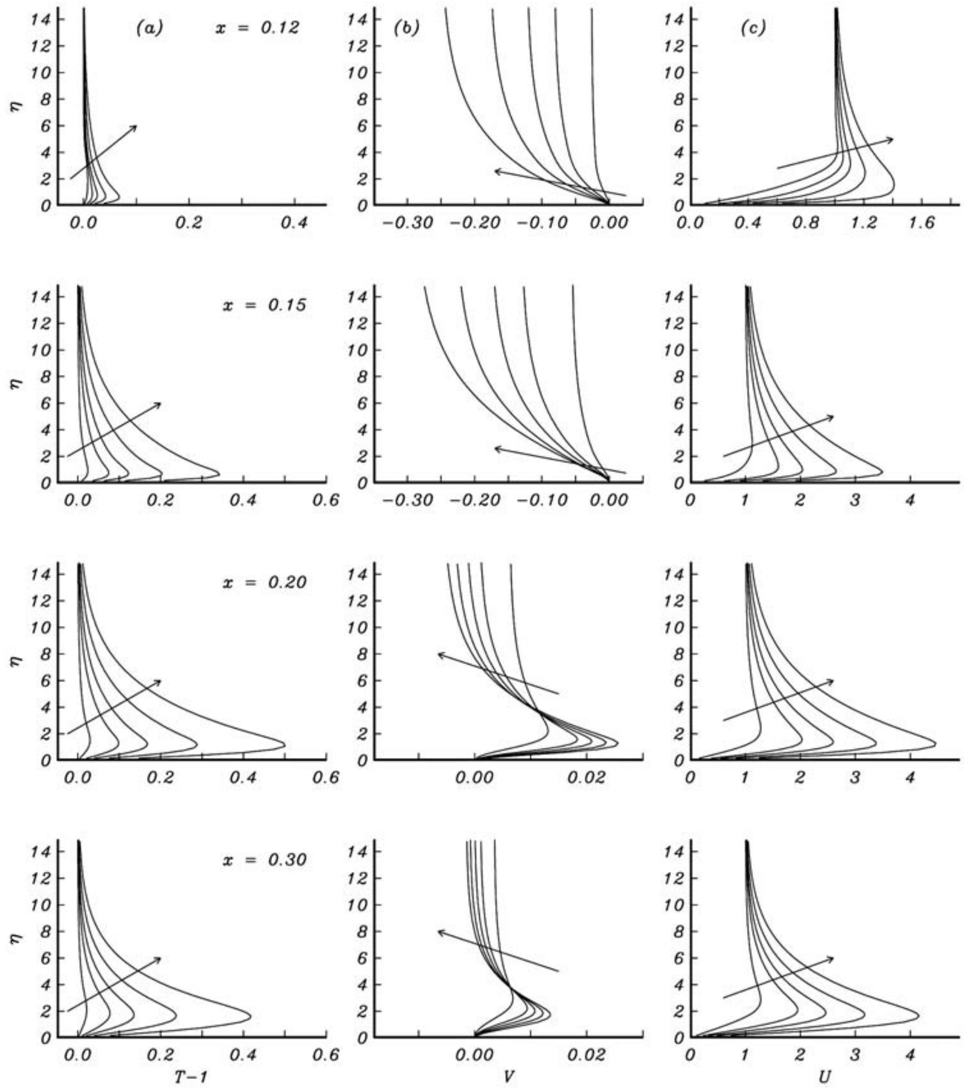


Figure 6—Effect of increasing source term magnitude q_o on basic buoyant flow at various x-locations. $U_e = 0.05 m/s; q_o = (1,5,10,20,40); y_s = 0; y_o = 4; \bar{x}_s = 0.15; x_L = 0.025; T_{wall} = T_\infty = 300K$; (*arrows point in direction of increasing* q_o). (a) Temperature profiles. (b) Wall normal velocity (*or updraft*) distributions. (c) Streamwise velocity distributions.

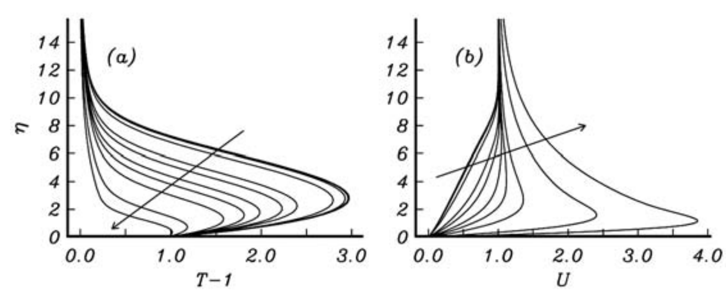


Figure 7—Profile distributions at $x = 0.175$ for varying Froude numbers corresponding to $U_e = (10.0,7.5,5.0,2.5,1.0,0.75,0.5,0.375,0.25,0.1,0.05)$ (*arrows point in direction of increasing* U_e). $q_o = 25$, $y_o = 4$, $T_{wall} = 600K$ (a) T temperature distributions. (b) U velocity distributions.

offers a facility to generate thermal variations in the boundary layer. In the absence of the heat source, inflectional profiles could have been generated by maintaining a different wall temperature from the ambient, and provided the Froude number (or $1/G_o$) is small enough, the same mechanism exists to generate inflectional profiles. The fact that inflectional profiles do not arise in figure 4 is that G_o is arranged to be of an almost negligible value, despite the fact that significant temperature differences (up to 900K) between the ambient and wall exist. To show that this is the case, figure 8 shows results for the case of maintaining uniform wall temperature at 600K, but computed for varying Froude numbers at a fixed position, and as expected inflectional profiles result for the low Froude number runs, and as indicated, thermal energy is used to accelerate the flow, thus resulting in less fuller temperature profiles compared to the high Froude number case.

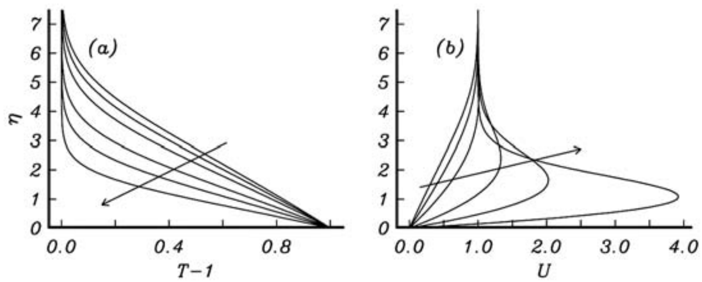


Figure 8—Profile distributions at $x = 0.3$ for varying Froude numbers corresponding to $U_e = (10.0, 0.5, 0.25, 0.1, 0.05, 0.02)$ (*arrows point in direction of increasing U_e*). Zero volumetric heat release; that is, $q_o = 0$, $T_{wall} = 600K$ buoyancy generated purely by maintaining a wall to ambient temperature difference. (a) T temperature distributions. (b) U velocity distributions.

The analogous case where, rather than the heated wall, the volumetric heat source produces the temperature difference is shown in figure 7. Observe that for low free-stream velocities the parameters $\hat{F}_o^2$ and G_o^{-1} in table 1 are similarly valued, while at high flow velocities this is not the case. This arises entirely from the fact that at low Froude numbers, as indicated in figures 6 and 7 and in relation to the earlier high Froude number results of figure 4, energy supplied in the form of heating is used to accelerate the streamwise velocity rather than raising field temperatures. Thus, in low Froude number situations the preference is for the thermal energy being utilised to accelerate the local flow, rather than raising temperatures. In the limit of extreme buoyancy, one then gets the situation where the flow quite aggressively uses as much of the heat energy in accelerating the local flow in the streamwise direction, leaving little in the temperature field.

The results of figure 6 are for an extreme value of the Froude number or an extremely buoyant flow, whereas in practise, provided the Froude number is of $O(1)$, one expects a tradeoff or competition between the propensity for the boundary layer to use the extra energy supplied by the heat source to either increase local boundary layer temperatures or locally accelerate the streamwise flow. This competition between the two is shown, for milder buoyancy driven case, in figure 9. In this case, free-stream velocity is about 0.5 m/s, and the effects of keeping the buoyancy fixed and increasing the heating through the source term are shown. We see a more typical situation

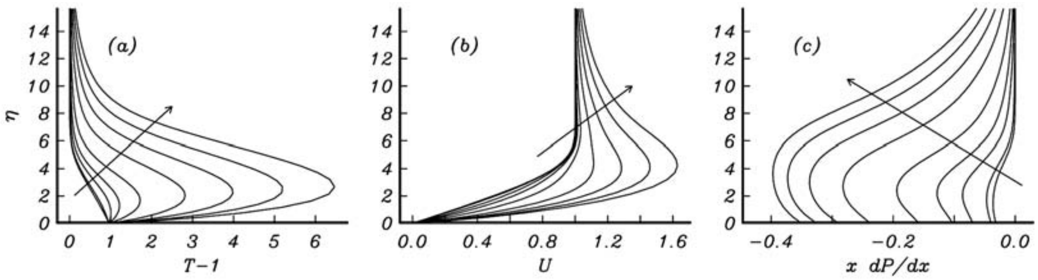


Figure 9—Profile distributions at x = 0.175 for fixed Froude number for varying source strength magnitude q_o = (0,1,5,10,20,40,60,80,100) (*arrows point in direction of increasing* q_o). U_e = 5m/s, y_o = 4, T_{wall} = 600K (a) T temperature distributions. (b) U velocity distributions. (c) Streamwise pressure gradient distributions.

that probably arises in fire situations, where both overshoots in the streamwise velocity and substantially increased temperature profiles arise. Figure 9c shows the induced pressure gradient, which is the factor in causing the acceleration of the streamwise flow.

The main point to note, however, is that the crucial parameter that governs the strength of the buoyancy is G_o, so the value of the ambient wind speed is immaterial and by appropriate choice of parameters—that is, viscosity or density say—a parameter situation can be created where buoyancy is a sizable factor, even though wind speeds may appear large.

Finally we present in figures 10 through 12 the main features uncovered in the analysis. Figure 10 shows temperature and streamwise velocity for a mildly buoyant flow, while figure 11 the case where the buoyancy is considerably stronger. In these computations we have also specified a wall temperature distribution shown in figure 1b; thus, beyond $x \sim 0.2$, the wall temperature is specified to be 300K, while upstream it is fixed at 600K. We note the extreme velocity overshoot arising for the $U_e = 0.05$ case; these overshoots in velocity persist well downstream of the heat source as do the raised temperatures, in spite of the fact that the wall temperature is specified to be the ambient. As already noted, buoyancy terms effectively force or use the energy supplied by the heating to accelerate the streamwise velocity at the expense of increasing the temperature field. This additional acceleration of the flow stream (due to heating) thus forces the horizontal boundary layer motion to be sustained for a larger extent downstream before it ultimately succumbs to the adverse pressure gradient generated by the buoyancy. Presumably in situations of continuous applied heat source in the downstream direction, this motion may well then be self-sustaining.

We further note the quite concentrated and strong downdraft region in the vicinity of the heat source in figure 12 and the switch over from a strong downdraft to an equally strong updraft in varying Froude number from low to high. The occurrence of weak downdraft behind the fireline, followed by relatively stronger updraft ahead of the fireline, has also been found in LES simulations of Linn and Cunningham (2005). Cunningham and others (2003) find that the magnitude of the heat source is a major factor in the magnitude of the vertical velocity produced and then go on to suggest that this plays a key role in the amount of time it takes for a buoyant parcel to rise through the shear layer and that the counter rotating vortex pair observed in their simulations has its origin near the ground as a pair of vortices oriented

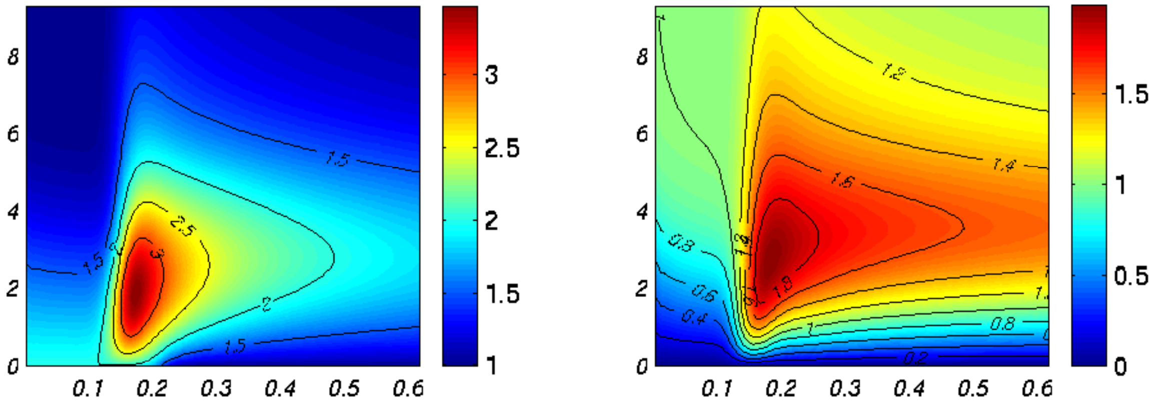


Figure 10—Mild buoyancy case corresponding to $U_e = 0.25$m/s; $y_o = 4$, $y_s = 2.0$, $q_o = 40$, $x_L = 0.05$, $T_{wall} = 600K$ (a) Temperature field. (b) Streamwise velocity field.

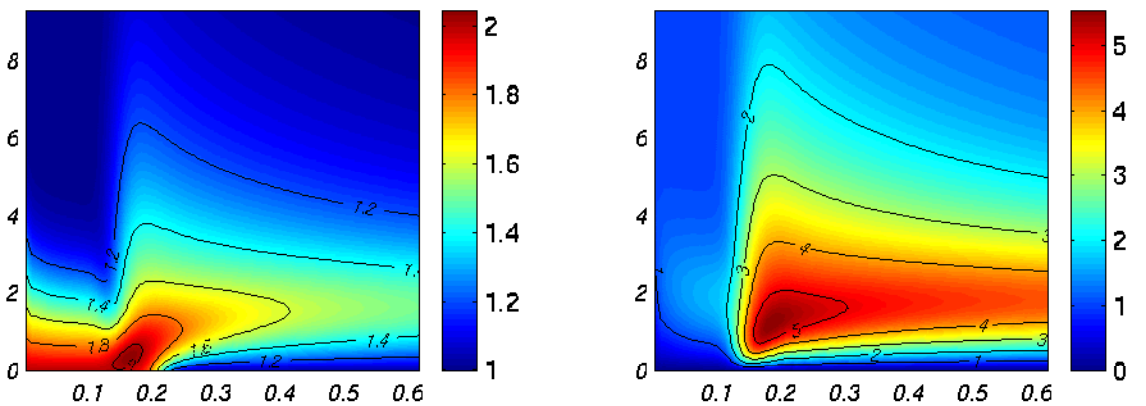


Figure 11—Strongly buoyant case corresponding to $U_e = 0.05$m/s; $y_o = 4$, $y_s = 2.0$, $q_o = 40$, $x_L = 0.05$, $T_{wall} = 600K$ (a) Temperature field. (b) Streamwise velocity field.

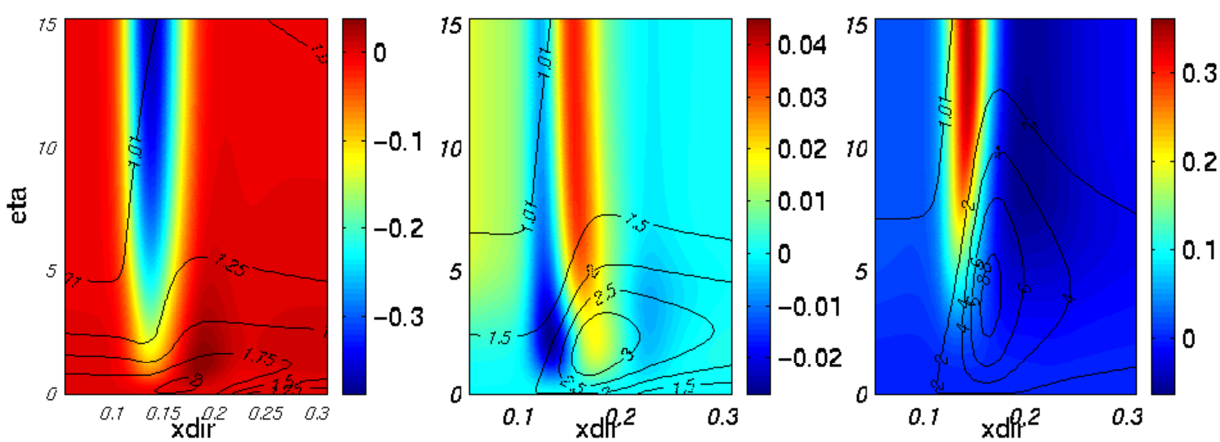


Figure 12—Wall normal velocity distribution for varying Froude number, for fixed source strength magnitude. Contours denote the superposed temperature field. (a) $U_e = 0.05$m/s; (b) $U_e = 0.25$ m/s, (c) $U_e = 2.5$ m/s. $q_o = 40$, $y_o = 4$, $T_{wall} = 600K$.

primarily in the vertical direction. Since buoyancy can only directly generate horizontal vorticity, the vertical vorticity can only be generated by tilting of the horizontal into vertical direction. In this regard, the strongly buoyant updraft plays a key role.

Cases where the streamwise velocity exceeds unity may play a role in the propagation of crown fires (fires burning through the tree canopy rather than through surface fuels). A recent observational study using infrared imagery to examine crown fire dynamics noted horizontal flows far greater than ambient winds by an order of magnitude (Coen and others 2004). They hypothesise that these bursts, as they refer to them, are the result of nonlinear interactions that transfer vertical momentum generated by buoyancy to horizontal momentum before buoyancy takes over and produces a more vertical plume rise. This theory would seem to be supported by the present work, in that we observe that the buoyancy term effectively forces or uses the energy supplied by the heating to accelerate the velocity.

Inflectional profiles have been noted before as being tied to extreme fire behaviour (Byram 1954).

However, the focus on the ambient wind profile is inflectional, not the input of heat generating an inflectional profile. The reasoning is that hot columns of rising air draw in air from the surroundings, thus leading to wind-induced acceleration of the local winds in the vicinity of the fire line. Clark and others (1996a) present cases of similar dynamics in a fully 3-D coupled model that produces significant fingering of the fireline in the spanwise direction at low Froude number values. They suggest that when the fireline's speed is slow enough, fire-generated winds break up the fireline. Though how this breakup occurs, from a rigorous physics or mathematical modeling viewpoint, is not addressed. They surmise that eventually convection and local dynamics become nonlinear, producing erratic shapes to both the fire line and convection. They hypothesise that large horizontal buoyancy gradients at the fire front produce strong horizontal vortices, and the vertical motions within the fire eventually lead to vortex tilting, producing vertical vorticity, and that in some cases these vertical vortices cause the breakup of the fireline. After breakup of the convection column, the formation of fingers is identified in the vicinity of the fire. They conclude that fire line breakup and formation of fingers are the result of light winds and thus a dynamically unstable fire line leading to the breakup of the two-dimensional column of hot air into multiple columns. Moreover, in addition to $\hat{F}_o^2$ being small, they conjecture that another ingredient required for fingering to occur is that of low-level negative shear, where the wind blows faster near the surface than just aloft. They suggest that this arises either from gust fronts, convective downdrafts and mountain valley flows, whereas our analysis shows that the fire itself can generate such inflectional flows. They speculate that dynamic fingering is caused by vertical tilting regions of intense horizontal negative shear at the fire front leading to narrow regions of high speed, hot air shooting out in front of the fire. This is a major process in fire spread on the micro-scale, which causes fires to jump as they spread.

Summary of Basic Flow Solutions

We have shown that using quite a simple two-dimensional model formulation, a wide variety of forced heat and buoyancy coupled problems can be examined. Adding in heat release by way of distributed heat release over a finite extent allows many of the basic features arising in fire propagation to be identified or captured. Our intention has been to strip away the complexity of using fully unsteady DNS multiphase based formulations and solution techniques in favour of a more rudimentary formulation in order to identify the key mechanisms arising and playing a major role in observed fire propagation. As such the model does produce features that typically arise in fires. Namely velocity overshoots or so-called super velocities caused by the coupling of buoyancy and heat release near the ground. The model suggests that in the low Froude number regime, heat release is directly responsible for causing the local streamwise wind speeds to accelerate drastically. Strongly inflectional stream wise velocity profiles are generated; thus, we can expect the more dangerous (from a boundary layer instability viewpoint) inviscid instabilities to arise. The analysis in this regime also shows that regions of high shear arise close to ground and that temperature profiles are generated that have been observed in typical forest fires. The model also correctly predicts the generation of strong updraft velocity followed by a weaker downdraft, though a role reversal is also predicted, whereby in high wind conditions heat release causes highly buoyant updrafts of air, while in low Froude number regimes the reverse happens and an equally strong downdraft arises. The model is easily extended to properly three-dimensional volumetric forcing, thus allowing for buoyancy dependence in (x, z)-directions and thus would allow the effect of fire-length in the spanwise direction to be simulated at a fraction of the computational cost of full DNS investigations.

Our interest in this problem originally arose from the viewpoint of addressing the instability properties of velocity and temperature profiles that typically arise in fire problems. There does not appear to have been any systematic study of examining the stability properties of boundary layer profiles of the type that do occur in fire-related problems. In particular as may be noted from figures 4, 5, and 7, typically quite dramatic and sizable temperature profiles arise, and the combination with the inflectional velocity profiles does not appear to have been examined or quantified from a boundary layer instability viewpoint. Of course, inflectional velocity profiles and their instability properties are well known, but the issue of sizable temperature profiles and their combination with inflectional velocity profiles have to our knowledge not been the subject of any systematic investigation. Moreover, in the study of the high Froude number case, we have shown temperature profiles of the order of 1200K are generated. The stability properties at this high temperature, low Mach number regime are of interest from the viewpoint of erratic fire behaviour, propagation, and also from the viewpoint of how vertical rotors, rotating rolls, and intense vortices develop. As shown in computations in this paper, strong horizontal gradients in buoyancy near the surface produce strong horizontal vorticity. As the horizontal vorticity is tilted into the vertical by the fire updraft, intense vertical vorticity may develop where large buoyancy and horizontal gradients of the vertical wind coexist. As is well known, within fires there are small vortical structures on the millimetre scale that tightly bend the flame fronts, up to vortex structures on length scales of many metres. Simulations of plumes from line sources by Cunningham and others (2003) find that as the plume rises, it is bent downstream, and a regular array of steady perturbations develop in the cross-stream direction along the plume cap. As time progresses, the plume then undergoes a transition from its initial two-dimensional structure to an eventual three-dimensional one, with this transition being evident in a region far from the heat source. The vorticity field shows that initially the dominant vortical structure is the spanwise vortex tube associated with the plume cap; while at later times streamwise vortex tubes become dominant.

To initiate an understanding of such complex features, the basis for investigation is the use of linear stability theory to look at trends and identify features that do lead to those observed and hypothesised above. Previous instability work has been almost wholly based on buoyancy associated with the low temperature Boussinesq assumption. The majority of earlier studies have been confined to examine stability of vortex structures where the coupling between the energy and momentum fields is weak and the fluid density or compressibility essentially plays no role apart from introducing the buoyancy associated pressure term into the equations. Thus, few works have considered fully compressible nonsimilar boundary layers and their consequent instability of the boundary layer profiles where the coupling between the energy and momentum fields is strong. Our principal interest in the following is how the effects of buoyancy influences the stability of the basic flows discussed above, in a fully compressible problem.

Linear Instability of Basic Flow

To conduct a linear stability analysis of the flow, first the standard decomposition of the flow variables into a main flow component and an (infinitesimally) small disturbance is applied. That is the total flow $\mathbb{Z}'$ described by the exact unsteady fully compressible Naiver-Stokes equations can be split into a basic *steady* flow and an *unsteady* component, hence

$$\mathbb{Z}'(x,y,z,t) = \bar{\mathbb{Z}}(y) + \Pi'(x,y,z,t),$$

with $\bar{\mathbb{Z}} \gg \Pi'$. In the present case only a 2-D and steady mean flow is assumed. On the other hand, the disturbances are assumed to be 3-D and thus can be written as

$$\Pi'(x,y,z,t) = \Pi(y)\exp^{i(\alpha x + \beta z - \omega t)}.$$

An eigenvalue problem arises and thus a dispersion relation of form

$$\mathbb{F}(\alpha,\beta,\omega,R_\delta,F_o^2) = 0$$

requires to be satisfied. We specify (β,ω) as free parameters, with (R_δ, F_o^2) flow dependent and solve for the spatial eigenvalue α. The objective is to map out the parameter space in β,ω,R_δ and F_o^2. We concentrate on two aspects: (1) the stability of profiles of typical form given by figures 4 and 5; (2) low Froude number coupled with the heat source basic flows of form given by figures 6 and 9.

Influence of Source Distribution, Zero Buoyancy

Neutral curves corresponding to figures 4 and 5 (T_{wall} = *300K* and T_{wall} = *600K* respectively) are shown in figure 13 for varying heat source magnitudes. We observe two effects: one is that increasing q_o increases the instability frequency envelope, and second, we see that the neutral curves (for a large enough value of q_o) are closed. That is, heat release first causes a local (or further) destabilisation of the flow, totally rearranging the flow structure, but this is beneficial in that downstream of the heat release, the flow is totally stabilised. For the T_{wall} = 600*K* simulation, the flow in the absence of the

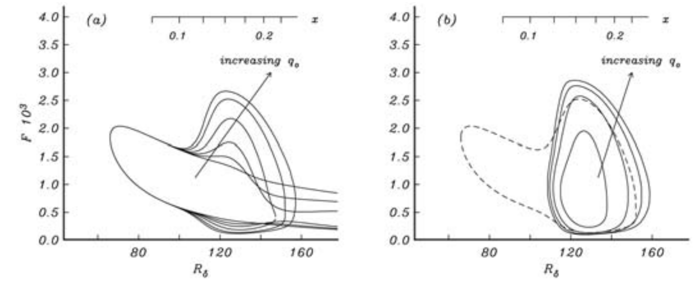


Figure 13—Zero buoyancy ($U_e = 10$ m/s) neutral curves for parameters of figures 5 and 4 for varying heat source magnitudes. $F = 10^3\ \omega\ /\ R_\delta$ m/is the circular frequency. (a) $q_o = (1,5,10,20,40,60)$; $T_{wall} = 600K$. (b) $q_o = (120,40,60,80)$; $T_{wall} = 300K$. Also superposed is the $q_o = 40$ result from figure (a) (*shown as dashed curve*).

volumetric heat source, becomes naturally unstable beyond $R_\delta \sim 66$; at about $R_\delta \sim 100$, corresponding to $x \sim 0.1$ (refer to fig. 1a), the instability envelope increases having its upper bound at about the point where peak heat is being released (x=0.15) and it then diminishes in size, and given the appropriate amount of heat the flow can be completely stabilised. Though not shown, further downstream we do find that as the flow readjusts to normalcy, the region of instability reappears, but this point can be shifted farther downstream by further increments in q_o. Of course q_o cannot be increased indefinitely, since ultimately the boundary layer shows a tendency to separate. But clearly we see that heat release causes a destabilisation of the flow in the vicinity of the heat source release region. These points are confirmed and reemphasised in the $T_{wall} = 300K$ case. In this case, heat is released well upstream in a region, which in normal circumstances exhibits no instability until about $R_\delta \sim 520$ (the critical Reynolds number for incompressible Blasius flow). Thus, heating generates the pocket of instability, and we further see that this is localised to the vicinity of the heat release region. Though not shown, the eigen-functions reveal that the unstable modes are thermally induced, in that temperature disturbances are the largest in magnitude. Though overall, the growth rates of these thermally induced unstable waves are found to be quite small.

Buoyancy Effects

Impact of decreasing Froude numbers on the neutral curves for 2-D disturbances is shown in figure 14a, while growth rates over the frequency span at various x positions for the lowest Froude number neutral curve, corresponding to $U_e = 0.5$m/s, are shown in figure 14b.We note that the $U_e = 10.0$m/s curve is closed and almost total stabilisation of flow is achieved, whereas for the lowest Froude number curve shown, the unstable frequency spectrum enlarges considerably in the heat release region while disturbances down to the stationary are unstable. In the limit of $\omega \rightarrow 0$ the growth rate and wavenumber both approach zero, while as $\omega \rightarrow \infty$ or large steamwise wavenumber limit, the disturbances ultimately return to being stable. Note that with increasing R_δ the growth rates increase substantially; thus, a rapid destabilisation occurs as a result of the heat release. Another feature is that as x increases the curves coalesce, and this may be due to the instability being essentially inviscid in structure, and so the value of R_δ becomes irrelevant.

Figure 15a shows growth rates for 3-D disturbances arising in the mildly buoyant flow examined in figure 14b and shows that in a certain frequency

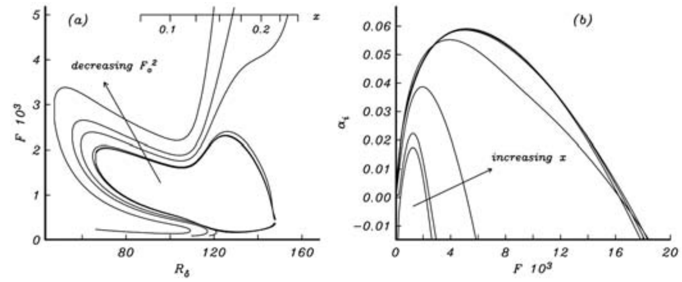


Figure 14—Neutral curves for increasing levels of buoyancy, computed for parameters corresponding to figure 7. Neutral curves are shown for Froude numbers corresponding to(U_e = 0.5, 0.75,1.0, 2.5,5.0,10.0); T_{wall} = 600K. (b) Amplification curves for varying frequency at various x-positions corresponding to the plot shown in (a) for the U_e = 0.5m/s case; arrow points in direction of increasing downstream distance in x corresponding to R_δ =100, 110,120, 130, 140, 150,158.

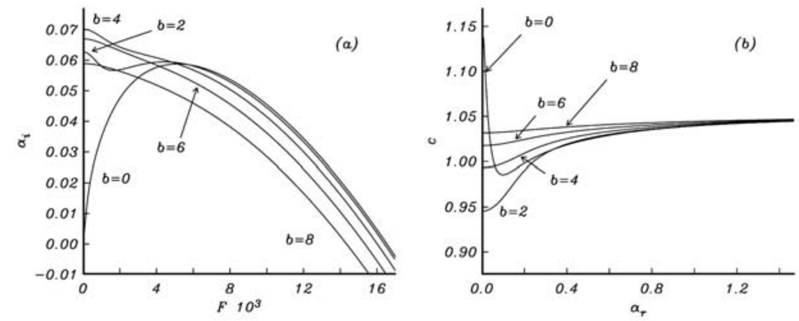


Figure 15—(a) Amplification curves for varying frequency for 3D disturbances at x = 0.224; R_δ =150; b = 1000, β/R_δ =for the mildly buoyant flow of U_e = 0.5 m/s. (b) The corresponding phase speed c variation with wavenumber α_r.

regime the 3-D disturbances are more destabilising than 2-D disturbances; with the stationary vortex being most unstable, while at high frequencies it is the 2-D disturbance that is most unstable. For stationary disturbances, we note from figure 15b that the streamwise wavenumbers are zero, and so these disturbances (the most dangerous from an instability viewpoint) are purely periodic in the spanwise direction only. Instability occurs over a finite range of β and at large enough β, disturbances return to being stable, while (though not shown) as $\beta \to 0$ the growth rates behave as $\alpha_t \sim \beta^{1/2}$.

The phase speed c, as ω (and thus α_r the wavenumber) tends to large values asymptotes to the maximum velocity overshoot value (in case shown this limit is ~ 1.05). This result is consistent with the Boussinesq based incompressible inviscid works of Mureithi and others (1997) and Denier and others (2001) who essentially build upon the more complete earlier, again Boussinesq based, asymptotic and numerical analysis of Hall and Morris (1993). The former two authors' findings were deduced primarily by a numerical solution to the 3-D version of the inviscid Taylor-Goldstein equation while our solutions are based at finite Reynolds number and allow for full compressibility, though for the quite low external wind speeds considered the Mach number effects are insignificant. Their inviscid solutions suggest that the flow is unstable across the whole wavenumber spectrum and that growth rates become progressively larger as α increases and then state that viscosity ultimately must return the flow to a stable regime as $\alpha \to \infty$. Our viscosity included results confirm this result. They also confirm the findings of Hall and Morris (1993) that for nonzero β the mode with the largest growth rate occurs for $\omega = 0$. That is, the dominant wave mode becomes purely steady and two-dimensional in the spanwise direction, and at leading order the waves travel with a phase speed equal to the maximum of the streamwise velocity. This situation with the phase speed though only really arises in the limit of $\omega \to \infty$ in regions where our viscous included stability analysis, suggesting that disturbances have returned to a stable regime.

We only show neutral curves for values of Froude number down to $U_e = 0.5$m/s; this is merely for brevity, in that for even lower Froude numbers the instability envelope increases considerably, both in terms of the frequency space and even larger growth rates. An analogous result to figure 15 but corresponding to the highly buoyant flow at $U_e = 0.05$m/s is shown in figure 16. This merely confirms the findings deduced from the mildly buoyant case, in that decreasing Froude number increases the instability and unstable parameter space. We note from the eigenfunctions (fig. 17) the high frequency most amplified 2-D disturbance is localised off the wall about the position where the streamwise velocity attains its maximum overshoot value, while the purely spanwise periodic disturbance (fig. 17a) is situated close to the wall. This is clearly viscous in nature, while the former is of the inviscid type (fig. 17b). In the above, we only report on the first or most amplified mode, though as Reynolds number increases unstable higher modes were also identified.

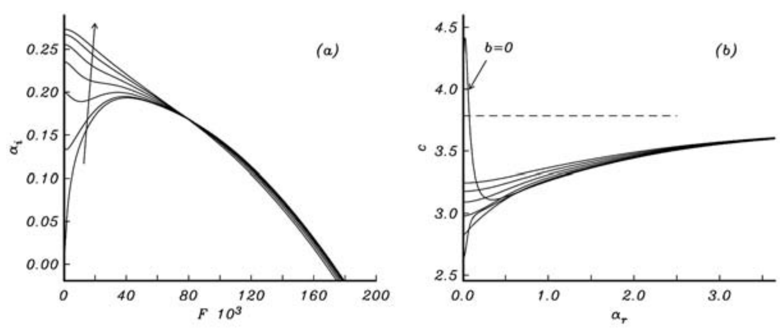


Figure 16—(a) Amplification curves for varying frequency for a number of 3-D disturbances ($b =$ 0,(2),12) at $x = 0.169$, $R_\delta = 130$; b= 1000 β/R_δ for the highly buoyant flow of $U_e = 0.05$ m/s. (b) The corresponding phase speed c variation with wavenumber α_r. The dashed line corresponds to the maximum velocity overshoot value of ~3.78, as $\alpha_{rv} \to \infty$ the curves asymptote to this value.

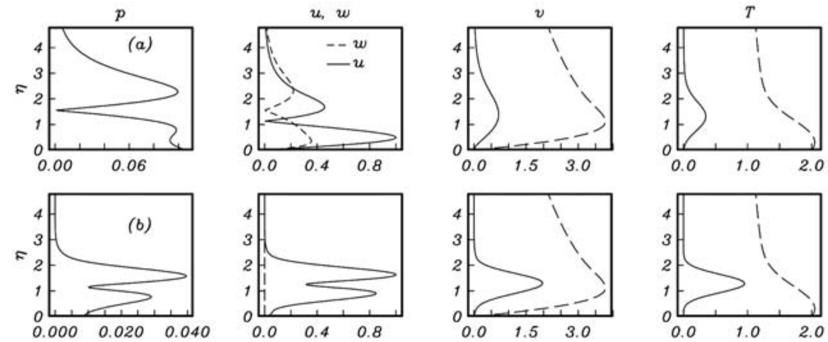


Figure 17— (a) Three-dimensional disturbance eigenfunctions computed for parameters of figure 16 at *F* = 0, *b* =12, the pure vortex most amplified mode. (b) Two-dimensional eigenfunctions at *F* = 120, *b* = 0. The dashed curve in the v-plots is the overshot inflectional basic velocity profile, while the curve in the T-plot is the basic temperature profile.

Conclusions

We may conjecture that in the two Froude number limits, there are two different routes to fire behaviour and destabilisation, with the Froude number playing a crucial role in the boundary layer development and consequential instability of the convecting flow. The work lends support to some of the earliest criteria established (Byram 1954), and recently put forth by Nelson (2003), that erratic fire behaviour occurs when the ratio of the power of the wind to the power of the fire is ≤ 1 (essentially a Froude number definition). In view of the low growth rates in the high Froude number case, perhaps the significant factor is the sensitivity of the boundary layer to separate and lift off the wall; this being caused by massive updrafts of buoyant air. The relatively weak nature of instabilities in this regime suggests that the convecting boundary layer or fireline development would otherwise be well behaved. This is consistent with the work of Clark and others (1996b), who find that in high ambient windflows, a stable fireline arises forming a continuous parabolic shape (their model was fully three-dimensional and unsteady) as the fire evolves.

We have shown that the addition of heat goes directly into forming a highly accelerated streamwise velocity or jetlike flow in the low Froude number limit. In this limit, certainly the inflectional nature of profiles plays a strong role and must be a key feature in observed fire features. Local acceleration of flows by buoyancy and instability of inflectional profiles has been known about for some considerable time; however, its relevance in fire related problems has not been identified until now. The work suggests that if the ambient profile is initially inflectional, the transition to the unstable modes should be more rapid. The work essentially shows that a massive destabilisation via the inflectional route takes place in the low Froude number regime and that stationary, zero streamwise and nonzero spanwise wavenumber viscous disturbances have the highest growth rates. The results show that the flow can support purely spanwise periodic disturbances (that is, vortices) and that it is feasible for these modes to have the largest growth rates. These are commonly referred to as pure vortex longitudinal "roll cell" modes. These might well be linked to cross roll features mentioned in the work of Cunningham and others (2003). Clark and others (1996b) identify similar features and state that a key requirement in breakup of the fireline is a low enough ambient wind (low Froude number) and thus speculate that the breakup is due to fire generated winds. Remarkably, in one of their figures, a distinct periodic spanwise vorticity field is seen, which they describe as *erratic* behaviour of the fireline.

In particular as regards the fingering phenomenon, Clark and others (1996b) hypothesise that once a fire line is long enough it cannot sustain a single convective updraft column and develops multiple columns due to long-line instabilities within the convection column. The convection attempts to form a long, vertically deep, nearly two-dimensional structure. Such two-dimensional structures are typically dynamically unstable due to either convective or shear instabilities and result in so-called cross-roll instabilities. Certainly fire-length (arising from a 3-D finite heat source) and side winds being drawn in may well play a role in the fingering phenomenon, but our analysis suggests that a possible mechanism might well be due or linked to the periodic spanwise stationary disturbances identified in our work. We find that it is the 3-D stationary disturbances that are the most unstable; these modes may have some bearing on the above description.

Acknowledgments

Part of this work was carried out while the first author was visiting the School of Computational Science at Florida State University. This work was supported by U.S. Department of Agriculture, Forest Service, Southern Research Station, Athens, GA, under a collaborative research agreement contract SRS 03-CA-11330136-056.

References

Banta, R.M.; Oliver, E.T.; Holloway, E.T.; Kropfli, R.A.; Bartram, B.W.; Cupp, R.E.; Post, M.J. 1992. Smoke column observations from two forest fires using Doppler Lidar and Doppler radar. J. Appl. Meteor. 31: 1328-1349.

Byram, G.M. 1954. Atmospheric conditions leading to blowup fires. Station Paper No. 35. Asheville, NC: U.S Department of Agriculture, Forest Service, Southeastern Forest Experiment Station.

Clark, T.L.; Jenkins, M.A.; Coen, J.; Packham, D. 1996a. A coupled atmosphere-fire model: Role of the Convective Froude number and dynamic Fingering at the fireline. Int. J. Wildland Fire 6(4): 177-190.

Clark, T.L.; Jenkins, M.A.; Coen, J.; Packham, D. 1996b. A coupled atmosphere-fire model: Convective feedback on fireline dynamics. J. Appl. Meteor. 35: 875-901.

Coen, J.; Mahalingham, S.; Daily, J. 2004. Infrared Imagery of Crown-Fire Dynamics during FROSTFIRE. J. Appl. Meteor. 43(9): 1241-1259.

Cunningham, P.; Hussaini, M.Y.; Goodrick, S.L.; Linn, R.R. 2003. Numerical simulations of buoyant plumes in a vertically sheared crossflow. Proceedings, American Meteorological Society Tenth Conference on Mesoscale Processes. Portland, OR. 3 p.

Daniels, P.G.; Gargaro, R.J. 1993. Buoyancy effects in stably stratified boundary layer flow. J. Fluid Mech. 250: 233-251.

Deardorff, J.W. 1973. The use of subgrid transport equations in a three-dimensional model of atmospheric turbulence. J. Fluids Eng. 95: 429-438.

Denier, J.O.; Stott, J.A.K.; Bassom, A.P. 2001. Three-dimensional inviscid waves in buoyant boundary layer flows. Fluid Dynamics Research. 28: 89-109.

Hall, P.; Morris, R. 1993. On the instability of boundary layers on heated flat plates. J. Fluid Mech. 245: 367-400.

Higuera, F.J. 1997. Boundary layer separation due to gas thermal expansion. Phys. Fluids. 9(10): 2841-2850.

Linn, R.R. 1997. A transport model for prediction of wildfire behaviour. Los Alamos National Laboratory Scientific Report. LA-13334-T, 195 pp. Los Alamos, NM.

Linn, R.R.; Cunningham, P. 2005. Numerical simulations of grass fires using a coupled atmosphere-fire model: Basic fire behaviour and dependence on wind speed. J. Geophysical Research. 110: D13107.

Morvan, D.; Dupuy, J.L. 2004. Modelling the propagation of a wildfire through a Mediterranean shrub using a multiphase formulation. Combustion and Flame 138: 199-210.

Mureithi, E.W.; Denier, J.P.; Stott, J.A.K. 1997. The effect of buoyancy on upper-branch Tollmien-Schlichting waves. IMA J. App. Math. 58: 19-50.

Noble, I.R.; Bary, G.A.V.; Gill, A.M. 1980. McArthur's fire-danger meters expressed as equations. Australian J. Ecology. 5: 201-203.

Nelson, R.M. Jr. 2003. Power of the fire—a thermodynamic analysis. Int. J. Wildland Fire. 12: 51-65.

Rothermel, R.C. 1972. A mathematical model for predicting fire spread in wild-land fuels. Gen. Tech. Rep. INT-115. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station.

This page is blank on purpose

Fuel Dynamics and Fire Behaviour in Australian Mallee and Heath Vegetation

Juanita Myers[1], Jim Gould[1], Miguel Cruz[1], and Meredith Henderson[2]

Abstract—*In southern Australia, shrubby heath vegetation together with woodlands dominated by multistemmed eucalypts (mallee) comprise areas of native vegetation with important biodiversity values. These vegetation types occur in semiarid and mediterranean climates and can experience large frequent fires. This study is investigating changes in the fuel complex with time, fuel moisture dynamics, vertical wind profile characteristics, fire propagation thresholds, rates of spread, and flame characteristics. The project is being conducted at Ngarkat Conservation Park in South Australia with data coming from experimental and prescribed burns conducted under a range of weather conditions. The final output of this project will be a prescribed burning guide to assist land management agencies to plan and safely conduct effective hazard reduction and ecological management burns in mallee and heath fuel types.*

Introduction

Low woodland and heath vegetation are fire prone environments in Australia and around the world. In mediterranean climates, typical shrub dominated vegetation such as chaparral (California) (Keeley and others 1999), kwongan (Western Australia) (Hassell and Dodson 2003; Keith and others 2002), fynbos (South Africa) (Schwilk and others 1997), and maquis and matorral (Mediterranean Basin) (Bilgili and Saglam 2003) are known for their flammability. In southern Australia, shrubby heath vegetation together with woodlands dominated by multistemmed eucalypts (mallee) represents significant areas of native vegetation that burns frequently (Bradstock and Cohn 2002; Keith and others 2002).

In the past, tracts of mallee woodlands covered much of the semiarid parts of southern Australia, including southern Western Australia (WA), southern South Australia (SA), northwestern Victoria, and western and central New South Wales (NSW) (Noble 1984). However, about 35 percent of this vegetation has been cleared (ANVA 2001) and relatively little of it remains in conservation reserves. One such reserve is the Ngarkat Conservation Park (CP), in eastern South Australia. This reserve comprises a mosaic of heath and mallee vegetation and experiences bushfires almost annually. This 270,000 ha (1,042 miles^2) reserve is part of an 800,000 ha (3,088 miles^2) section of contiguous native mallee and heath vegetation extending into the neighbouring state of Victoria.

Ngarkat CP is habitat for a number of threatened flora and fauna, contains floral resources for the apiary industry, and is used for recreation. These values are threatened by large bushfires. These bushfires usually occur in late spring and summer, can be of high intensity, and have on occasion burnt in excess of 100,000 ha (386 miles^2) in single events (Department for Environment and Heritage, South Australia, unpublished fire history database, 2007).

In: Butler, Bret W.; Cook, Wayne, comps. 2007. The fire environment—innovations, management, and policy; conference proceedings. 26-30 March 2007; Destin, FL. Proceedings RMRS-P-46CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 662 p. CD-ROM.

[1] Experimental Scientist, Research Leader, and Research Scientist, respectively, Ensis Forest Biosecurity and Protection, Commonwealth Scientific and Research Organisation (CSIRO), Canberra, Australia, Bushfire Cooperative Research Centre (CRC) East Melbourne, Victoria, Australia. Lead author at juanita.myers@ensisjv.com

[2] Senior Fire Research Officer, South Australian Department for Environment and Heritage, Adelaide, South Australia, Australia, Bushfire CRC East Melbourne, Victoria, Australia.

The loss of large tracts of native vegetation in a single fire in this fragmented landscape is not a desirable management or conservation outcome. Most of the fires in the park result from lightning ignitions and may be exacerbated by extended drought periods and suppression difficulty. Therefore, the current focus of management is on the prevention of large fires across the reserve, managed through prescribed burning. For managers to use prescribed burns effectively in this landscape requires more robust information on both fuel dynamics and fire behaviour.

Studies of fire behaviour and fuels have been undertaken in the mallee heathlands of southwest Western Australia (McCaw 1997). McCaw (1997) found existing fire danger rating systems and fire behaviour models are not suitable in mallee heath fuel types. The rate of spread in these fuel types is consistently faster (up to 200 percent) than those predicted for other scrub fuel types. The exception to this is the South African fynbos scrub fuel, which tends to exhibit faster rates of spread under similar conditions (Van Wilgen and others 1985). A major problem encountered was that the current fire danger rating systems and spread models are not able to accurately predict conditions of fire spread. Inaccuracies in model output arise from the inability of these models to account for the threshold dead fuel moisture content, above which fires will not spread in mallee heath. This critical threshold for Western Australian mallee heathlands was found to be a dead fuel moisture content in the litter layer of no greater than 8 percent (McCaw and others 1995, 2003; McCaw 1997).

A number of other studies have been carried out in Australian heathlands, investigating fuel moisture relationships and prediction of fuel moisture content (Catchpole and others 2001; Pippen 1999), determining ignition thresholds related to fuel moisture and fire development (Plucinski and Catchpole 2002; Plucinski 2003).

The aim of this project is to develop a prescribed burning guide to assist land management agencies to plan and safely conduct prescribed burning for effective hazard reduction and ecological sensitive management in South Australian mallee and heath vegetation. The specific objectives are: (1) characterise changes in the fuel complex with time; (2) model the seasonal and diurnal fuel moisture dynamics of live and dead fuel components; (3) determine the vertical wind profile in these fuel types; (4) model the fire environment conditions that will sustain fire spread (propagation thresholds); and (5) model rate of fire spread and flame characteristics.

This study will be collecting data from controlled experimental and prescribed burns in Ngarkat CP. The models developed from this research in South Australia will be tested for their applicability in mallee and heath in other states of Australia. In this paper we describe a project in progress and highlight the context and experimental and modelling approaches proposed.

Outline of Experiments

Quantifying Fuels for Fire Behaviour

Mallee and heath in semiarid and mediterranean Australia are characterised by a highly discontinuous fuel complex (Bradstock and Cohn 2002). Mallee woodlands are made up of short (2 to 10 m; 7 to 33 ft tall) multistemmed eucalypts, often (but not always) with a shrubby understory.

In the mallee, the surface fuel and suspended bark fuel are the main fuel layers that carry the flame front and are concentrated around the base of individual multistemmed eucalypt clump. The heath fuel type is made up of scattered small-leafed shrubs, or clumps of shrubs (up to 1 m; 3 ft tall), the sparse litter of which is usually in a tightly packed litter bed and can be partially buried by sand (Bradstock and Gill 1993). In this fuel type, the fire spreads in the low shrub canopy. In both cases (mallee and heath), the fuel layer that carries the flame front is discontinuous, with little fuel in the gap between the clumps of fuel.

The fuels that provide the energy flux that enables a fire to spread have generally been assumed to be those that are consumed in the continuous flaming zone of a fire front. The load of fine fuels, such as dead leaf, bark and twig litter <6 mm (¼ inches) in diameter, has been used as the major fuel variable (in many studies the only fuel variable) to predict fire spread (McArthur 1967; Peet 1965). Although fine fuel load has been the basis of Australian fire spread models in the past, and may be useful in providing practical information for burning guides, it has not been a significant variable in a number of recent studies (Buckley 1992; Burrows 1994; Cheney and others 1992, 1993). In complex fuels, the simple measure of total fine fuel is inadequate to describe the fuels that contribute to the forward rate of spread.

It is important to get a good estimate of fuel quantity, structure, composition, continuity, and height in order to quantify the effect of low-intensity prescribed burning in modifying the behaviour of wildfires. Detailed fuel sampling techniques can quantify the fuel loads of the surface (ground litter fuel) and near-surface (suspended live and dead fine fuel above the ground surface, but not on it) fuel layers, but these methods are not suited to operational use for assessment of fuels.

The development of more sophisticated burning guidelines requires a sound understanding of fire behaviour and suppression difficulty in fuels of different structure and composition. Australian studies (Cheney and others 1992; Gould and others 2001; McCarthy and others 1999; McCaw and others 2003; Project Vesta unpublished reports) have identified the importance of fuel structure in determining fire behaviour and ease of suppression. They have also developed a system for quantifying fuel structure with a numerical index that can be used as a fuel predictor variable to replace fuel load.

Rating systems that assess the relative hazard of fuel factors that affect fire behaviour and suppression difficulty represent a new approach in fuel assessment (McCarthy and others 1999; Gould and others 2001; Project Vesta unpublished progress reports). The fuel hazard rating systems developed by Wilson (1992, 1993) and McCarthy and others (1998) for eucalypt bark, elevated fuel, and surface fuel into a combined overall fuel hazard rating provided a simple, easy-to-use method for operational assessment of the hazard presented by fuels. This assessment emphasises the whole fuel complex by combining a hazard rating for each of the different fuel layers—bark, elevated, and surface fuels—using visual fuel characteristics.

This project will examine what changes need to be made for the system to be applicable to mallee and heath vegetation. Fuels load will be quantified through a combination of destructive and nondestructive sampling and visual systems of scoring structure and hazard as described above. The fuel assessment will characterise the changes in the fuel complex with time and compare the mallee and heath fuel types.

Fire Behaviour

Models to better predict fire behaviour in mallee and heath fuels are an important tool for managing prescribed burns. Improved fire spread predictions will be invaluable for the management of wildfires, providing more timely warnings of threat, and aiding decisionmaking on suppression tactics.

In order to improve fire behaviour models, it is necessary to encompass a wide range of fuel moisture and weather conditions in experimental burns. To achieve this, experimental burnings are being carried out in three seasons: in mid autumn (May 2006), early autumn (April 2007), and late summer (Feb/March 2008). To capture the differences in fire behaviour between the mallee and heath fuel types, and between different fuel ages under identical atmospheric conditions, simultaneous ignitions between different fuel types and ages will be conducted wherever possible. The fire behaviour under these conditions can then be related to the fuel characteristics.

Fire propagation threshold—Of the range of fire behaviour information necessary for the planning and conducting of prescribed burning, the determination of the threshold conditions under which the fire will spread (the fire propagation threshold) is critical. This is because prescribed burnings are mostly conducted under marginal burning conditions.

Due to the discontinuous nature of mallee and heath fuel complexes (Bradstock and Gill 1993; Bruner and Klebenow 1979; McCaw 1997), fire spread requires conditions that will allow the development of a flame angle, depth, and length that will bridge the gaps between individual shrubs or clumps, and/or initiate short range spotting that allows the fire to bypass the small scale fuel discontinuities. Under the conditions sought for prescribed burning, this creates highly nonlinear fire behaviour, with an abrupt increase in rate of spread when the conditions for sustained fire propagation are met.

Modelling of the propagation threshold in these discontinuous fuel complexes can be approached through a mechanistic framework as initiated by Bradstock and Gill (1993) or through logistic regression analysis, which attempts to describe the likelihood of an event, in this case fire spread, occurring (Fernandes and others 2002; Marsden-Smedley and Catchpole 2001).

We will use the logistic regression approach to model the propagation threshold. Propagation will be defined as successful if the fire spreads 100 m without self-extinguishing. A series of smaller scale (1 ha; 2.5 acre) fire spread experiments will be conducted under a range of conditions in each fuel type and age class in order to determine the propagation threshold in each. To achieve sufficient replication, these data will be supplemented by data collected at operational prescribed burns in these fuel types.

Fire behaviour parameters—During experimental burns, fine fuel moisture and weather parameters will be measured, including wind measurements. The fire behaviour parameters being measured will include forward and lateral rates of spread, flame dimensions, intensity, head fire width, spotting distance, fuel consumption, and the fuel layers influencing fire spread.

The limited size of the experimental fire plots (3 ha; 7 acres) will mean that we need to test whether the predictions from our models can be confidently extrapolated to fires occurring on a larger scale (Marsden-Smedley and Catchpole 1995; McCaw 1997). The experimental design includes model validation against larger scale experimental fires and against reliable prescribed burn and wildfire data.

Contribution to Improved Bushfire Management

The results of this research will better quantify the effects of fuel structure, fuel moisture dynamics, and wind on fire behaviour in mallee and heath vegetation. This will provide fire spread models that have an application to a wider range of mallee, heath, and other shrubland fuel types for both wildfire and prescribed burn situations.

New functions describing the relationship between fire spread and wind will be designed so that they can be used to predict the behaviour of high-intensity wildfires. This could be useful for analysing zones of potential wildfire impact and providing timely public warning. Fire spread predictions can be applied to data on suppression effectiveness limits to develop better fire management strategies.

Acknowledgments

We thank the South Australian Department for Environment and Heritage Murraylands Region staff and Brett Stephens (Regional Fire Management Officer) for their support in conducting the experimental burning program. Also, the Bushfire Cooperative Research Centre contributed to the research funding and provided financial support for attending this conference.

References

ANVA. 2001. Australian native vegetation assessment. National Land and Water Resources Audit and Commonwealth of Australia, Canberra.

Bilgili, E.; Saglam, B. 2003. Fire behaviour in maquis fuels in Turkey. Forest Ecology and Management. 184: 201-207.

Bradstock, R.A.; Cohn, J.S. 2002. Fire regimes and biodiversity in semi-arid mallee ecosystems. In: Flammable Australia: the fire regimes and biodiversity of a continent. (eds R.A. Bradstock, J.E. Williams and A.M. Gill) Cambridge, UK: Cambridge University Press: 238-258.

Bradstock, R.A.; Gill, A.M. 1993. Fire in semi-arid Mallee shrublands: size of flames from discrete fuel arrays and their role in the spread of fire. Int. J. Wildland Fire 3: 3-12.

Bruner, A.D.; Klebenow, D.A. 1979. Predicting success of prescribed fires in pinyon-juniper woodland in Nevada. Res. Pap. INT-219. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station.

Buckley, A.J. 1992. Fuel reducing a stand of eucalypt regrowth in east Gippsland-A case study. Research Report No. 33. Victoria, Australia: Department of Conservation and Environment. 29 p.

Burrows, N.D. 1994. Experimental development of a fire management model for Jarrah (*Eucalyptus marginata* Donn ex. Sm) forest. PhD thesis. Canberra, Australia: Australian National University, Department of Forestry. 293 p.

Catchpole, E.A.; Catchpole, W.R.; Viney, N.R.; McCaw, W.L.; Marsden-Smedley, J.B. 2001. Estimating fuel response time and predicting fuel moisture content from field data. International Journal of Wildland Fire 10(2): 215-222.

Catchpole, W.R.; Bradstock, R.A.; Choate, J.; Fogarty, L.G.; Gellie, N.; McCarthy, G.J.; McCaw, W.L.; Marsden-Smedley, J.B.; Pearce, G. 1998. Cooperative development of prediction equations for fire behaviour in heathlands and shrublands. In: Proceedings, 3rd International Conference on Forest Fire Research and 14th Fire and Forest Meteorology Conference. (ed. Viegas, D.X.) 16-20 November 1998, Luso, Coimbra, Portugal: 631-645.

Cheney, N.P.; Gould, J.S.; Catchpole, W.R. 1993. The influence of fuel, weather and fie shape variables on fire-spread in grassland. Int. J. of Wildland Fire 3(1): 31-44.

Cheney, N.P.; Gould, J.S.; Knight, I. 1992. A prescribed burning guide for young regrowth forest of Silvertop ash. Research Paper No. 16. For. Comm. of New South Wales. 92 p.

Fernandes, P.M.; Botelho, H.S.; Loureiro, C. 2002. Models for the sustained ignition and behaviour of low-to-moderately intense fires in maritime pine stands. In: Forest Fire Research & Wildland Fire Safety. Proceedings of the IV International Conference on Forest Fire Research/2002 Wildland Fire Safety Summit. (ed. D.X. Viegas) Rotterdam, The Netherlands: Millpress Scientific Publications. [CD-ROM]. 11 p.

Gould, J.S.; Cheney, N.P.; McCaw, L. 2001. Project Vesta: Research into the effects of fuel structure and fuel load on behaviour of moderate to high-intensity fires in dry eucalypt forest: Progress Report. Australasian Bushfire Conference Proceedings. 3–6 July 2001. Christchurch. New Zealand: 13-21.

Hassell, C.W.; Dodson, J.R. 2003. The fire history of south-west Western Australia prior to European settlement in 1826-1829. In: Proceedings, Fire in ecosystems of south-west Western Australia: Impacts and management. 16-18 April 2002 Perth, Australia. (eds I. Abbott and N. Burrows) Leiden, The Netherlands: Backhuys Publisers: 71-85.

Keeley, J.E.; Fotheringham, C.J.; Morais, M. 1999. Reexamining fire suppression impacts on brushland fire regimes. Science 284: 1829-1832.

Keith, D.A.; McCaw, W.L.; Whelan, R.J. 2002. Fire regimes in Australian heathlands and their effetcs on plants and animals. In: Flammable Australia: the fire regimes and biodiversity of a continent. (eds R.A. Bradstock, J.E. Williams and A.M. Gill) Cambridge, UK: Cambridge University Press: 199-237.

Marsden-Smedley, J.B.; Catchpole, W.R. 1995. Fire behaviour modelling in Tasmanian buttongrass moorlands. II. Fire behaviour. Int. J. Wildland Fire 5(4): 215-228.

Marsden-Smedley, J.B.; Catchpole, W.R. 2001. Fire modelling in Tasmanian Buttongrass Moorlands. IV. Sustaining versus non-sustaining fires. Int. J. Wildland Fire 10: 255-262.

McArthur, A.G. 1967. Fire behaviour in Eucalypt Forests. Commonwealth of Australia Forestry and Timber Bureau Leaflet No. 107. Canberra. 36 p.

McCarthy, G.J.; Tolhurst, K.G.; Chatto, K. 1998. Overall fuel hazard guide. Fire Management Research Report No. 47. Victoria, Australia: Department of Natural Resources and Environment. 33 p.

McCarthy, G.J.; Tolhurst, K.G.; Chatto, K. 1999. Overall fuel hazard guide. 3rd edition. Fire Management Research Report No. 47. Victoria, Australia: Department of Natural Resources and Environment. 28 p.

McCaw, W.L. 1997. Predicting fire spread in Western Australian mallee heath shrubland. PhD thesis. Canberra, Australia: University of New South Wales, University College, School of Mathematics and Statistics. 235 p.

McCaw, W.L.; Burrows, N.D.; Friend, G.R.; Gill, A.M. 1995. Predicting fire spread in Western Australian mallee-heath. In: Proceedings, Landscape Fires '93: Proceedings of an Australian Bushfire Conference, Perth, Western Australia. 27-29 September 1993. CALM Science, No. 4 Supplement: 35-42.

McCaw, W.L.; Cheney, N.P.; Gould, J.S. 2003. Do eucalypt forest fires burn faster and hotter in older fuels? Implication for hazard reduction burning. In: Proceedings, 3rd International Wildland Fire Conference and Exhibition. 3–6 October 2003. Sydney, NSW, Australia. [CD-ROM]

McCaw, L.; Cheney, P.; Sneeuwjagt, R. 2003. Development of a scientific understanding of fire behaviour and use in south-west Western Australia. In: Proceedings, Fire in ecosystems of south west Western Australia: Impacts and management. 16-18 April 2002. Perth, Australia (eds I. Abbott and N. Burrows). Leiden, The Netherlands: Backhuys Publishers: 171-188.

Noble, J.C. 1984. Mallee. In: Management of Australia's Rangelands. (eds G.N. Harrington, A.D. Wilson, and M.D. Young) Melbourne, Australia: CSIRO: 223-240.

Peet, G.B. 1965. A fire danger rating and controlled burning guide for northern jarrah forest of Western Australia. Forests Department Western Australia Bulletin No. 74.

Pippen, B.G. 1999. Predicting fine fuel moisture in shrubby vegetation. Bachelor of Science (Forestry) Honours thesis. Canberra, Australia: Australian National University, Department of Forestry. 71 p.

Plucinski, M.P. 2003. The investigation of factors governing ignition and development of fires in heathland vegetation. PhD thesis. Canberra, Australia: University of New South Wales, Australian Defence Force Academy, School of Mathematics and Statistics. 347 p.

Plucinski, M.P.; Catchpole, W.R. 2002. Vertical development of fire in shrubland fuels. In: Forest fire research and wildland fire safety: Proceedings of IV International Conference on Forest Fire Research 2002 Wildland Fire Safety Summit. (ed. D.X. Viegas). Luso, Coimbra, Portugal, 18-23 November 2002. Rotterdam, The Netherlands: Millpress Science Publishers. [CD-ROM]

Schwilk, D.W.; Keeley, J.E.; Bond, W.J. 1997. The intermediate disturbance hypothesis does not explain fire and diversity pattern in fynbos. Plant Ecology 132: 77-84.

Van Wilgen, B.W.; Maitre, D.C.; Kruger, F.J. 1985. Fire behaviour in South African fynbos (macchia) vegetation and predictions from Rothermel's fire model. Journal of Applied Ecology 22(1): 207-216.

Wilson, A.A.G. 1992. Eucalypt bark hazard guide. Research Report No. 32. Victoria, Australia: Department of Conservation and Environment, Fire Management Branch. 17 p.

Wilson, A.A.G. 1993. Elevated fuel guide. Research Report No. 35. Victoria, Australia: Department of Conservation and Environment, Fire Management Branch. 22 p.

This page is blank on purpose

Bucklands Crossing Firefighter Burnover—A Case Study of Fire Behaviour and Firefighter Safety Implications

H. Grant Pearce[1]

Abstract—*On March 24, 1998, a crew of eight rural firefighters were burned over while attempting to suppress a backburning sector of the Bucklands Crossing Fire in North Otago, New Zealand. The fire demonstrates how factors typical of the New Zealand fire environment – steep slopes, highly flammable shrub fuels, and a strong foehn wind effect – combined to produce extreme fire behaviour. Several firefighters sustained varying degrees of injury. They were hit by a blowup that was most likely caused by a rapid reburn through previously underburned shrub fuels. The exact trigger for upslope spread and transition to a crown fire was not definitively identified; however, it was most likely the result of strong winds and localised turbulence, combining with steep topography and highly flammable, preheated shrub fuels. The case study report prepared on this burnover describes the activities of personnel leading up to and during the incident in relation to the fire environment and fire behaviour. Possible causes of the blowup are reviewed, and observed fire behaviour compared to that predicted by available models. Particular emphasis is placed on the contribution and alignment of fire environment factors and their role in triggering fire behaviour escalation. Aspects of firefighter safety during the incident are also discussed, including the performance of protective clothing. The findings highlight the need for increased training of firefighters in fire behaviour and, in particular, greater situational awareness of the fire environment and indicators of extreme fire behaviour potential. The case study provides a number of lessons learned that have relevance worldwide.*

Introduction

On March 24, 1998, a crew of eight New Zealand rural firefighters were burned over while attempting to suppress a sector of the Bucklands Crossing Fire in North Otago, New Zealand, that was burning downhill. Three firefighters sustained burn injuries, one serious, and a fourth crew member was hurt escaping into previously burned fuels. The crew were hit by a blowup that was most likely caused by a rapid reburn through previously underburned shrub fuels, a situation highly reminiscent of the 1994 South Canyon Fire in Colorado, USA, where 14 firefighters were killed. The fire demonstrates how factors typical of the New Zealand fire environment – steep slopes, highly flammable shrub fuels, and a strong foehn wind effect – can combine to produce extreme fire behaviour. A case study produced on the incident describes the factors leading up to the burnover, and presents a number of key lessons learned that have relevance in New Zealand as well as for the wider global fire community.

In: Butler, Bret W.; Cook, Wayne, comps. 2007. The fire environment—innovations, management, and policy; conference proceedings. 26-30 March 2007; Destin, FL. Proceedings RMRS-P-46CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 662 p. CD-ROM.

[1] Fire Scientist, Ensis - Forest Biosecurity and Protection, Scion, Christchurch, New Zealand. grant.pearce@ensisjv.com

Case Study

A detailed case study entitled “Fire behaviour and firefighter safety implications associated with the Bucklands Crossing Fire burnover of 24 March 1998” by Pearce and others (2004; see References section for ordering information) describes the activities of personnel leading up to and during the incident in relation to the fire environment and fire behaviour. Within the case study, possible causes of the blowup are reviewed, and observed fire behaviour is compared to that predicted by available models. Particular emphasis is placed on the contribution and alignment of fire environment factors and their role in triggering the temporary escalation to extreme fire behaviour. Aspects of firefighter safety during the incident are also discussed, including the performance of protective clothing. The findings highlight the need for increased training of firefighters in fire behaviour and, in particular, greater situational awareness of the fire environment and indicators of extreme fire behaviour potential. The case study provides a number of lessons learned that have relevance worldwide.

This paper (and the associated poster) aims to promote wider international awareness of the case study’s existence, and represents a further effort at information transfer that follows on from the communication of initial findings soon after the incident (Pearce and others 1998), the production of the detailed case study (Pearce and others 2004), and a brief review of the case study and key lessons learned (Anderson 2004).

Incident Summary

At 07:47 a.m. on Tuesday, 24 March 1998, a fire was reported by a local musterer on his way to work near Bucklands Crossing, some 40 km (25 miles) north of Dunedin (fig. 1). The fire is believed to have been ignited by sparks resulting from powerlines contacting adjacent vegetation in high winds (see fig. 2). Initially, NZ Fire Service structural firefighters from Waikouaiti and Palmerston responded. They were later supported by rural fire crews from Dunedin City Council, local forestry companies and the Department of Conservation. Two helicopters were also used, although the strong, gusty winds initially prevented effective aerial fire suppression.

At around 11:25 a.m., a crew of eight rural firefighters were burned over while attempting to suppress a backing sector of the fire. The crew had parked their fire appliance on the crest of a steep ridge in a burnt out sector of the fire, and were deploying a hoseline downhill toward a fire edge burning slowly downslope (see fig. 3). The fire had already burnt out the catchment on one side of this ridge and was backing downhill beneath manuka (*Leptospermum scoparium*) shrub fuels down into the adjacent catchment where the crew were deploying the hoseline. Before being able to charge this hoseline, the crew were overrun by a “fireball” exploding from the gorse-filled (*Ulex europaeus*) gully beneath them (see fig. 4). Three firefighters sustained burn injuries, one serious, while a fourth crew member received minor injuries whilst evacuating. The driver and another crew member took shelter behind the appliance and, along with the remaining two crew members, were uninjured. (Fire shelters are not used in New Zealand, so their use was not an option available to firefighters in this situation. However, it is unlikely that crew members would have had sufficient time to properly deploy shelters due to the rapid approach

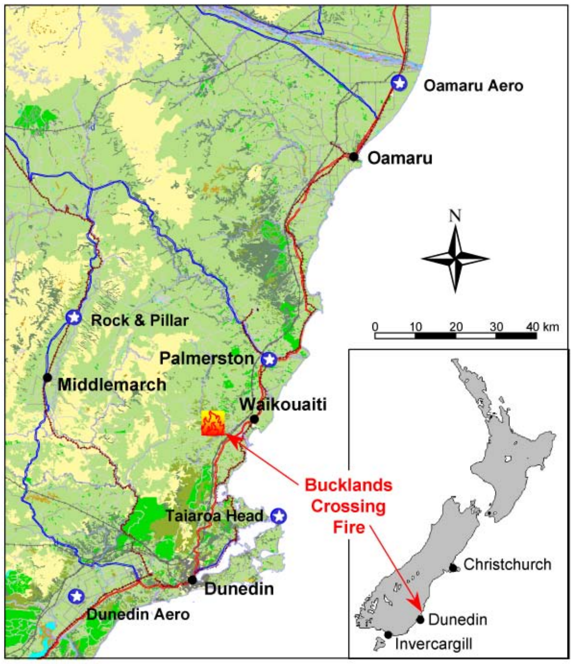


Figure 1—Location of the Bucklands Crossing Fire in relation to local population centres (●) and weather stations (✪).

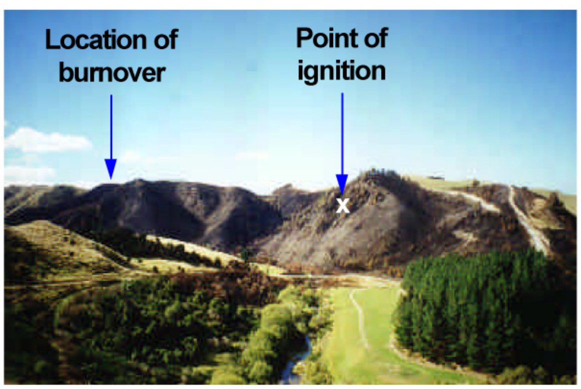


Figure 2—General view of the Bucklands Crossing Fire looking northeast to the fire's point of ignition and burnover location.

of the fire and strong, gusty wind conditions.) Damage to the fire appliance as a result of the burnover was also significant (see fig. 5).

The fire continued to burn for several hours after the incident before being contained later in the day. However, mopping up of hot spots continued over the next 7 days and the fire was not declared out until April 2. The fire burned an area of around 200 ha (495 acres), including two small woodlots of *Pinus radiata* totalling 20 ha (50 acres); the remainder of the area was grazed pasture and manuka or gorse-covered slopes. Several kilometres of fencing were damaged and some stock were also lost.

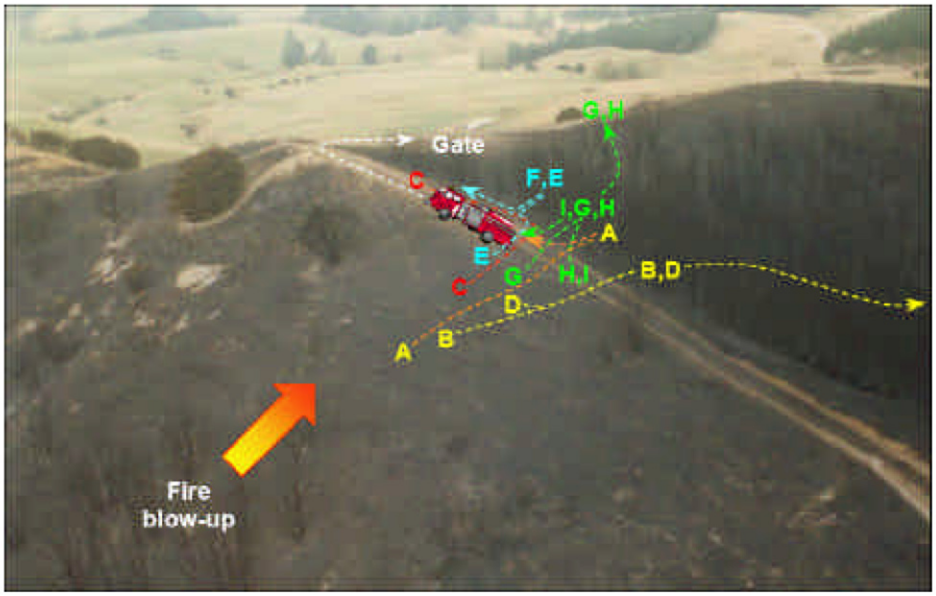


Figure 3—Locations and escape paths taken by the fire crew members during the burnover (letters denote individual firefighters).

Figure 4—Topography in the area of the ridge where the burnover incident occurred.

Figure 5—Damage to the fire appliance, including tail lights, foam proportioner, pump cover and rubber hose fittings.

Fire Environment

The fire occurred in rugged terrain comprising steep slopes that drop sharply to the meandering course of the Waikouaiti River below. Slopes of 30 to 40° (55 to 85 percent) are common, and many rock outcrops occur throughout the fire area. Several side gullies drain into the main river course with steep, narrow ridges in between. The burnover occurred on one of these ridges (fig. 4; also see fig. 6), which consisted of a 30° (58 percent) slope on the lee side which had been burned over earlier, a narrow ridge crest some 4 to 5 m (13 to 16 ft) wide, and a 25° (47 percent) slope on the upwind side leading down to the shrub fuels under which the fire was backing downhill.

Fuels in the broader fire area consisted of radiata pine woodlots, manuka, and gorse shrubs, and grazed pasture, some with scattered tussock grasses. Dense 2 to 3 m (6 to 10 ft) tall manuka shrubs covered the lee side of the ridge on which the incident occurred. This had been burnt out earlier in a rapid uphill fire run. Grass fuels with scattered short tussocks covered the open ridgetop where the appliance was parked (see fig. 6), and this too had been burnt out prior to the crew arriving. These grass fuels extended some 30 to 40 m (100 to 130 ft) down the upwind slope to 3 to 4 m (10 to 13 ft) tall manuka shrubs (fig. 7 left). This shrub vegetation was initially only underburnt, but burned out completely at a later time. The manuka stand extended some 30 to 50 m (100 to 165 ft) to the gorse-filled gully bottom below (fig. 7 right).

Figure 6—Views of the ridge on which the burnover incident occurred, illustrating the steepness of the slope in the direction from which the flame front came, the burnt out grass fuels along the ridge crest, and the distance between the vegetation and the site where the fire appliance was parked (as indicated by the utility).

Figure 7—Fuels in the burnover area, including (left) partially burned manuka shrub fuels on the ridge adjacent to where the burnover occurred, and (right) burnt gorse fuels below the location of the burnover, in the area where the blowup is believed to have originated.

The fire occurred during warm, windy conditions in a period of extended dryness. Weather and Fire Weather Index (FWI) System (Van Wagner 1987) values (see fig. 8a) for midday on March 24 were: temperature 25.5 °C (78 °F), relative humidity 35 percent, wind speed 16 km/h (10 mph), 6 days since >0.6 mm (0.02 inches) rain, Fine Fuel Moisture Code (FFMC) 92.0, Duff Moisture Code (DMC) 41, Drought Code (DC) 569, Initial Spread Index (ISI) 12.9, Buildup Index (BUI) 70, and Fire Weather Index (FWI) 31. Recorded temperatures on the day of the fire reached 27 °C (81 °F) and higher values were reported at the fire site (fig. 8b); however, these values of temperature and relative humidity were not unusually high or low, respectively, for this area. Gale force northwesterly winds that exceeded 80 km/h (50 mph) initially restricted aerial suppression operations and, although they dropped off during the day, the erratic strength and direction of the wind contributed to unpredictable fire behaviour.

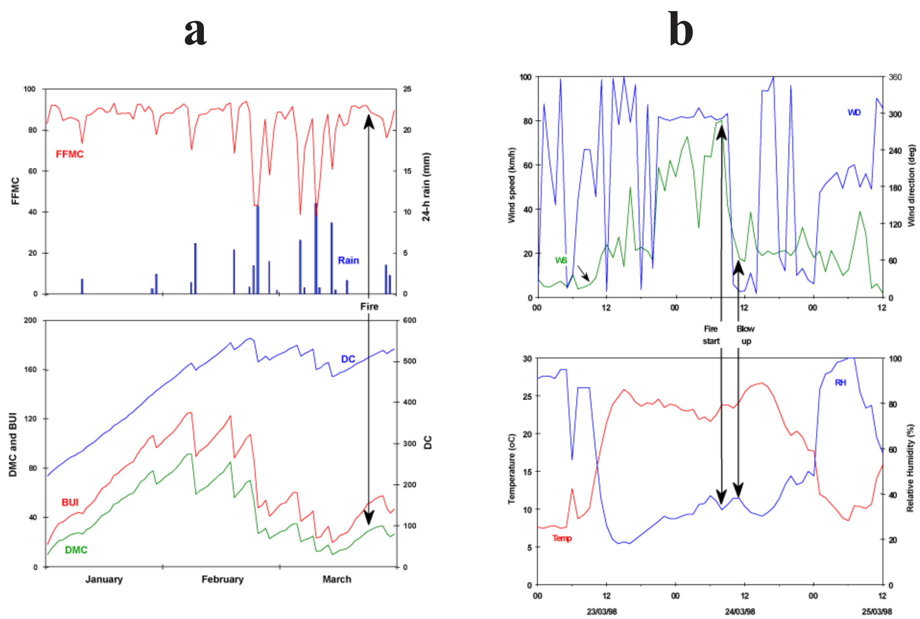


Figure 8—(a) Wetting and drying cycles for the FWI System moisture codes leading up to ignition of the Bucklands Crossing Fire on 24 March 1998; and (b) diurnal weather patterns recorded before, during, and after the initial run of the Bucklands Crossing Fire.

Fire Behaviour

The firefighters involved in the Bucklands Crossing Fire burnover reported being hit by a "fireball" originating from the gully below them. This may have been the result of a collapsing fire whirl or convection column, flashover, or even a carbon dust explosion. However, the most likely cause was a flame extension or "rollover" associated with an uphill run and reburn through the preheated shrub canopy. The collapse of the fire front as such a run reached the end of the shrub stand (see fig. 9) would push flames along the ground and, together with the pulsing of the flame front as volatile gases are burned, would create an effect similar to that of a fireball or flashover observed by the firefighters. It would also produce extreme flame lengths capable of reaching the 30 to 50 m (100 to 165 ft) to the ridge where the fire appliance was parked.

Figure 9—Example of flame front collapse in New Zealand manuka shrub fuels during experimental burning trials observed from consecutive photographs.

While the situation may seem unusual, similar incidents have happened in the past (surface fuels consumed/canopy fuels unburned and preheated, steep slope, severe fire weather, including upslope winds or flow)—for example, the 1994 South Canyon Fire in the USA (Butler and others 1998). In particular, the potential for extreme or "unusual" fire behaviour existing from a preheated canopy has been recognised for many years (Editor 1958; NWCG 1993, 2006). Fatalities and "near hits" are often intimately linked to temporary escalations in extreme fire behaviour (see for example Alexander 2004; Wilson 1977). The Bucklands Crossing Fire illustrates that the development of extreme fire behaviour can take many forms. In this case, the fire effectively burned as an independent crown fire.

So was the situation predictable? It is unlikely that the momentary escalation in extreme fire behaviour would have been predicted in a quantitative sense with currently available models (such as Viegas 2006). The situation is not one that would necessarily be modelled in a computer simulation, addressed through outdoor experimental burning or studied in a laboratory setting (M. Alexander, pers. comm.). However, there have been enough similar situations in the past to at least qualitatively be cognizant of the potential for extreme fire behaviour. While the exact cause of the blowup could not be definitively identified, a number of factors relating to recognition of extreme fire behaviour potential and associated implications for firefighter safety were highlighted as a result of the incident and are described in detail in the case study, including:

- Common denominators of fatal and "near hit" fires (Millman 1993, 2000; NWCG 1996, Wilson 1977).
- Alignment of fire environment factors (Campbell 1991; Cheney and others 2001).
- Effect of atmospheric stability and upper level winds (Byram 1954).
- Transition from surface to crown fires (Butler and others 1998).

Firefighter Safety

The Bucklands Crossing Fire is also of interest from the human factors standpoint. The firefighters perceived this situation as benign; otherwise, they would not have engaged the fire in the manner they did (that is, approaching the fire from an upslope location). However, obviously some degree of complacency and/or lack of situational awareness were also involved. Several fundamental principles of safe firefighting were breached, and the authors of the case study have taken care to point these out without criticising the individuals (and with their permission and support) or decisions taken, in the hope that these valuable lessons can be learned from.

One of the basic safety rules recognised by firefighters around the world is to never place oneself uphill on a slope above unburned fuels with a fire burning beneath you (see for example NWCG 2004). In deploying where they did in this instance, the crew leader and his crew broke this basic rule and immediately placed themselves in a potentially dangerous situation. While the crew leader did recognise the potential for the fire to "flare-up" and spent a considerable amount of time sizing up the fire prior to choosing to locate where they did, he believed that the fire would spread upgully under the influence of the local windflow. With the benefit of hindsight, he should have recognised the potential that existed for a rapid upslope run toward the crew's location, due to the combined influences of the slope steepness, partially burned shrub fuels, and predominant, rather than localised, wind direction. Downhill fireline construction from above a fire has been identified as a particularly dangerous tactic only to be undertaken when there is no tactical alternative; so much so, that it has its own checklist of guidelines surrounding its use (NWCG 2004). In addition to the potential for a rapid uphill run of fire, the inherent dangers in use of this tactic also include the inability to establish a safe anchor point and that a safe escape route from a fire travelling uphill cannot be assumed (ETC and CIFFC 2000).

The concept of LCES (Lookout(s), Communication(s), Escape routes and Safety zone(s); after Gleason 1991) or LACES (where the 'A' stands for Awareness or Anchor points; after Teie 1994; Thorburn and Alexander 2001) is also an internationally recognized set of fireline safety reminders that can dramatically reduce the probability of an entrapment or burnover. While it was not used in firefighter training in New Zealand at the time (but has subsequently been adopted as a result of this incident), consideration of a number of the factors encapsulated within the LACES concept may have resulted in a different outcome. The deployment of a lookout with a good overview of the fire area may have identified the potential for an escalation in fire activity that might have altered the crew leader's deployment tactics or provided earlier warning. In conducting his sizeup, it could also be debated that the crew leader reacted to observed fire activity as opposed to being aware of the fire behaviour potential presented by the immediate fire environment factors, both individually and in combination. In addition, the ability to assess the broader fire environment to anticipate or recognise factors that may lead to dangerous situations is also essential. In this case the crew were unaware of the exact location of the fire or associated level of fire activity in the gully below them, and therefore of the blowup potential that existed as a result. The provision of information from adjacent sectors or use of a lookout to observe the wider fire area could therefore have facilitated broader awareness and appreciation of both current and potential fire behaviour. Suppression tactics and strategies should also consider the values-at-risk against the need for suppression. In this instance, the injuries were sustained in attempting to suppress an area of vegetation burning within the fire perimeter with little or no value. A culture of situational awareness, and continual review of strategies and tactics based on the fire environment, therefore needs to be instilled in all firefighters and fire management personnel (Anderson 2004).

The firefighters involved in the burnover incident were saved from more severe injuries by the short duration of their exposure to heat and flame, the fact that they were correctly attired in their protective clothing (fig. 10), and that they received immediate attention from onsite medical services. While these were positive outcomes, there were also a number of other safety issues that were identified as a result of the incident that are addressed in the case study. In addition to the performance of personal protective equipment (PPE), these include:

- firefighter training and competency
- safety rules and reminders
- operational procedures
- alternative escape options (also see Alexander 2006)

Figure 10—Damage to personal protective clothing from Firefighter C (who received the most serious burn injuries), including Nomex coveralls, cotton T-shirt and fibreglass helmet.

Key Lessons Learned

The Bucklands Crossing burnover incident highlighted a number of factors that, had they been considered, might have indicated that the crew were undertaking suppression in a potentially dangerous situation.

- The crew were approaching the fire from above, on a steep slope with partially burned fuels between them and the fire in the gully below (that is, downhill fireline construction).
- Firefighters must have an understanding in the subjects of personal safety and vegetation fire behaviour, and must apply this knowledge at all times during sizeup and ongoing fire suppression.
- Firefighters must consider both the individual and combined influences of the fire environment factors on current and potential fire behaviour.
- Fire crews must also have an appreciation of fire behaviour potential in the broader fire environment, in addition to the immediate area in which they are working (that is, situational awareness).
- The lack of a lookout that could monitor fire activity in the area beneath the crew was a serious oversight in this particular case.
- A culture of situational awareness, and constant review of strategies and tactics in light of changes in the fire environment, need to be instilled in all fireline and supervisory personnel.

- Suppression strategies and tactics should also consider the values-at-risk against the need for suppression.
- Firefighter training should use reminders such as the Common Denominators and LACES to reinforce potentially problematic aspects of fire behaviour and firefighter safety.
- All training undertaken must also emphasise the correct use of protective equipment.
- Examples such as this incident can be used to clearly demonstrate the benefits of picking up on the lessons learned.

There are a great many fuel/vegetation types and fire environments in the world where a similar situation could develop to the Bucklands Crossing Fire burnover – hence the importance of disseminating this kind of information internationally to the wider global fire community.

Acknowledgments

The advice and feedback received from Dr. Marty Alexander (Canadian Forest Service) on this paper and the associated poster are greatly appreciated. Comments provided by internal reviewers (Stuart Anderson and Jim Gould, Ensis Bushfire Research Group) are also gratefully acknowledged.

References

Alexander, M.E., pers. comm. Senior Fire Behavior Research Officer, Natural Resources Canada, Canadian Forest Service, Northern Forestry Centre, Edmonton, and Adjunct Professor, Department of Renewable Resources, University of Alberta, Edmonton, Alberta, Canada.

Alexander, M.E. 2004. What triggered the Brewer Fire blowup remains the mystery. Fire Management Today 64(2): 56-57.

Alexander, M.E. 2006. You are about to be entrapped or burned over by a wildfire: what are your survival options? In: D.X. Viegas (ed.). Proceedings of 5th International Conference on Forest Fire Research, 27-30 November 2006, Figueira da Foz, Portugal. [CD-ROM]. Amsterdam, The Netherlands: Elsevier B.V. 12 p.

Anderson, S. 2004. A close call in Otago – some lessons to be learned: A review of "Fire behaviour and firefighter safety implications associated with the Bucklands Crossing Fire burnover of 24 March 1998" by H.G. Pearce, R.W Hamilton and R.I. Millman. Fire Technology Transfer Note 29 (May 2004). Christchurch: New Zealand Forest Research Institute, Forest and Rural Fire Research Programme. 2 p.

Butler, B.W.; Bartlette, R.A.; Bradshaw, L.S.; Cohen, J.D.; Andrews, P.L.; Putnam, T.; Mangan, R.J. 1998. Fire behaviour associated with the 1994 South Canyon Fire on Storm King Mountain, Colorado. Research Paper RMRS-RP-9. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 82 p.

Byram, G.M. 1954. Atmospheric conditions related to blowup fires. Station Paper No. 35. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station. 30 p. [reprinted as National Fire Equipment System (NFES) 2239. Boise, Idaho: National Wildfire Coordinating Group, Boise Interagency Fire Center].

Campbell, D. 1991. The Campbell Prediction System. Ojai Printing, California: Wildland Fire Specialists.

Cheney, N.P.; Gould, J.S.; McCaw, L. 2001. The Dead-Man Zone – a neglected area of firefighter safety. Australian Forestry 64(1): 45-50.

Editor. 1958. Safe practices under blowup conditions – a training outline for the crew boss. Fire Control Notes 19(1): 3-7.

ETC and CIFFC. 2000. Wildland fire – safety on the fireline. [CD-ROM]. Hinton, Alberta, Canada: Environmental Training Centre (ETC); and Winnipeg, Manitoba, Canada: Canadian Interagency Fire Centre (CIFFC), National Training Working Group.

Gleason, P. 1991. LCES – a key to safety in the wildland fire environment. Fire Management Notes 52(4): 9. [reprinted as Fire Management Today 64(1): 70-71].

Millman, R.I. 1993. Firefighting tragedies and near misses. In: Proceedings, Forest and Rural Fire Association of New Zealand (FRFANZ) 3rd Annual Conference, 4-6 August 1993, Wellington. Rotorua: Forest and Rural Fire Association of New Zealand: 84-101.

Millman, R.I. 2000. Injuries and near hits at vegetation fires. In: Conference Proceedings, Forest and Rural Fire Association of New Zealand (FRFANZ) Annual Conference, 2-3 August 2000, Napier. Rotorua: Forest and Rural Fire Association of New Zealand.

National Wildfire Coordinating Group. 1993. Fireline safety reference. National Fire Equipment System Publication NFES 2243. Boise, ID: National Wildfire Coordinating Group, Boise Interagency Fire Center.

National Wildfire Coordinating Group. 1996. Common denominators of fire behaviour on tragedy and near-miss wildland fires. National Fire Equipment System Publication NFES 2225. Boise, ID: National Wildfire Coordinating Group, Boise Interagency Fire Center. 25 p.

National Wildfire Coordinating Group. 2006. Incident response pocket guide. National Fire Equipment System Publication NFES 1077. Boise, ID: National Wildfire Coordinating Group, Boise Interagency Fire Center. 96 p.

Pearce, G.; Hamilton, R.; Millman, I. 1998. The Bucklands Crossing fire burnover. Fire Technology Transfer Note 19 (December 1998). Christchurch: New Zealand Forest Research Institute, Forest and Rural Fire Research Programme. 4 p.

Pearce, H.G.; Hamilton, R.W.; Millman, R.I. 2004. Fire behaviour and firefighter safety implications associated with the Bucklands Crossing Fire burnover of 24 March 1998. Forest Research, Rotorua, in association with the New Zealand Fire Service Commission and National Rural Fire Authority, Wellington. Forest Research Bulletin No. 197, Forest and Rural Fire Scientific and Technical Series, Report No. 4. 62 p. (Copies of the case study are available for download in PDF format from the Ensis Bushfire Research website at ww.ensisjv.com/bushfire, or in hard copy for purchase from: Publications, Scion/Ensis, Private Bag 3020, Rotorua, New Zealand.)

Teie, W.C. 1994. Firefighter's Handbook on Wildland Firefighting. Rescue, CA: Deer Valley Press.

Thorburn, W.R.; Alexander, M.E. 2001. LACES versus LCES: Adopting an "A" for "Anchor Points" to improve wildland firefighter safety. In: Proceedings of the 2001 International Wildland Fire Safety Summit, November 6-8, 2001, Missoula, Montana. Montana City, MT: International Association of Wildland Fire. 10 p.

Van Wagner, C.E. 1987. Development and structure of the Canadian Forest Fire Weather Index System. Forestry Technical Report 35. Ottawa, Ontario: Canadian Forestry Service. 37 p.

Viegas, D.X. 2006. Parametric study of an eruptive fire behaviour model. International Journal of Wildland Fire 15(2): 169-177.

Wilson, C.C. 1977. Fatal and near-fatal forest fires – the common denominators. International Fire Chief 43(9): 9-10, 12-15.

**This
page is
blank
on purpose**

Mathematical Modeling of Forest Fire Initiation in Three Dimensional Setting

Valeriy Perminov[1]

***Abstract**—In this study, the assignment and theoretical investigations of the problems of forest fire initiation were carried out, including development of a mathematical model for description of heat and mass transfer processes in overterrestrial layer of atmosphere at crown forest fire initiation, taking into account their mutual influence. Mathematical model of forest fire was based on an analysis of experimental data and using concept and methods from reactive media mechanics. In the context of the general mathematical model of forest fires, this study gives a new mathematical setting and method of numerical solution of a problem of a forest fire modeling. The boundary-value problem is solved numerically using the method of splitting according to physical processes. In this paper the assignment and theoretical investigations of the problems of forest fire initiation are carried out.*

Introduction

One of the objectives of these studies is the improvement of knowledge on the fundamental physical mechanisms that control forest fire initiation. A great deal of work has been done on the theoretical problem of forest fire initiation. Crown fires are initiated by convective and radiative heat transfer from surface fires. However, convection is the main heat transfer mechanism. The first explanation of this process was given by Van Wagner (1977). The theory proposed there depends on three simple crown properties: crown base height, bulk density, and moisture content of forest fuel. Also, crown fire initiation and hazard have been studied and modeled in detail (see for example Alexander 1998; Van Wagner 1999; Xanthopoulos 1990; Rothermel 1991a,b; Cruz and others 2002; Albini and others 1995; Scott and Reinhardt 2001).The more complete discussion of the problem of modeling forest fires is provided by a cycle of works produced by a group of coworkers at Tomsk University (Grishin 1997; Grishin and Perminov 1998; Perminov 1995 and 1998). In particular, a mathematical model of forest fires was obtained by Grishin (1997) based on an analysis of known and original experimental data (Grishin 1997; Konev 1977), and using concepts and methods from reactive media mechanics. The physical two-phase models used in Morvan and Dupuy (2001 and 2004) may be considered as a continuation and extension of the formulation proposed by Grishin and Perminov. However, the investigation of crown fires has been limited mainly to cases of forest fires initiation without taking into account the mutual interaction of the forest fires and three dimensional atmosphere flows.

In: Butler, Bret W.; Cook, Wayne, comps. 2007. The fire environment—innovations, management, and policy; conference proceedings. 26-30 March 2007; Destin, FL. Proceedings RMRS-P-46CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 662 p. CD-ROM.

[1] Belovo Branch, Kemerovo State University, Belovo, Kemerovo region, Russia. p_valer@mail.ru

Problem Formulation

The basic assumptions adopted during the deduction of equations and boundary and initial conditions:

1. The forest represents a multiphase, multistoried, spatially heterogeneous medium.
2. In the fire zone the forest is a porous-dispersed, two-temperature, single-velocity, reactive medium.
3. The forest canopy is supposed to be nondeformed media (trunks, large branches, small twigs, and needles) and affects only the magnitude of the force of resistance in the equation of conservation of momentum in the gas phase—that is, the medium is assumed to be quasisolid (almost nondeformable during wind gusts).
4. Let there be a so-called "ventilated" forest massif, in which the volume of fractions of condensed forest fuel phases, consisting of dry organic matter, water in liquid state, solid pyrolysis products, and ash, can be neglected compared to the volume fraction of gas phase (components of air and gaseous pyrolysis products).
5. The flow has a developed turbulent nature and molecular transfer is neglected.
6. Gaseous phase density doesn't depend on the pressure because of the low velocities of the flow in comparison with the velocity of the sound.

Let the coordinate reference point x_1, x_2, $x_3 = 0$ be situated at the centre of the surface forest fire source at the height of the roughness level, axis $0x_1$ directed parallel to the Earth's surface to the right in the direction of the unperturbed wind speed, axis $0x_2$ directed perpendicular to $0x_1$ and axis $0x_3$ directed upward (fig. 1).

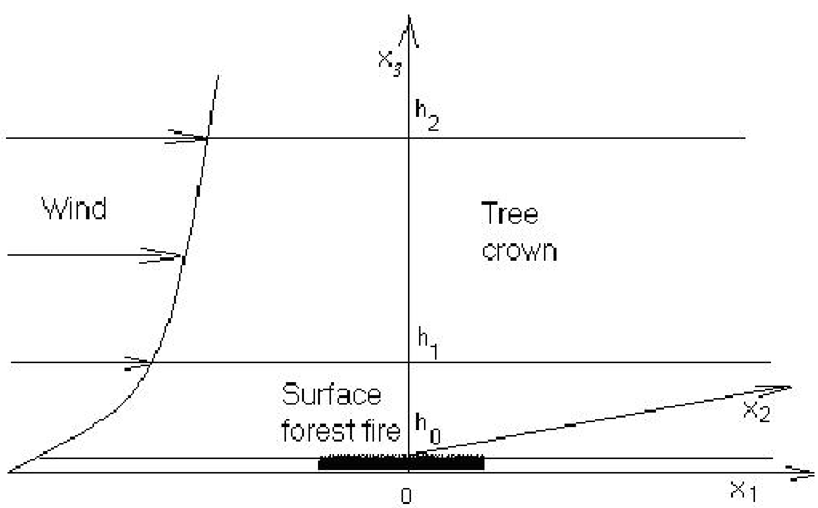


Figure 1—Coordinate reference point information.

Using the results of Grishin and Perminov from their studies conducted 1995 through 1998, and known experimental data (Konev 1977), we have the following sufficiently general equations, which define the state of the medium in the forest fire zone, written using tensor notation:

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x_j}(\rho v_j)=m, \quad j=1,2,3, \quad i=1,2,3; \tag{1}$$

$$\rho\frac{dv_i}{dt}=-\frac{\partial P}{\partial x_i}+\frac{\partial}{\partial x_j}(-\rho\overline{v_i'v_j'})-\rho s c_d v_i |v|-\rho g_i - m v_i; \tag{2}$$

$$\rho c_p\frac{dT}{dt}=\frac{\partial}{\partial x_j}(-\rho c_p \overline{v_j' v_i' T'})+q_5R_5-\alpha_v(T-T_s)+k_g(cU_R-4\sigma T^4); \tag{3}$$

$$\rho\frac{dc_\alpha}{dt}=\frac{\partial}{\partial x_j}(-\rho\overline{v_j'c_\alpha'})+R_{5\alpha}-mc_\alpha, \ \alpha=1,5; \tag{4}$$

$$\frac{\partial}{\partial x_j}\left(\frac{c}{3k}\frac{\partial U_R}{\partial x_j}\right)-kcU_R+4k_S\sigma T_S^4+4k_g\sigma T^4=0, k=k_g+k_S; \tag{5}$$

$$\sum_{i=1}^{4}\rho_i c_{pi}\varphi_i\frac{\partial T_S}{\partial t}=q_3R_3-q_2R_2+k_s(cU_R-4\sigma T_S^4)+\alpha_V(T-T_S); \tag{6}$$

$$\rho_1\frac{\partial\varphi_1}{\partial t}=-R_1,\ \rho_2\frac{\partial\varphi_2}{\partial t}=-R_2,\rho_3\frac{\partial\varphi_3}{\partial t}=\alpha_C R_1-\frac{M_C}{M_1}R_3,\ \rho_4\frac{\partial\varphi_4}{\partial t}=0; \tag{7}$$

$$\sum_{\alpha=1}^{5}c_\alpha=1,\ p_e=\rho RT\sum_{\alpha=1}^{5}\frac{c_\alpha}{M_\alpha},\ v=(v_1,v_2,v_3), g=(0,0,g),\ m=(1-\alpha_c)R_1+R_2+\frac{M_c}{M_1}R_3+R_{54}+R_{55}.$$

Here and above $\frac{d}{dt}$ is the symbol of the total (substantial) derivative; α_v is the coefficient of phase exchange; ρ - density of gas – dispersed phase, t is time; v_i - the velocity components; T, T_S, - temperatures of gas and solid phases, U_R – density of radiation energy, k – coefficient of radiation attenuation, P – pressure; c_p – constant pressure specific heat of the gas phase, c_{pi}, ρ_i, φ_i – specific heat, density and volume of fraction of condensed phase: 1 – dry organic substance, 2 – moisture, 3 – condensed pyrolysis products, 4 – mineral part of forest fuel), R_i – the mass rates of chemical reactions, q_i – thermal effects of chemical reactions; k_g , k_S – radiation absorption coefficients for gas and condensed phases; T_e – the ambient temperature; c_α – mass concentrations of α - component of gas – dispersed medium, index α=1,2,...,5, where 1 corresponds to the density of oxygen, 2 – to carbon monoxide CO, 3 – to carbon dioxide and inert components of air, 4 – to particles of black, 5 – to particles of smoke; R – universal gas constant; M_α , M_C, and M molecular mass of α – components of the gas phase, carbon and air mixture; g is the gravity acceleration; c_d is an empirical coefficient of the resistance of the vegetation, s is the specific surface of the forest fuel in the given forest stratum, v_g – mass fraction of gas combustible products of pyrolysis, α_4 and α_5 – empirical constants. To define source terms that characterize inflow (outflow of mass) in a volume unit of the gas-dispersed phase, the following formulae were used for the rate of formulation of the gas-dispersed mixture $\dot{m}$, outflow of oxygen R_{51}, changing carbon monoxide R_{52}, generation of black R_{54} and smoke particles R_{55}.

$$R_{51} = -R_3 - \frac{M_1}{2M_2} R_5, R_{52} = v_g(1-\alpha_c)R_1 - R_5, R_{53} = 0, R_{54} = \alpha_4 R_1, R_{55} = \frac{\alpha_5 v_3}{v_3 + v_{3*}} R_3.$$

Reaction rates of these various contributions (pyrolysis, evaporation, combustion of coke, and volatile combustible products of pyrolysis) are approximated by Arrhenius laws whose parameters (preexponential constant k_i and activation energy E_i) are evaluated using data for mathematical models (Grishin and Perminov 1995-1998):

$$R_1 = k_1\rho_1\varphi_1 \exp\left(-\frac{E_1}{RT_s}\right), R_2 = k_2\rho_2\varphi_2 T_s^{-0.5} \exp\left(-\frac{E_2}{RT_s}\right),$$

$$R_3 = k_3\rho\varphi_3 s_\sigma c_1 \exp\left(-\frac{E_3}{RT_s}\right), R_5 = k_5 M_2 \left(\frac{c_1 M}{M_1}\right)^{0.25} \frac{c_2 M}{M_2} T^{-2.25} \exp\left(-\frac{E_5}{RT}\right).$$

Coefficients of multiphase (gas and solid phase) heat and mass exchange are defined $\alpha_V = \alpha S - \gamma C_P m, S = 4\varphi_S / d_S$. Here $\alpha = Nu\lambda/d_S$ – coefficient of heat exchange for sample of forest combustible material (for example, needle), Nu – Nusselt number for cylinder, λ – coefficient of heat conductivity for pine needle; γ – parameter, which characterizes the relation between molecular masses of ambient and inflow gases.

The system of equations 1 through 7 must be solved taking into account the initial and boundary conditions:

$$t = 0 : v_1 = 0, v_2 = 0, v_3 = 0, T = T_e, c_\alpha = c_{\alpha e}, T_s = T_e, \varphi_1 = \varphi_{ie}; \quad (8)$$

$$x_1 = -x_{1e} : v_1 = V_e, v_2 = 0, \frac{\partial v_3}{\partial x_1} = 0, T = T_e, c_\alpha = c_{\alpha e}, -\frac{c}{3k}\frac{\partial U_R}{\partial x_1} + cU_R / 2 = 0; \quad (9)$$

$$x_1 = x_{1e} : \frac{\partial v_1}{\partial x_1} = 0, \frac{\partial v_2}{\partial x_1} = 0, \frac{\partial v_3}{\partial x_1} = 0, \frac{\partial c_\alpha}{\partial x_1} = 0, \frac{\partial T}{\partial x_1} = 0, \frac{c}{3k}\frac{\partial U_R}{\partial x_1} + \frac{c}{2}U_R = 0; \quad (10)$$

$$x_2 = x_{20} : \frac{\partial v_1}{\partial x_2} = 0, \frac{\partial v_2}{\partial x_2} = 0, \frac{\partial v_3}{\partial x_2} = 0, \frac{\partial c_\alpha}{\partial x_2} = 0, \frac{\partial T}{\partial x_2} = 0, -\frac{c}{3k}\frac{\partial U_R}{\partial x_2} + \frac{c}{2}U_R = 0; \quad (11)$$

$$x_2 = x_{2e} : \frac{\partial v_1}{\partial x_2} = 0, \frac{\partial v_2}{\partial x_2} = 0, \frac{\partial v_3}{\partial x_2} = 0, \frac{\partial c_\alpha}{\partial x_2} = 0, \frac{\partial T}{\partial x_2} = 0, \frac{c}{3k}\frac{\partial U_R}{\partial x_2} + \frac{c}{2}U_R = 0; \quad (12)$$

$$x_3 = 0 : v_1 = 0, v_2 = 0, \frac{\partial c_\alpha}{\partial x_3} = 0, -\frac{c}{3k}\frac{\partial U_R}{\partial x_3} + \frac{c}{2}U_R = 0, v_3 = v_{30}, T = T_g, |x_1| \le \Delta, |x_2| \le \Delta, \quad (13)$$

$$v_3 = 0, \ T = T_e, |x_1| > \Delta, |x_2| > \Delta;$$

$$x_3 = x_{3e} : \frac{\partial v_1}{\partial x_3} = 0, \frac{\partial v_2}{\partial x_3} = 0, \frac{\partial v_3}{\partial x_3} = 0, \frac{\partial c_\alpha}{\partial x_3} = 0, \frac{\partial T}{\partial x_3} = 0, \frac{c}{3k}\frac{\partial U_R}{\partial x_3} + \frac{c}{2}U_R = 0. \quad (14)$$

The conditions of symmetry are used because of the patterns of flow and distributions of all scalar functions are symmetrical relatively to the axes Ox_2.

The source of ignition is defined as a function of time at $|x_1| \le \Delta_{x_1}, |x_2| \le \Delta_{x_2}$ and turned off after the forest fire initiation. It is supposed that the optical properties of a medium are independent of radiation wavelength (the assumption that the medium is “grey”), and the so-called diffusion approximation for radiation flux density was used for a mathematical description of radiation transport during forest fires. The components of the tensor of turbulent stresses, as well as the turbulent fluxes of heat and mass, are written in terms of the gradients of the average flow properties (Grishin 1997). It should be noted that this system of equations describes processes of transfer within the entire region of the forest massif, which includes the space between the underlying surface and the base of the forest canopy, the forest canopy, and the space above it, while the appropriate components of the data base are used to calculate the specific properties of the various forest strata and the near-ground layer of atmosphere. This approach substantially simplifies the technology of solving problems of predicting the state of the medium in the fire zone numerically. The thermodynamic, thermophysical and structural characteristics correspond to the forest fuels in the canopy of a different type of forest; for example, pine forest (Grishin 1997; Perminov 1995).

Calculation Method and Results

The boundary-value problems 1 through 7 we solve numerically using the method of splitting according to physical processes (Perminov 1995). In the first stage, the hydrodynamic pattern of flow and distribution of scalar functions was calculated. The system of ordinary differential equations of chemical kinetics obtained as a result of splitting was then integrated. A discrete analog was obtained by means of the control volume method using the SIMPLE like algorithm (Patankar 1981). The accuracy of the program was checked by the method of inserted analytical solutions. The time step was selected automatically. Fields of temperature, velocity, component mass fractions, and volume fractions of phases were obtained numerically.

Figure 2 illustrates the time dependence of dimensionless temperatures of gas and condensed phases (a), concentrations of components (b), and relative volume fractions of solid phases (c) at crown base of the forest

$$a)(1-\overline{T}=T/T_e, 2-\overline{T}_s=T_s/T_e, T_e=300K),$$
$$b)(1-\overline{C}_1=C_1/C_{1e}, 2-\overline{C}_2=C_2/C_{1e}, C_{1e}=0.23),$$
$$c)(1-\overline{\varphi}_1=\varphi_1/\varphi_{1e}, 2-\overline{\varphi}_2=\varphi_2/\varphi_{2e}, 2-\overline{\varphi}_3=\varphi_3/\varphi_{3e}).$$

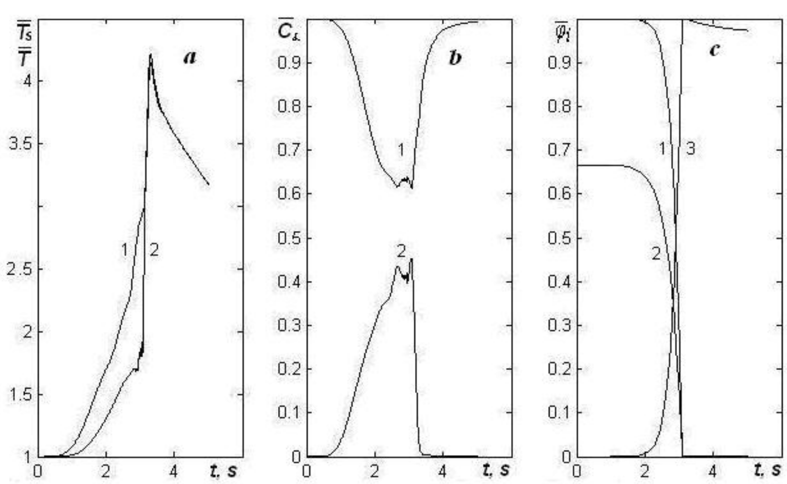


Figure 2—Relationships of (a) dimensionless temperatures, (b) concentrations, and (c) volume fractions in the lower boundary of the forest canopy.

At the moment of ignition the gas combustible products of pyrolysis burn away, and the concentration of oxygen is rapidly reduced. The temperatures of both phases reach a maximum value at the point of ignition. The ignition processes are of a gas-phase nature—that is, initial heating of solid and gaseous phases occurs and moisture is evaporated. Then the decomposition process into condensed and volatile pyrolysis products starts, the latter being ignited in the forest canopy. Note also that the transfer of energy from the fire source takes place due to radiation; the value of radiation heat flux density is small compared to that of the convective heat flux. As a result of heating of forest fuel elements, moisture evaporates, and pyrolysis occurs accompanied by the release of gaseous products, which then ignite. The effect of the wind on the zone of forest fire initiation is shown in figures 3 through 5, which present the space distribution of field of temperature for gas phase for different instants of time when a wind velocity V_e= 7 m/s. We can note that the isosurfaces are deformed by the action of wind. The isosurfaces of the temperature of gas phase 1,2,3 и 4 correspond to the temperatures $\overline{T}$ = 1.2., 2, 3 and 4. In the vicinity of the source of heat and mass release, heated air masses and products of pyrolysis and combustion float up. The wind field in the forest canopy interacts with the gas-jet obstacle that forms from the surface forest fire source and from the ignited forest canopy base. Recirculating flow forms beyond the zone of heat and mass release, while on the windward side the movement of the air flowing past the ignition region accelerates. Under the influence of the wind the tilt angle of the flame is increased. As a result this part of the forest canopy, which is shifted in the direction of the wind from the center of the surface forest fire source, is subjected to a more intensive warming up. The isosurfaces of the gas phase are deformed in the direction of the wind. Figures 4 and 5 present the distribution of the velocity and isosurfaces of the temperature at the different instants of time when a wind velocity V_e= 7 m/s.

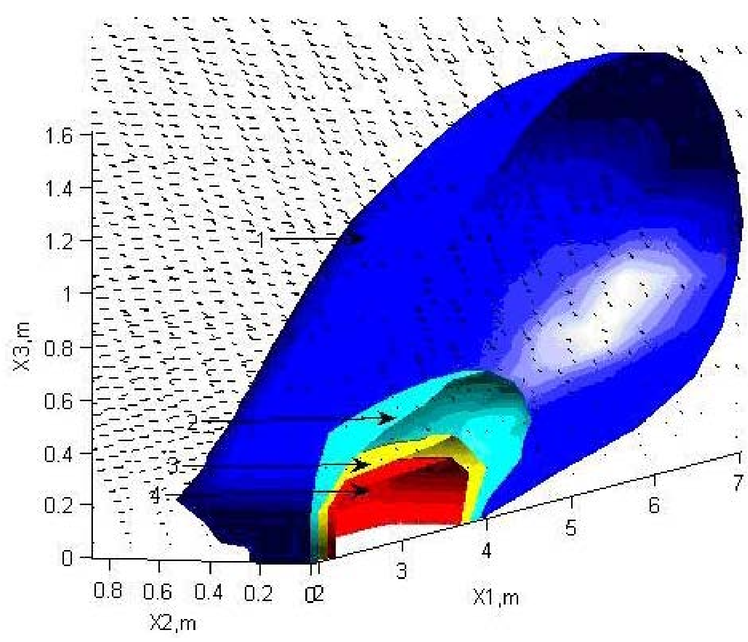


Figure 3—The vectorial field of velocity and temperature at *t=3.3 s.*

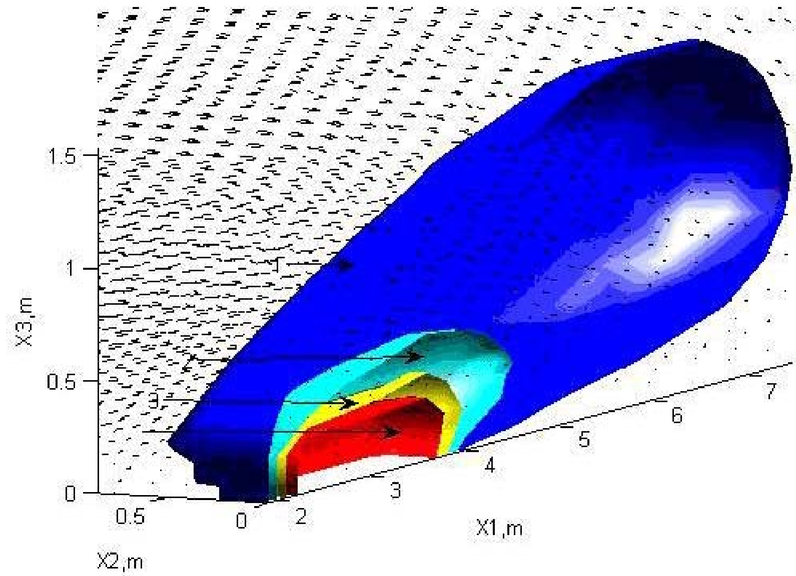


Figure 4—The vectorial field of velocity and temperature at *t=3.8 s*.

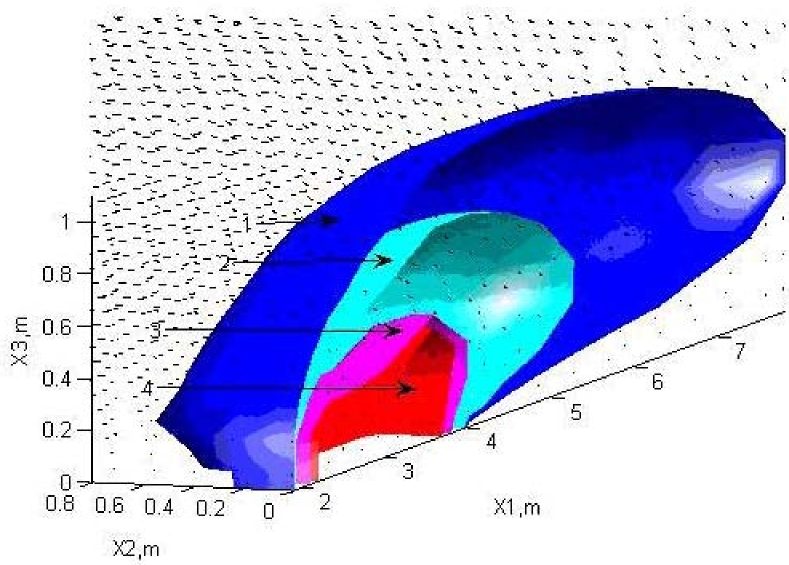


Figure 5—The vectorial field of velocity and temperature at *t=4.8 s*.

Conclusions

Mathematical model and the result of the calculation give an opportunity to evaluate critical condition of the forest fire initiation and spread, which allows applying the given model for preventing fires. The model overestimates the rate of the crown forest fires spread. The results obtained agree with the laws of physics and experimental data (Grishin 1997; Konev 1977). This work represents the attempt for application of three dimensional models for description of crown forest fires initiation and spread.

Acknowledgment

This paper was supported in part by the RFBR Grant 07-01-96047-p_ural_a.

References

Albini, F.A.; and others. 1995. Modeling ignition and burning rate of large woody natural fuels. Int. Journal of Wildland Fire 5(2): 81-91.

Alexander, M.E. 1998. Crown fire thresholds in exotic pine plantations of Australasia. PhD thesis. Department of Forestry, Australian National University.

Cruz, M.G.; and others. 2002. Predicting crown fire behavior to support forest fire management decision-making. [CD-ROM]. In: IV International conference on forest fire research. Luso-Coimbra, Portugal. (Ed. D. X. Viegas). 11. Millpress.

Grishin, A.M. 1997. Mathematical Modeling Forest Fire and New Methods Fighting Them. Tomsk: Publishing House of Tomsk University.

Grishin, A.M.; Perminov, V.A. 1998. Mathematical modeling of the ignition of tree crowns. Combustion, Explosion, and Shock Waves 34: 378-386.

Konev, E.V. 1977. The physical foundation of vegetative materials combustion. Novosibirsk: Nauka, Russia.

Morvan, D.; Dupuy, J.L. 2001. Modeling of fire spread through a forest fuel bed using a multiphase formulation. Combustion and Flame 127: 1981-1994.

Morvan, D.; Dupuy, J.L. 2004. Modeling the propagation of wildfire through a Mediterranean shrub using a multiphase formulation. Combustion and Flame. 138: 199-210.

Patankar, S.V. 1981. Numerical Heat Transfer and Fluid Flow. New York: Hemisphere Publishing Corporation.

Perminov, V.A. 1995. Mathematical Modeling of Crown and Mass Forest Fires Initiation With the Allowance for the Radiative-Convective Heat and Mass Transfer and Two Temperatures of Medium. Ph.D thesis. Tomsk State University.

Perminov, V.A. 1998. Mathematical modeling of crown forest fire initiation. In: III International conference on forest fire research and 14th conference on fire and forest meteorology. Luso, Portugal. (Ed. D.X.Viegas): 419-431.

Rothermel, R.C. 1991a. Crown fire analysis and interpretation. In: 11th International conference on fire and forest meteorology. Missoula, Montana, USA.

Rothermel, R.C. 1991b. Predicting behavior of the 1988 Yellowstone Fires: projections versus reality. Int. Journal of Wildland Fire. 1: 1-10.

Scott, J.H.; Reinhardt, E.D. 2001. Assessing crown fire potential by linking models of surface and crown fire behavior. RMRS-RP-29, Fort Collins, CO, USA: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Van Wagner, C.E. 1977. Conditions for the start and spread of crown fire. Canadian Journal of Forest Research 7: 23-34.

Van Wagner, C.E. 1979. Prediction of crown fire behavior in conifer stands. In: 10th conference on fire and forest meteorology. Ottawa, Ontario. (Eds D. C. MacIver, H. Auld, and R. Whitewood): 207-212.

Van Wagner, C.E. 1999. Prediction of crown fire behavior in two stands of jack pine. Canadian Journal of Forest Research 23: 445-449.

Xanthopoulos, G. 1990. Development of a wildland crown fire initiation model. PhD thesis. University of Montana.

Preliminary Results of Fire Behavior in Maquis Fuels Under Varying Weather and Slope Conditions in Turkey

Bülent Saglam[1], Ertugrul Bilgili[2], Ömer Kücük[3], Bahar Dinc Durmaz[2], and Ismail Baysal[4]

Abstract*—The prediction of fire behavior is of vital importance to all fire management planning and decisionmaking processes including fire prevention, presuppression planning, and fire use. The effect of slope on fire behavior is well acknowledged, yet its effect on fire behavior is not well accounted for. Determining the effects of slope on fire behavior under field conditions can prove invaluable and will allow for the testing of earlier studies conducted under laboratory conditions and help increase the accuracy of fire behavior prediction models. The present study was carried out in Kesan Forest Enterprise in the province of Edirne, Turkey (40°35′ N and 26°31′ E). Although the site was selected for its structural homogeneity, there was an apparent variation in the fuel loadings in different plots. Surface fine fuel (0 to 0.5 cm) loading ranged from 1.07 to 2.10 kg m^{-2}, coarse fuel (0.6 to 2.5 cm) loading from 0.97 to 1.75 kg m^{-2}, and total fuel loading from 1.52 to 5.67 kg m^{-2}. Within the plots burned in this study slope ranged form 1 to 15 percent. Weather conditions during the burns were within the narrow range without wind speed. Air temperature ranged from 25.6 to 33.5 °C, relative humidity from 37 to 62 percent, and wind speed from 5.3 to 17 m min^{-1}. Rate of spread ranged from 0.58 to 8.43 m min^{-1}, fuel consumption from 1.02 to 2.30 kg m^{-2}, and fire intensity from 134 to 2847.6 kW m^{-1}. Of the fire behavior characteristics, rate of spread was related to wind speed, slope and moisture contents of live fuels, and fuel consumption was related to fuel loading and moisture contents of live fuels, whereas fire intensity was related to wind speed, slope and moisture contents of live fuels. Results obtained in this study should be invaluable in overall fire management practices, especially in the Mediterranean Region.*

Introduction

Fire is a common feature of Mediterranean landscapes and has a pervasive influence on its forests and their management. An increasingly important requirement of forest and land management in fire-prone ecosystems is the ability to predict fire behavior. Shrublands are one of the most important fire-prone plant communities and have crucial importance for fire management in Turkey. Shrub fuel types are known to be exceptionally flammable and capable of sustaining extreme fire intensity even at moderate fire danger levels (Wouters 1993; Fogarty 1996), thus posing a threat to human life and property (Fernandes 2001). The shrub complexes are known by various names such as fynbos (South Africa), mattoral (Chile), garrique (France), chaparral (California, USA) (Zhou and others 2007), and maquis in Turkey. Maquis grows extensively, neighboring on or adjacent to open forests of oak and pine, and as an understory in these forest types. Thus, determining the effect of varying weather and slope conditions on fire behavior in maquis fuel types has vital importance to all fire management planning and decision making processes.

In: Butler, Bret W.; Cook, Wayne, comps. 2007. The fire environment—innovations, management, and policy; conference proceedings. 26-30 March 2007; Destin, FL. Proceedings RMRS-P-46CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 662 p. CD-ROM.

[1] Arvin Coruh University, Faculty of Forestry, Artvin, Turkey. saglambul@gmail.com.

[2] Karadeniz Technical University, Faculty of Forestry, Trabzon, Turkey.

[3] Kastamonu University, Faculty of Forestry, Kastamonu, Turkey.

[4] Düzce University, Faculty of Forestry, Konuralp, Düzce, Turkey.

The literature review reveals that only a limited number of studies have established the relation between slope and fire behavior (Ward 1971; Rothermel 1972; Hirano and others 1974; Van Wagner 1977; Drysdale and Macmillan 1992; Weise 1993; Weise and Biging 1994; Viegas and others 1994; Dupuy 1995; Van Wagner 1968, 1988; Mendes-Lopes and others 2003; Bilgili and Saglam 2003; Viegas 2004; Zhou and others 2007). Testing slope in fire behavior models is mostly conducted in experimental burns in laboratories, and field burns are conducted on level terrain.

However, results obtained under laboratory conditions do not always reflect the situation under field conditions. Determining the effects of slope on fire behavior under field conditions can prove invaluable and will allow for the testing of earlier studies conducted under laboratory conditions and help increase the accuracy of fire behavior prediction models. The results generated from this study will constitute the basic and fundamental steps toward establishing a fire danger rating system in Turkey and should be invaluable in all phases of fire management planning.

Materials and Methods

The Study Area

The study is situated in Kesan Forest Enterprise in the province of Edirne, Turkey, at 40°35'N and 26°31'E on various slope conditions, and is 30 m above sea level. The community studied includes maquis formations of the *Quercus-Phillyraea* alliance that occupy areas with different degrees of perturbation and usually have *Q. coccifera* as the dominant species. Soils in the area are generally shallow and loam and sandy loam of limestone origin. The vegetation was an open shrubland with an average height of 1.30 m.

In July 2005, a series of 17 burning plots were established at the experimental burning site. Each plot was more or less 0.04 ha (15×25 m) and was delimited by a 5 m wide firebreak in which vegetation was eliminated through bulldozing to mineral soil. A complete fire weather station was established on the site 10 days prior to the burnings. Air temperature, relative humidity, 2 m open wind speed and precipitation were recorded at 13:00 local standard time.

Preburn Fuel Sampling

Fifteen plots (2×2 m) were randomly selected to determine the fuel loadings. The sampled maquis plots were cleared and categorized by diameter. Regression relationships between fuel loadings, vegetation cover, and mean height were established using the sampling data. Fuels loading in the burning plots were estimated using the relationships generated.

Postburn Fuel Sampling

Postburn fuel loading was estimated after each fire to determine fuel consumption. Remaining fuel in each plot was estimated by clipping, oven drying, and weighing all material from three randomly selected sample plots (2×2 m). Fuel consumption was calculated based on the difference between pre- and postburn fuel loadings.

Fuel Moisture Contents

Moisture content of vegetation was obtained from clipped samples immediately before each burning. Samples were oven-dried at 105 °C for 24 hours, and the fuel moisture was expressed as a percentage of dried weight.

Environmental Variables and Fire Behavior

Wind speed, relative humidity, and air temperature were recorded at 15 second intervals during each fire. Plots were burned over 7 days under varying temperature, relative humidity, moisture, wind speed, and slope conditions. Fires were started with a drip torch to rapidly establish a fire line along the windward edge of each plot. Fire intensity was calculated using Byram's equation, $I=hwr$, where, I is the fire line intensity (kW m^{-1}), h is heat yield of the fuel (kJ kg^{-1}), w is the dry weight of the fuels consumed by the fire (kg m^{-2}), and r is the rate of spread of the flame front (m s^{-1}). In this study, energy contents of 19000 kJ kg^{-1} were used based on the relevant information (Brown and Davis 1973; Alexander 1982).

Results

Preburn fuel characteristics for each plot are presented in table 1. Although the site was selected for its structural homogeneity, there was an apparent variation in the fuel loadings in different plots. Surface fine fuel (0 to 0.5 cm) loading ranged from 1.07 to 2.10 kg m^{-2}, coarse fuel (0.6 to 2.5 cm) loading from 0.97 to 1.75 kg m^{-2}, and total fuel loading from 1.52 to 5.67 kg m^{-2}.

Table 2 displays the observed variations in fire behavior values and fire weather conditions recorded on site during each experimental fire. Weather

Table 1—Preburn fuel characteristics associated with the experimental fires.

Fire	H			Fuel loadings (kg m^{-2})					Moisture contents (%)	
no.	(m)	VC	HxC	<0,5 cm	<1 cm	Dead	0,6-2,5 cm	Total	Live fuels	Dead fuels
1	0,63	0,70	0,44	1,11	1,35	0,02	0,98	1,60	77,88	11,07
2	1,00	0,75	0,75	1,35	1,70	0,15	1,19	2,68	102,78	17,99
3	1,50	0,83	1,24	1,86	2,28	0,35	1,51	4,42	102,78	17,99
4	1,30	0,80	1,04	1,64	2,04	0,27	1,38	3,70	109,33	9,40
5	1,15	0,80	0,92	1,55	1,90	0,22	1,30	3,28	100,00	8,26
6	0,60	0,70	0,42	1,10	1,32	0,01	0,97	1,52	100,00	8,26
7	2,00	0,80	1,60	2,05	2,69	0,50	1,75	5,67	98,00	8,26
8	1,05	0,83	0,87	1,56	1,84	0,20	1,26	3,11	100,00	8,26
9	1,50	0,83	1,24	1,86	2,28	0,35	1,51	4,42	89,47	13,86
10	1,70	0,80	1,36	1,87	2,41	0,40	1,59	4,83	69,40	8,73
11	1,50	0,65	0,98	1,26	1,96	0,24	1,34	3,48	69,40	8,73
12	1,75	0,85	1,49	2,10	2,56	0,46	1,68	5,28	89,26	14,34
13	1,35	0,85	1,15	1,82	2,16	0,31	1,45	4,08	89,26	14,34
14	0,75	0,70	0,52	1,15	1,44	0,05	1,03	1,89	79,84	9,76
15	1,15	0,80	0,92	1,55	1,90	0,22	1,30	3,28	81,07	10,49
16	1,55	0,85	1,32	1,96	2,36	0,38	1,56	4,68	75,97	7,58
17	0,75	0,65	0,49	1,07	1,40	0,04	1,01	1,76	75,97	7,58
Mean	1,25	0,78	0,99	1,58	1,98	0,25	1,34	3,51	88,85	10,88
Min.	0,60	0,65	0,42	1,07	1,32	0,01	0,97	1,52	69,40	7,58
Max.	2,00	0,85	1,60	2,10	2,69	0,50	1,75	5,67	109,33	17,99
SD	0,41	0,07	0,37	0,35	0,43	0,15	0,25	1,30	12,79	3,50
SE	0,10	0,02	0,09	0,09	0,10	0,04	0,06	0,32	3,10	0,85
N	17	17	17	17	17	17	17	17	17	17

Table 2—Fire behavior values and fire weather conditions associated with the experimental fires.

Fire no.	T (°C)	RH (%)	W ($m\ min^{-1}$)	S (%)	ROS ($m\ min^{-1}$) Observed	ROS ($m\ min^{-1}$) Predicted	FC ($kg\ m^{-2}$) Observed	FC ($kg\ m^{-2}$) Predicted	FI ($kW\ m^{-1}$) Observed	FI ($kW\ m^{-1}$) Predicted
1	25,6	62	11,2	1	1,94	1,53	1,15	1,28	497,61	657,58
2	32,2	42	7,8	10	2,23	2,36	1,40	1,38	720,69	1022,78
3	33,2	39	8,6	10	2,80	2,60	1,95	1,96	1215,07	1070,61
4	31,8	42	10,9	10	3,30	3,52	1,74	1,64	1279,08	1394,34
5	32,2	41	7,2	8	2,84	1,50	1,62	1,61	1025,24	678,55
6	32,2	41	7,8	8	0,58	2,06	1,02	1,17	134,00	882,02
7	32,2	55	7,7	10	1,56	2,37	2,30	2,12	861,92	978,97
8	33,0	41	7,5	9	3,11	1,86	1,57	1,63	1088,75	823,66
9	33,5	37	5,3	10	1,64	1,30	1,95	1,99	710,45	643,38
10	32,2	42	13,5	3	2,76	3,09	2,18	2,08	1473,53	893,24
11	32,5	46	12,9	4	3,19	2,90	1,52	1,45	1189,58	1062,68
12	32,6	38	10,4	12	2,20	3,90	2,11	2,27	1156,68	1541,47
13	32,6	38	11,6	15	5,95	4,61	2,01	1,94	2847,60	1744,58
14	32,7	41	15,7	13	5,10	6,14	1,44	1,26	1742,65	2399,98
15	31,4	45	16,2	13	5,93	6,21	1,76	1,70	2677,75	2265,03
16	27,7	62	15,2	14	5,10	6,17	2,01	2,21	2288,85	2310,22
17	27,0	60	17,0	14	8,43	6,03	1,19	1,24	2243,23	2647,17
Mean	31,4	45	11,0	10	3,45	3,42	1,70	1,70	1361,92	1353,90
Min.	25,6	37	5,3	1	0,58	1,30	1,02	1,17	134,00	643,38
Max.	33,5	62	17,0	15	8,43	6,21	2,30	2,27	2847,60	2647,17
SD	2,3	9	3,6	4	2,01	1,78	0,38	0,37	764,88	674,45
SE	0,6	2	0,9	1	0,49	0,43	0,09	0,09	185,51	163,58
N	17	17	17	17	17	17	17	17	17	17

conditions during the burns were within the narrow range without wind speed. Air temperature ranged from 25.6 to 33.5 °C, relative humidity from 37 to 62 percent, and wind speed from 5.3 to 17 m min^{-1}. Rate of spread ranged from 0.58 to 8.43 m min^{-1}, fuel consumption from 1.02 to 2.30 kg m^{-2}, and fire intensity from 134 to 2847.6 kW m^{-1} (table 2).

Correlation and regression analyses were undertaken to investigate the relationships between fire behavior characteristics and associated fuel properties and weather conditions. Table 3 displays the correlation coefficients showing trends and relationships among the independent and dependent variables. The most fitted relationships are given in table 4. Equations are presented with one or two independent variables as the second independent variable increased the percent variability explained by the equation.

Rate of spread of fire was highly correlated with wind speed (r= 0.791; P=0.001) and slope (r= 0.597; P=0.01). Wind speed alone explained 63 percent of the observed variation (P<0.001) in the rate of fire spread. Slope as the second independent variable improved the rate of spread prediction significantly (R^2=0.791; P<0.0001). Rate of spread observed by these experimental fires was poorly related to the slope alone (R^2=0.357; P<0.01). The addition of moisture contents of live fuels as the second independent variables significantly improved the percent variability explained (R^2=0.657; P<0.001). Wind speed and slope had a positive effect on rate of spread fire and fire intensity, while live fuel moisture content had a negative effect (table 3). The expectation of critical effect of live fuel moisture content on fire behavior would be significant; mainly its influence on ignitability (for example, Wilson 1985) and combustion rate (for example, Rothermel 1972; Catchpole and others 1998) was established in this study, while the effect of dead fuel moisture content, because of too few fuels, was not determined. Figure 1a shows the predicted versus observed rate of spread values.

Table 3—Correlation matrix between the variables used in the analyses.

	T	RH	ROS	FI	FC	W	S	MC_l	MC_d	H	VC	H×C	FL_f	FL_t
T	1													
RH	–,897(**)	1												
ROS	–,367	,298	1											
FI	–,163	,132	,890(**)	1										
FC	,383	–,199	–,068	,290	1									
W	–,487(*)	,436	,791(**)	,736(**)	–,093	1								
S	,105	–,089	,597(*)	,634(**)	,221	,260	1							
MC_l	,424	–,432	–,412	–,400	–,024	–,715(**)	,208	1						
MC_d	,299	–,468	–,183	–,073	,129	–,320	,152	,268	1					
H	,383	–,137	–,198	,113	,933(**)	–,165	,058	–,059	,071	1				
VC	,365	–,350	–,140	,205	,778(**)	–,331	,333	,361	,286	,608(**)	1			
HxC	,380	–,173	–,194	,143	,968(**)	–,204	,140	,024	,123	,982(**)	,741(**)	1		
FL_f	,356	–,217	–,182	,170	,956(**)	–,252	,246	,144	,194	,893(**)	,882(**)	,962(**)	1	
FL_t	,382	–,175	–,196	,141	,968(**)	–,206	,139	,025	,125	,981(**)	,742(**)	1,000(**)	,963(**)	1

** Correlation is significant at the 0.01 level (2-tailed).
* Correlation is significant at the 0.05 level (2-tailed).
☺T, air temperature (°C); RH, relative humidity (%); ROS, rate of spread (m min^{-1}); FI, fire intensity (kW m^{-1}); FC, fuel consumption (kg m^{-2}); W, wind speed (kph), S, slope (%); MCl, moisture contents of live fuels (%); MCd, moisture contents of dead fuels (%); H, mean vegetation height (cm); VC, vegetation cover (%); H×C, (mean vegetation height × vegetation cover)/10000; FLf, fine fuel loading (<0.6cm; kg m^{-2}); FLt, total fuel loading (kg m^{-2}).

Table 4—Regression equations for predicting fire spread, fuel consumption, and fire intensity in maquis fuels based on the data in this study.

		Constant	Coefficients		R^2	SEE
No	Model	a	b	c		
1a	ROS=a+b S	0.534	0.302		0.357	1.664
1b	ROS=a+b S+c MCl	14.925	0.361	–0.321	0.657	1.257
1c	ROS=a+b W	–1.357	0.438		0.626	1.268
1d	ROS=a+b W+c S	–2.747	0.378	0.213	0.791	0.982
2a	FC=a+b FLt	0.709	0.283		0.937	0.098
2b	FC=a+b FLf	0.720	1.031		0.914	0.115
2c	FC=a+b FLf+c MCl	0.865	1.056	–0.018	0.941	0.099
3a	FI= a+b S	183.264	122.178		0.402	611.044
3b	FI = a+b S+c MCl	5623.701	144.498	121.189	0.698	449.628
3c	FI =a+b W	–341.268	155.326		0.542	534.456
3c	FI =a+b W+c S	–939.026	129.342	91.497	0.752	406.905
3d	FI =a+b W (2 fire excluded)	–209.409	139.598		0.689	367.365
3e	FI =a+b W+c S (2 fire excluded)	–637.126	127.621	65.608	0.846	268.743

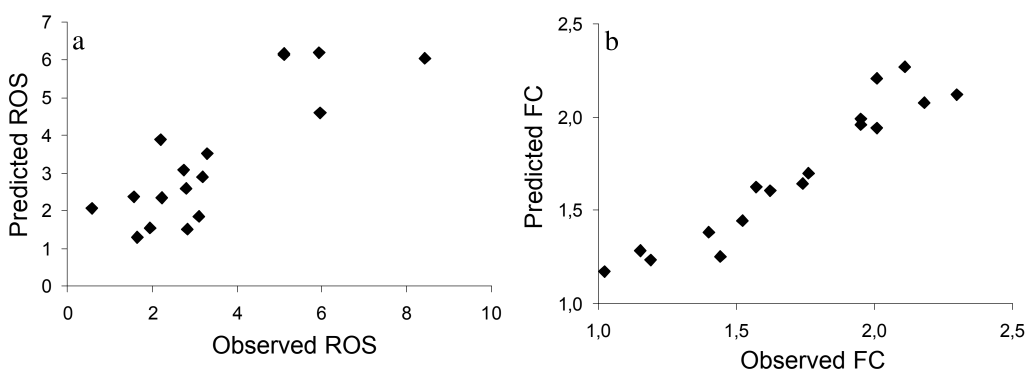


Figure 1—Relationship between predicted and observed rates of fire spread (a), and predicted and observed fuel consumption (b).

Fuel consumption generated by these experimental fires was significantly related to fine fuel loading (<0.6 cm), total fuel loading, and moisture contents of live fuel. Total fuel loading and fine fuel loading alone explained 94 and 91 percent of the observed variation (*P*<0.001) in the fuel consumption, respectively (table 4). The addition of the moisture contents of live fuels as a second independent variable with the fine fuel loading, slightly improved the variability explained (94 percent; *P*<0.001). The relationship between predicted and observed fuel consumption is shown in figure 1b.

Fire intensity was closely related to wind speed (r=0.736; P=0.001) and slope (r=0.634; P=0.001), and slightly related to moisture contents of live fuel (r=-0.400; P=0.001). Slope alone explained 40 percent of the observed variation of fire intensity. The addition of live fuel moisture content as a second independent variables improved the fire intensity prediction significantly (R^2=0.698; *P*<0.001). By the same token, wind speed alone explained 54 percent of the observed variation of fire intensity. The addition of slope as a second independent variables improved the fire intensity prediction (R^2=0.752; *P*<0.0001). When the minimum and maximum observed fire intensity data (fig. 2a) are excluded from the analyses, wind speed alone explained 69 percent of the observed variation of fire intensity. The addition of slope as a second independent variable improved the fire intensity prediction (R^2=0.846; *P*<0.0001; fig. 2b). When this study is completed with a wide range of weather and slope conditions for about 45 experimental fires, these data could be used in the analyses.

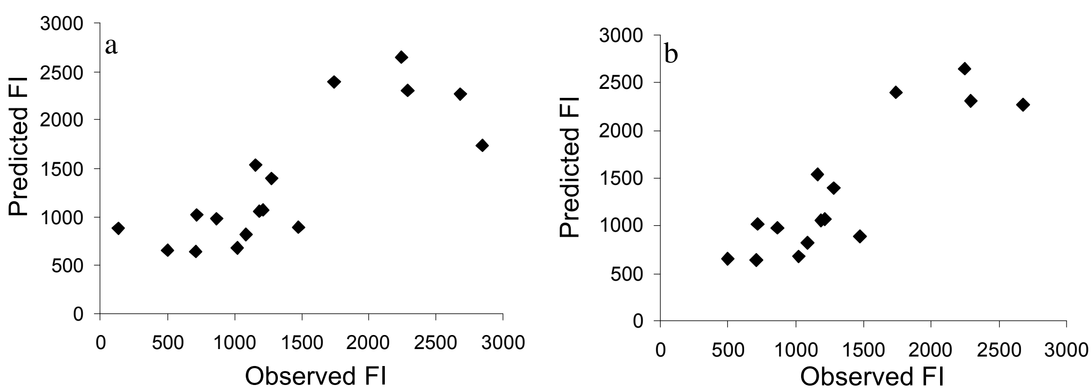


Figure 2—Relationship between predicted and observed fire intensity with whole fire intensity data (a), and (b) without the minimum and maximum fire intensity data.

Discussion and Conclusions

The preliminary results presented in this study come from the first efforts dealing with the prediction of fire behavior under various weather and slope effect in maquis fuels in Turkey. In that respect, the study makes an invaluable contribution to fire behavior analyses in maquis fuels in the Mediterranean Region. The results were based on 17 experimental fires. Differences in fire behavior were clearly shown to be a function of wind speed, slope, moisture contents of live fuels and fuel loading.

Analyses indicated that wind speed was the most significant single predictor of rate of spread of fire and fire intensity, explaining 63 and 69 percent of the variance observed, respectively. Similarly, rate of spread and fire intensity observed by these experimental fires was slightly related to the slope alone (R^2=0.357; R^2=0.402), respectively. It is important to address the effect of slope on fire spread as topography has a pronounced effect on fire behavior (see for example Noble and others 1980; Forestry Canada 1992; Mendes-Lopes and others 2003; Viegas 2004; Zhou and others 2007). Our results on rate of spread of fire agree with literature (Cheney and others 1993; Johnson and Miyanishi 1995; Burgan and others 1998; Piñol and others 1998; Baeza and others 2002), and support a negative relationship with moisture contents of fuels. On the contrary, because of the little amount of dead fuels, the effect of dead fuel moisture content on fire behavior has not been addressed in this study. Fernandes (2001) indicated that when live fuels are an important fraction of the total fuel load, dead fuel moisture content has a limited influence on the overall moisture content, and consequently, it is logical to expect also a limited effect on fire spread. Fuel consumption generated by these experimental fires was significantly related to fine fuel loading (<0.6 cm), total fuel loading, and moisture contents of live fuel. The addition of the moisture contents of live fuels as a second independent variable with the fine fuel loading explained 94 percent of the observed variation fuel consumption ($P<0.001$). Fire intensity observed in this study (mean 1361.92 kW m^{-1}) agree with those found in Trabaud (1979) in *Quercus coccifera* shrubland (1880 kW m^{-1}).

Given that the study is based on a relatively small number of fires with relatively narrow range of weather, slope, and fuel conditions in open area conditions, more extensive experimentation is required for a comprehensive explanation of fire behavior and the effect of slope and weather parameter on fire behavior for developing fire behavior prediction models in maquis fuels. Future effort will attempt to complete a series of about 45 experimental fires with a wide range of weather and slope conditions to analyze and understand fire behavior in maquis fuels.

Acknowledgments

This study was conducted with the cooperation and efforts of many people. The authors greatly acknowledge the assistance of Kesan State Forest District staff who contributed to the field work. Special thanks are due to State Forest Fire Command Unit staff that cooperated and assisted throughout the study. This study supported by The Scientific and Technological Research Council of Turkey, Career Development Program (3501), Agriculture, Veterinary and Forestry Sciences Division, Project No: 105O523.

References

Alexander, M.E. 1982. Calculating and interpreting forest fire intensities. Can. J. Bot. 60, 349-357.

Baeza, M.J.; De Luis, M.; Raventos, J.; Escarre, A. 2002. Factors influencing fire behavior in srublands of different stand ages and the implication for using prescribed burning to reduce wildfire risk. J. Environ. Mang. 65, 199-208.

Bilgili, E.; Sağlam, B. 2003. Fire Behavior in Maquis in Turkey, Forest Ecology and Management 184, 201-207.

Brown, A.A.; Davis, K.P. 1973. Forest fire: Control and use, 2nd Ed. New York: McGraw-Hill.

Burgan, R.E.; Klawer, R.W.; Klawer, J.M. 1998. Fuel models and fire potential from satellite and surface observations. Int. J. Wildland Fire 8, 159-170.

Byram, G.M. 1959, Combustion of Forest Fuels. In: Forest Fire: Control and Use. K. P. Davis (ed). New York: McGraw-Hill: 61-89.

Catchpole, W.; Bradstock, R.; Choate, J., Fogarty, L.; Gellie, N.; McCarty, G.; McCaw, L.; Marsden-Smedley, J.; Pearce, G. 1998. Cooperative Development of Equations for Heathland Fire Behaviour. In: Viegas, D.X. (ed.). Proc. 3rd Int. Conf. On Forest Fire Research/14th Fire and Forest Meteorology Conf., Luso, 16-20 November 1998. ADAI, University of Coimbra: 631-645.

Cheney, N.P.; Gould, J.S.; Catchpole, W.R. 1993. The influence of fuel, weather and fire shape variables on fire-spread in grassland. Int. J. Wildland Fire 8 (1), 31-44.

Coimbra, H.A. 1968. Control Burning in Eucalypt Forests in Victoria, Australia. J. For. 66 (8), 601-605.

Drysdale, D.D.; Macmillian, A.J.R. 1992. Flame spread on inclined surfaces. Fire Safety Journal 18:245-254.

Dupuy, J.L. 1995. Slope and fuel load effects on fire behavior: laboratory experiments in pine needles fuel beds, Int. J. Wildland Fire 5, 153-164.

Fernandes, P.M. 2001. Fire spread prediction in shrub fuels in Portugal. For. Ecol. Manage. 144, 67-74.

Forestry Canada. 1992, Development and Structure of the Canadian Forest Fire Behavior Prediction System, Forestry Canada. Fire Danger Group, Inf. Rep., St-X-3.

Hirano, T.H.; Noreikis, S.E.; Waterman, T.E. 1974. Postulation of flame spread mechanisms. Combustion and Flame 22:353-363.

Johnson, E.A.; Miyanishi, K. 1995. The need for consideration of fire behavior and effect in prescribed burning. Rest. Ecol. 3, 271-278.

Mendes-Lopes, J.M.C.; Ventura, J.M.P.; Amaral, J.M.P. 2003. Flame characteristics, temperature–time curves, and rate of spread in fires propagating in a bed of Pinus pinaster needles. Int. J. Wildland Fire 12, 67-84.

Noble, I.R.; Bary, G.A.V.; Gill, A.M. 1980. McArthur's Fire Danger Meters Expressed as Equations. Aust. J. Ecol. 5,201-203.

Piñol, J.; Filella, I.; Ogaya, R.; Peñuelas J. 1998. Ground-based spectroradiometric estimation of live fine fuel moisture of Mediterranean plants. Agr. and For. Meteo. 90, 173-186.

Rothermel, R.C. 1972. A Mathematical Model for Predicting Fire Spread in Wildland Fuels. Res. Pap. INT-115. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station.

Trabaud, L. 1979. Etude du comportoment du feu dans la garrique de chêne kermes à partir des températures et des vitesses de propagation. Ann. Sci. For. 36, 13-35.

Van Wagner, C.E. 1968. Fire Behavior Mechanisms in a Red Pine Plantation. Publ. No. 1229. Ottawa, Ontario, Canada: Canadian Department of Forest and Rural Development, Forestry Branch.

Van Wagner, C.E. 1977. Effect of Slope on Fire Spread Rate. Bi-Mon.Res. Notes 33:7-8. Environ. Can., Canadian Forest Service.

Van Wagner, C.E. 1988. Effect of slope on fire spreading downhill. Can. J. For. Res., Notes, 18:818-820.

Viegas, D.X.; Neto, L.P. 1991. Wall shear-stress as a parameter to correlate the rate of spread of a wind induced forest fire. Int. J. Wildland Fire 1, 177-188.

Viegas, D.X. 2004. Slope and wind effects on fire propagation. Int. J. Wildland Fire 13, 143-156.

Viegas, D.X.; Varela, V.G.M.; Borges, C.P. 1994. On the evolution of a linear fire front in a slope. In: Proceedings of the 2nd International Conference on Forest Fire Research, Coimbra, Portugal, November 21-24, 1994: 301-318.

Ward, D.E. 1971. A controlled experiment to study factors influencing fire rate of spread in *Pinus pinaster* letter. Forest Notes 9(3):39-47. Perth, Australia: Forest Department.

Weise, D.R. 1993. Modeling wind and slope induced wildland fire behavior. Ph.D. dissertation, University of California. 130 p.

Weise, D.R.; Biging, G.S. 1994. Effects of wind velocity and slope on fire behavior. Fourth International Symposium on Fire Safety Science, Ottawa, Ontario, Canada. June 13-17, 1994.

Wilson, R. 1985. Observation of extinction and marginal burning states in free burning porous fuel beds. Combust. Sci. Technol. 44,179-173.

Zhou, X.; Mahalingam, S.; Weise, D. 2007. Experimental study and large eddy simulation of effects of terrain slope on marginal burning in shrub fuel beds, Proc. Combust. Inst. 31, 2547-2555.

This page is blank on purpose

Fuels Management

This page is blank on purpose

Fine Scale Vegetation Classification and Fuel Load Mapping for Prescribed Burning

Andrew D. Bailey[1] and Robert Mickler[1]

***Abstract**—Fire managers in the Coastal Plain of the Southeastern United States use prescribed burning as a tool to reduce fuel loads in a variety of vegetation types, many of which have elevated fuel loads due to a history of fire suppression. While standardized fuel models are useful in prescribed burn planning, those models do not quantify site-specific fuel loads that reflect land use change, natural disturbances, and previous management. Furthermore, data on the fuel consumed during prescribed burning are generally unavailable. In an effort to accurately measure and map fuel loading and consumption at a site-specific level, fuels and vegetative communities were characterized in five burn compartments at the Air Force Dare County Bombing Range and Alligator River National Wildlife Refuge in eastern North Carolina. Aerial photography, digital softcopy photogrammetry, and GIS were used to map vegetation to the alliance level of the National Vegetation Classification System (NVCS). Within each vegetation alliance, fuel loads in the shrub, herbaceous, litter, duff, and 1-, 10-, 100-, and 1000- hour down woody fuel categories were measured using USDA Forest Service Forest Inventory and Analysis (FIA) phase 3 protocols. In addition, FIA phase 2 protocol plots were used to characterize live and standing dead tree biomass and forest canopy. Measured fuel loads were then compared to standardized fuel models to describe site-specific deviations. Following prescribed burning, fuel load plots were remeasured, and fuel consumption was calculated from pre- and postburn biomass. Consumption measurements were used to calculate prescribed fire emission factors, assess the achievement of prescribed burn goals, and validate the Blue Sky Smoke Modeling Framework in the Southeastern U.S. Coastal Plain.*

Introduction

The area burned by uncontrolled wildland fires increased over the latter decades of the 20th century (GAO 2005), and into the 21st century. This increase can be attributed to effective wildland fire suppression during the middle of the 20th century, which has lengthened fire return intervals in many parts of the country. Longer fire intervals have led to a buildup of flammable dead and live vegetation in unburned areas. Elevated levels of fuel loading, combined with the extreme weather conditions under which wildfires typically burn, create uncontrollable wildfires that often put human life and private property at risk. Fires under these conditions frequently burn with more intensity than areas managed for fuel reduction by mechanical or prescribed fire fuel treatments (Graham and others 2004; Carey and Schumann 2003).

In an effort to reduce the risk of wildfire, land managers are using prescribed fire to burn areas under controlled conditions. Using prescribed fire, land managers hope to periodically reduce fuel loads and modify forest structure to become more resistant to catastrophic wildfire. Managers use fire behavior modeling tools such as FARSITE (Finney 1998) and BEHAVE

In: Butler, Bret W.; Cook, Wayne, comps. 2007. The fire environment—innovations, management, and policy; conference proceedings. 26-30 March 2007; Destin, FL. Proceedings RMRS-P-46CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 662 p. CD-ROM.

[1] Associate Biologist and Program Manager, respectively, Alion Science and Technology, Durham, NC. Lead author adbailey@AlionScience.com

(Andrews and others 2005) to plan for prescribed burns and predict fire behavior. The BlueSky RAINS Smoke Modeling Framework (O'Neill and others 2003; McKenzie and others 2006) and VSmoke (Lavdas 1996) models allow managers to determine and mitigate the impacts of smoke from prescribed fires. The successful implementation of these tools necessitates the accurate quantification of wildland fuel loads.

Fuel loadings are typically reported in tons/acre by component for the standard 1-hour, 10-hour, 100-hour, 1000-hour, and litter fuel load classes. Often, fuel reporting also includes fuel bed depth and heights of live and dead herbaceous plants and shrubs. Standardized fuel models developed by Rothermel (1972), Albini (1976), Anderson (1982), and Scott and Burgan (2005) use a text description or a key so that managers may choose an appropriate set of fuel loadings for a specific site. The Natural Fuels Photo Series Publications (Ottmar and Vihnanek 2000) use close range stereo photography to depict vegetation types and fuel loads. The manager chooses the best representation of a site by browsing the photography and then reading the associated fuel loadings from a chart. Computer models may also be used to determine fuel loads. In the Fuelbed Characterization and Classification System (FCCS) (Sandberg 2001) users choose from a series of prototype fuelbeds representing vegetation descriptions and are able to modify vegetation composition and structure. The model then calculates or infers quantitative fuel characteristics and probable fire parameters.

Fuel loads from the approaches described above are based on measurements made in the field, but usually have been generalized across the continental United States or across a region of the country. The generalizations can lead to inaccuracies when applied to a specific site. Site history, including land use change, natural disturbances, and previous management actions—including previous prescribed burns—can lead to significant deviations from standard fuel loading models. Rosenfeld (2003) found that measured fuel loads based on ecological associations are more accurate than those provided with standard fuel models.

In situations where a high degree of accuracy is required, plot- or transect-based inventory procedures that directly measure site conditions are more appropriate (Otmar and Vihnanek 2000). Georeferenced fuel load measurement plots are a means to describe actual fuel loading characteristics, because fine woody fuels, litter, and duff are hidden by the canopy or are too small to detect with aerial imagery (Keane and others 2001). The most widely used method for the direct measurement of wildland fuels is Brown's (1974) line-intersect method. The U.S. Department of Agriculture, Forest Service integrated this method into the Forest Inventory Analysis (FIA) Program plot design to determine fuel loads, carbon storage, and wildlife habitat. Coupling the FIA plot design with GPS plot locations provides the necessary accuracy for fuel load measurement that can be combined with computer mapping techniques to make fine scale maps useful for a number of purposes.

In this study, the FIA plot design was applied in tandem with fine-scale softcopy aerial photography and digital mapping to quantify and map pre- and postfire wildland fuel loading for a prescribed burn on the Air Force Dare County Bombing Range (DCBR) and Alligator River National Wildlife Refuge (ARNWR) in the Coastal Plain of North Carolina. Large-scale maps of fuel loading developed during this project were designed to be useful to local land managers working on individual burns. These fuel loadings and the associated maps were used for prescribed burn planning, assessment of prescribed burn objectives, and to provide data for the validation of the BlueSky RAINS Smoke Modeling Framework in the Southeastern United States.

Methods

Site Description

The mainland of Dare County, North Carolina, is made up of numerous fire-adapted ecosystems under Federal ownership in proximity to one another. Nearly 200,000 acres in Dare County are managed by the U.S. Fish and Wildlife Service and the U.S. Air Force. The Dare County mainland is a peninsula 14 miles across, bordered on the north by the Albemarle Sound, on the east and south by the brackish Croatan and Pamlico Sounds, respectively, and on the west by the freshwater Alligator River. The long axis of the peninsula extends 29 miles from north to south. The Outer Banks barrier island chain provides protection from the Atlantic Ocean some 20 miles to the east. Though there are two small tidal creeks on the peninsula, there is virtually no relief, and elevations range from sea level to 4 ft above sea level. Over 90 percent of the peninsula is made up of organic "muck" soils. Fire, salinity, and organic soil depth are the main ecological factors affecting vegetation development. Our study site (fig. 1) consisted of two burn units totaling 1,525 acres on Ponzer, Belhaven, and Pungo muck soils, with peatland pocosin vegetation.

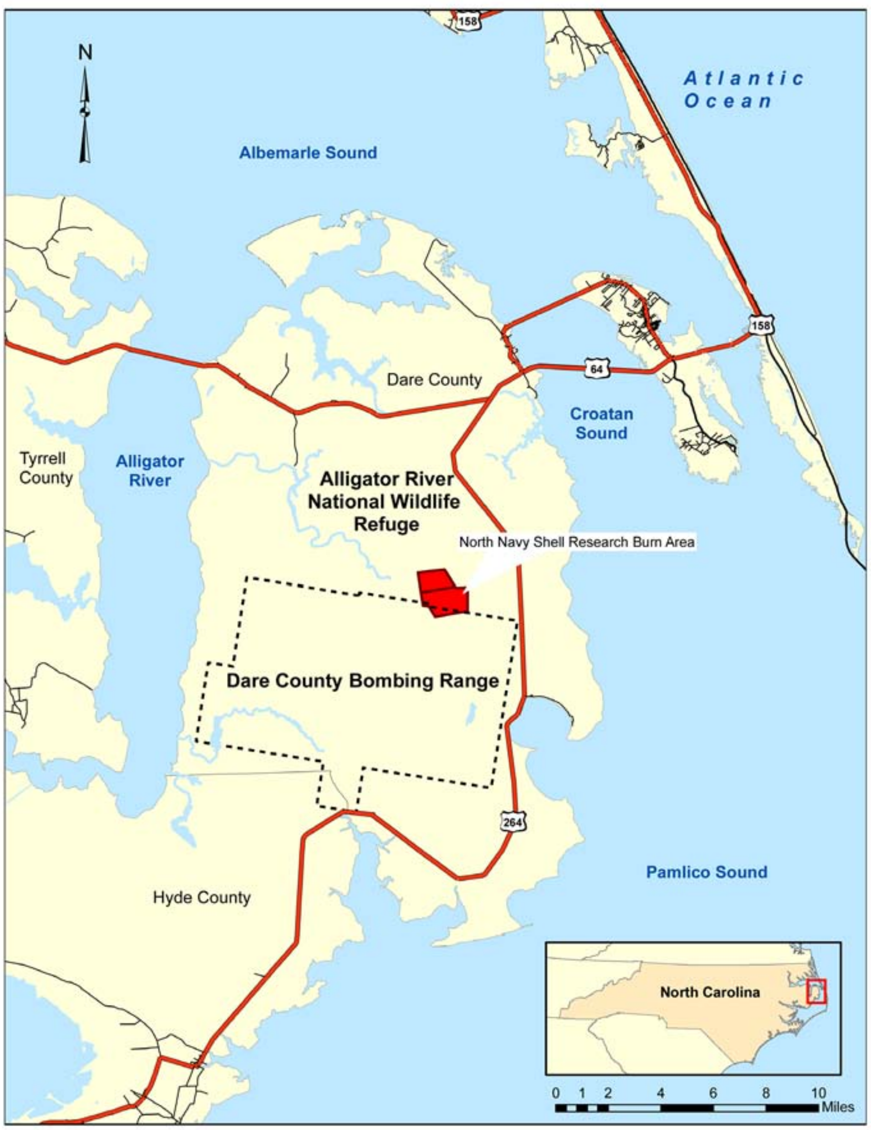


Figure 1—Location of the research site. The Alligator River National Wildlife Refuge and Dare County Bombing Range are located on a long, low peninsula in eastern North Carolina near the Atlantic Ocean.

Aerial Photography

An aerial photography mission flown in spring 2004 captured 496 color-infrared photographs with a spatial resolution of 7.5 inches per pixel (Bailey and Mickler 2005). Twenty-five of these photographs were used to provide 100 percent coverage of the research burn units. The digitized photographs were orthorectified and used to develop an orthophoto mosaic for use as a base layer during fuel load and vegetation community mapping. The digitized photographs were also used to develop a "block file" product, which allowed stereo photo pairs to be viewed on a computer in 3-D, as if viewing the imagery with a stereoscope. Benefits of this approach include onscreen panning and zooming, direct GIS database creation, and image manipulation capabilities. This product allowed the viewer to discriminate between objects in the canopy and objects on the ground, providing further analysis capabilities for determining canopy and understory vegetation and canopy cover estimates.

Mapping

Using the orthophoto mosaic, stereo blockfile, a digital elevation model, surface hydrology data, and a digital soil survey, polygons representing distinct vegetation communities were delineated to the alliance level of the NVCS (http://www.natureserve.org/explorer/servlet/NatureServe?init=Ecol). The NVCS is an ecosystem-based classification scheme in which vegetation communities are grouped by their characteristic physiognomy and floristic composition. To differentiate vegetation types on the orthophoto mosaic and stereo blockfile, seven photogrammetric interpretation attributes were used: size, shape, shadow, color, texture, pattern, and association with other objects (Avery 1992). The heads-up stereo photography allowed easy differentiation of vegetation communities with differing dominant tree heights, canopy shapes, and canopy closure. These were the critical strata used to discriminate between NVC alliances (Grossman 1998). Soil, elevation, and hydrology data were used to further inform the vegetation classification. When variation in structure within a vegetation alliance appeared great enough to affect fuel loading and fire behavior, a modifier was added to indicate this difference. A large minimum mapping unit of 2.5 acres was used to ensure that polygons captured variation in fuel loading within ecosystems.

Fuel Load Measurement

A permanent plot network was established to directly measure fuel loading within the research units. The plot design (fig. 2), based on the USDA Forest Service FIA phase 2 and phase 3 plots, was used to characterize live biomass and pre- and postburn down woody materials (DWM). A sampling grid was laid over the study area, and one plot was placed randomly within each grid cell. Grid cells were subsampled to ensure that a minimum of three plots were placed within each vegetation alliance. We used field protocols based on methods establish by the USDA Forest Service in Field Instructions for Southern Forest Inventory (http://fia.fs.fed.us/library/field-guides-methods-proc/). DWM data were collected using a line-intersect method to sample down wood along transects (Brown 1974). Down deadwood was characterized as coarse woody material (CWM, woody pieces greater than 3.0 inches in diameter), or fine woody material (FWM, small = 0.1 to 0.24 inch, medium = 0.25 to 0.9 inch, and large = 1 to 2.9 inches in diameter). The extent and height of live and dead shrub and herbaceous vegetation were measured on a

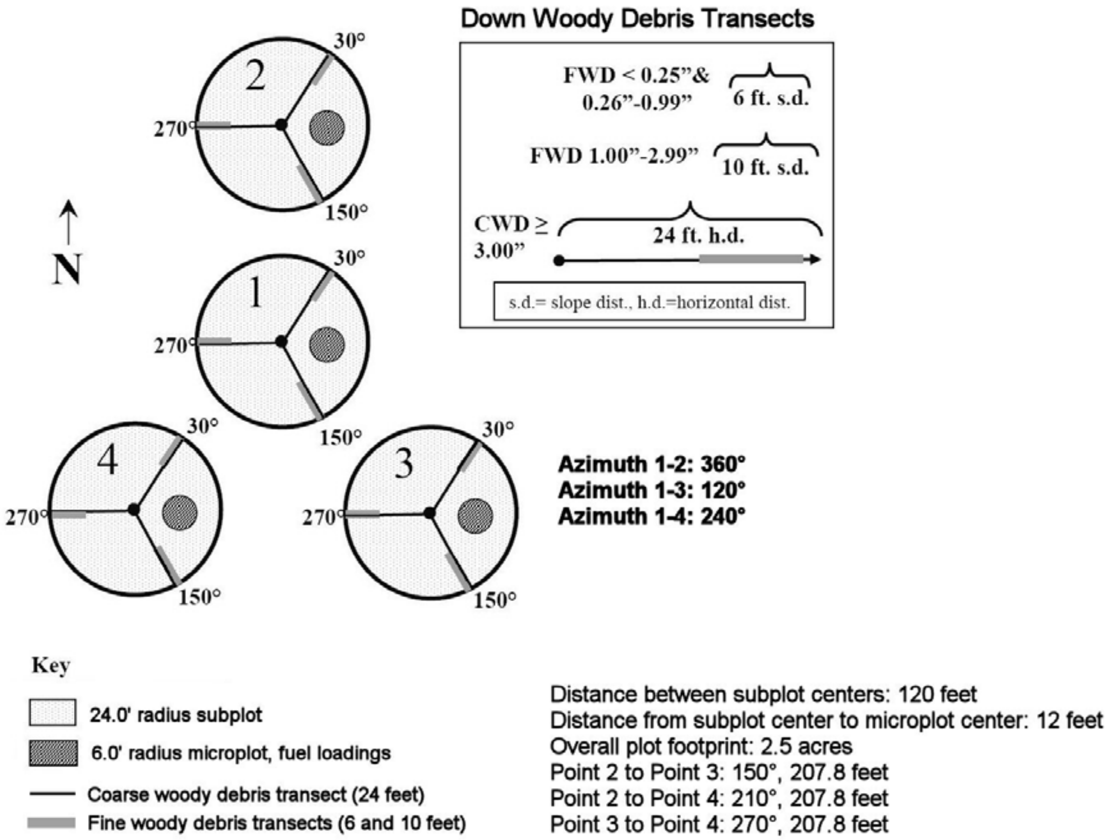


Figure 2—The USDA Forest Service Forest Inventory and Analysis plot design, used in this study to quantify wildland fuel loading. Each plot contains four circular subplots, each with a radius of 24 ft. Fine and coarse woody material is inventoried along three transects on each subplot. Litter layer and fuelbed depths are measured at the end of each transect. Live and dead shrub and herbaceous fuels are assessed in a 6-ft radius circular microplot within each subplot. (Figure adapted from fig. 14-1 in the USDA Forest Service Phase 3 Field Guide – Down Woody Materials.)

6-ft diameter microplot located within each subplot. FIA methodology was augmented with additional data on the vertical distribution of DWM for input into the FARSITE fire behavior model. The depths of the litter layer and fuelbed were taken at the 24-ft location on each transect. The biomass of the duff layer (Oa soil horizon) was estimated from the specific gravity of oven dried sampling frame soil samples for each soil series found on the field plots.

Biomass Scaling

Plot-level biomass estimates were combined to produce a mean per-unit-area biomass value for each vegetation alliance. The measurements were combined with material density (specific gravity) values in linear equations to compile dry-weight mass (tons/acre) for each DWM component (Mickler and Bailey 2005). Previous equations have been developed primarily for Western U.S. species (Brown 1974), necessitating the development of fuel class biomass algorithms for additional forest species and decay classes in the research area. Additional microplots were established for destructive sampling of shrub and herbaceous vegetation to develop new biomass equations.

Prescribed Burn and Post Burn Fuel Load Measurement

Following fuel load measurement, the research units were burned according to the North Navy Shell Compartment Prescribed Fire Plan (Simpson, and others 2004) on March 4, 2006. Aerial ignitions were conducted via helicopter using a Plastic Sphere Dispenser (PSD) machine to implement a grid pattern of ignitions that allowed for a backing fire with short periods of downwind fire activity. Fire intensity was generally moderate; most fire activity occurred in the litter and dead shrub strata, with occasional torching of the overstory aided by fuel ladders. The burn was substantially extinguished by rising humidity overnight with little residual smoldering. Following the prescribed burn, all plots were relocated and remeasured following the same protocols. The difference between prefire and postfire measurement represents the actual amount of fuel consumed during the burn.

Results

The aerial photo mosaic and vegetation map are displayed in figures 3 and 4, respectively. Seven vegetation alliances were mapped and appeared to occur along an increasing moisture gradient from southeast to northwest. The Shining Fetterbush – Little Gallberry Saturated Wooded Shrubland (12 acres) and the Sweetbay – Swampbay Saturated Forest (3 acres) made up a small proportion of the study area and were excluded from fuel loading analysis. In order of increasing moisture, the five alliances mapped were:

- Pond Pine Saturated Woodland (457 acres)
- Pond Pine Saturated Woodland – Overstocked (1349 acres)
- Loblolly Pine Saturated Forest (65 acres)
- Loblolly Pine – Atlantic White Cedar – Red Maple – Swamp Blackgum Saturated Forest (mixed pine/hardwood forest, 94 acres)
- Swamp Blackgum – Red Maple – Tuliptree Saturated Forest (maple forest, 68 acres)

Within the pond pine woodland alliance, high canopy coverage and low canopy coverage variants were observed and mapped separately. Following field measurements, the values within these variants were determined to be similar and were combined for this analysis into one pond pine woodland alliance.

Fuel loadings for each plot before and after the prescribed burn are reported in table 1. Fuel loadings by vegetation alliance are reported in figure 5. Prior to the prescribed fire, litter and FWM fuel loading were highest in the loblolly pine forest (12.09 tons/acre) and pond pine woodland (11.19 tons/acre). These two forest alliances each contained more than 7 tons/acre in the litter fuel class. The mixed pine/hardwood forest alliance contained 9.64 tons/acre of litter and FWM, with 4.94 tons/acre occurring in litter fuel class and 4.23 tons/acre in the medium (0.25 to 0.9 inch) and large (1.0 to 2.9 inch) classes. While duff made up the largest component in the fuel load, the prescribed burn was conducted when the possibility of consuming duff was at its lowest. No duff or coarse woody material (3+ inches in diameter, 1000 hour fuels) were consumed in any vegetation class during the burn.

Consumption is reported in table 2. The fire consumed 4.94 tons/acre in the loblolly pine forest alliance, which was 40.8 percent of the preburn litter and FWM fuel load. The most complete consumption occurred in the litter

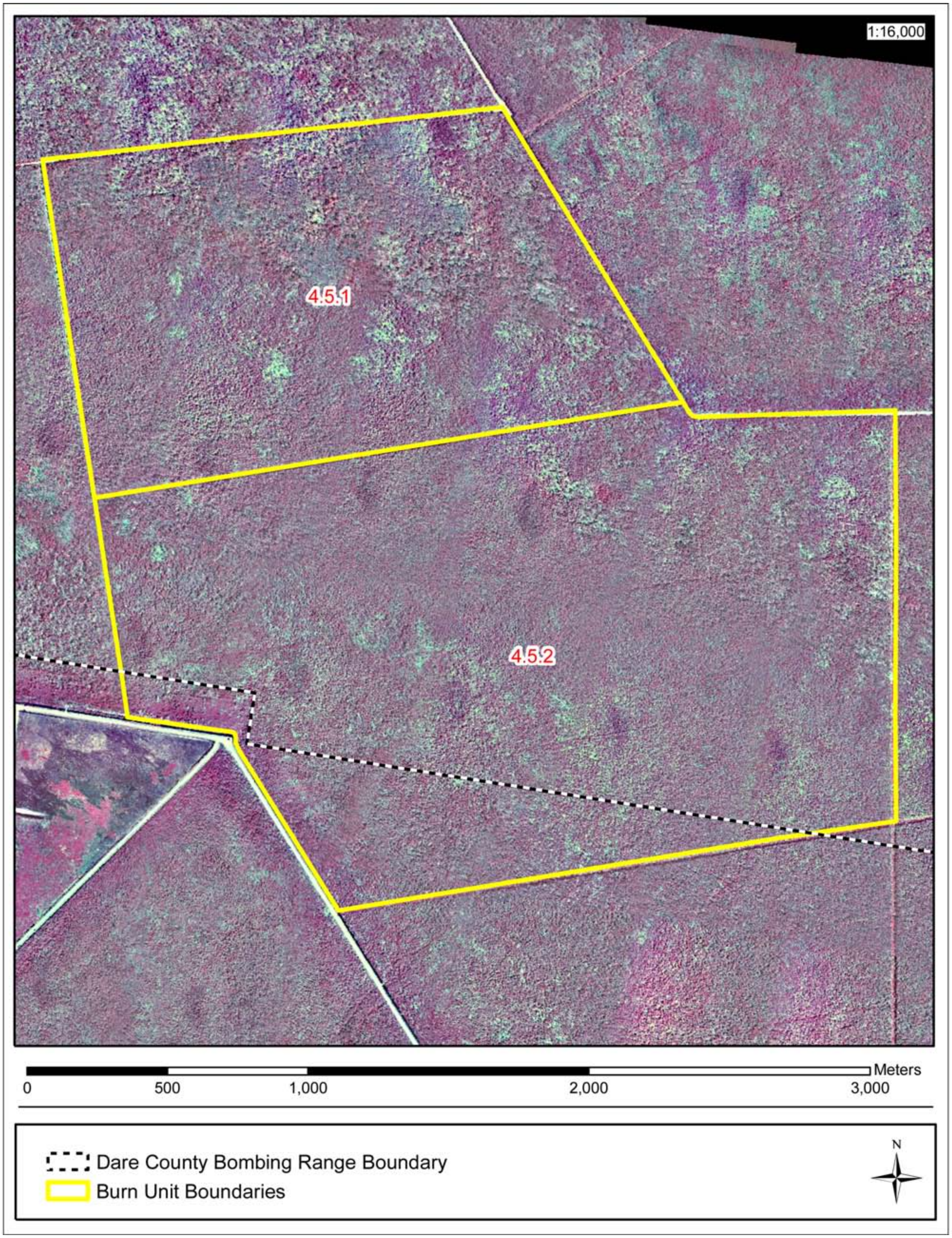


Figure 3—The finished orthorectified aerial photo mosaic for the study site. Each pixel represents a 7.5 x 7.5 inch area on the ground.

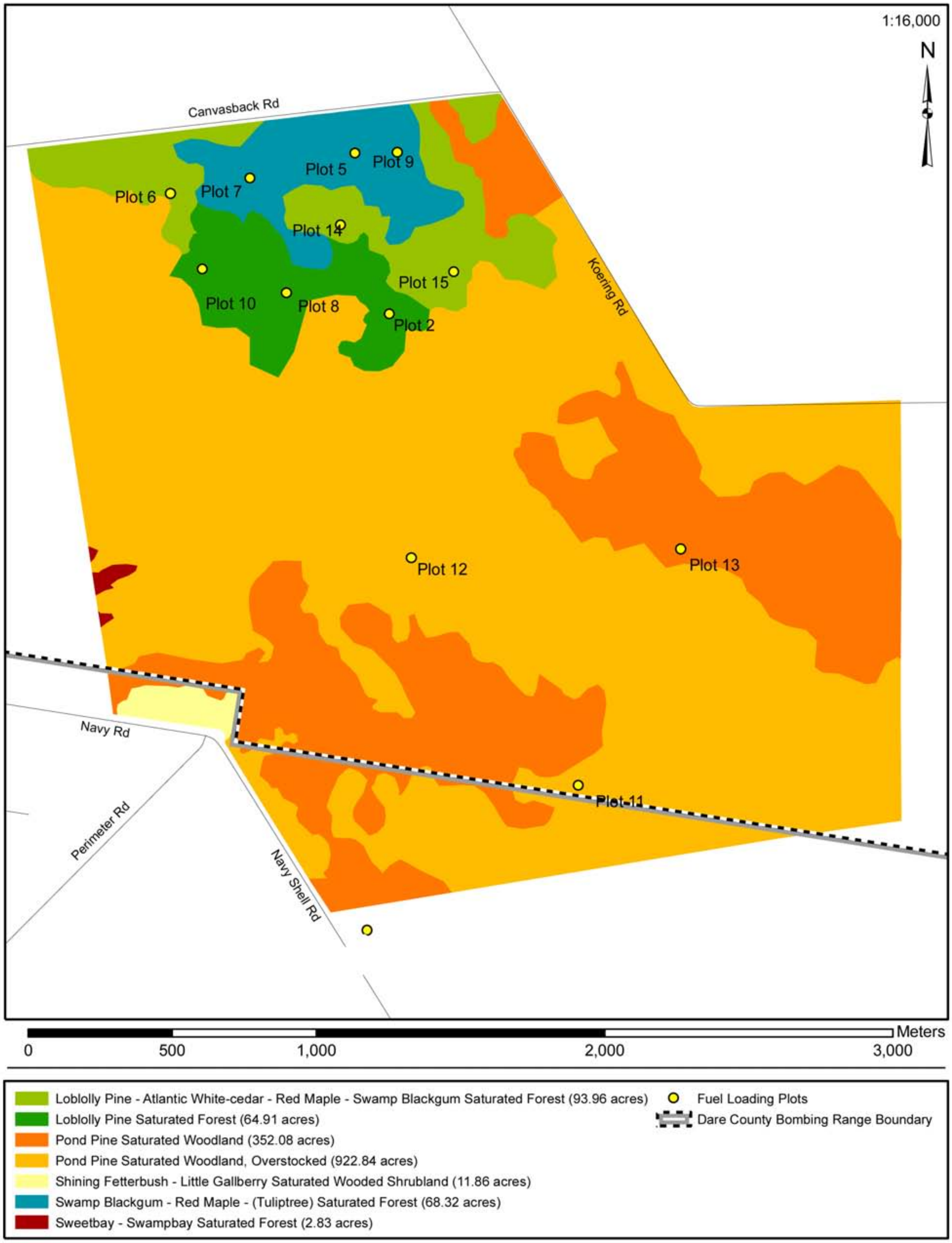


Figure 4—The finished vegetation alliance map for the study area. Seven alliances were mapped on 1,525 acres.

Table 1—Pre- and postburn biomass (all measurements in tons/acre).

		Preburn biomass					Postburn biomass				
Plot	**Vegetation alliance**	**Duff**	**Litter**	**FWM small**	**FWM medium**	**FWM large**	**Duff**	**Litter**	**FWM small**	**FWM medium**	**FWM large**
2	Loblolly pine forest	299.95	7.23	0.25	1.33	1.94	299.95	7.23	0.15	1.16	1.25
8	Loblolly pine forest	299.95	8.32	0.28	2.52	2.36	299.95	1.80	0.08	1.74	1.67
10	Loblolly pine forest	299.95	7.14	0.29	1.99	2.64	299.95	2.75	0.12	1.58	1.94
	Average	**299.95**	**7.56**	**0.27**	**1.95**	**2.31**	**299.95**	**3.93**	**0.12**	**1.49**	**1.62**
11	Pond pine woodland	513.07	6.75	0.39	1.67	1.11	513.07	2.62	0.15	1.28	0.83
12	Pond pine woodland	513.07	7.37	0.38	2.01	2.22	513.07	0.84	0.03	0.92	2.08
13	Pond pine woodland	189.44	7.57	0.24	1.77	2.08	189.44	0.68	0.04	1.31	2.36
	Average	**405.20**	**7.23**	**0.34**	**1.82**	**1.81**	**405.20**	**1.38**	**0.07**	**1.17**	**1.76**
6	Mixed pine/ hardwood forest	189.44	3.07	0.42	1.33	1.94	189.44	3.07	0.42	1.33	1.94
14	Mixed pine/ hardwood forest	299.95	4.52	0.31	1.48	1.39	299.95	4.52	0.31	1.48	1.39
15	Mixed pine/ hardwood forest	189.44	7.23	0.70	3.49	3.05	189.44	5.30	0.70	3.49	3.05
	Average	**226.28**	**4.94**	**0.48**	**2.10**	**2.13**	**226.28**	**4.30**	**0.48**	**2.10**	**2.13**
5	Maple forest	299.95	1.46	0.40	1.02	1.67	299.95	1.46	0.40	1.02	1.67
7	Maple forest	299.95	1.75	0.30	1.21	0.42	299.95	1.75	0.30	1.21	0.42
9	Maple forest	189.44	2.28	0.29	1.19	2.92	189.44	2.28	0.29	1.19	2.92
	Average	**263.11**	**1.83**	**0.33**	**1.14**	**1.67**	**263.11**	**1.83**	**0.33**	**1.14**	**1.67**

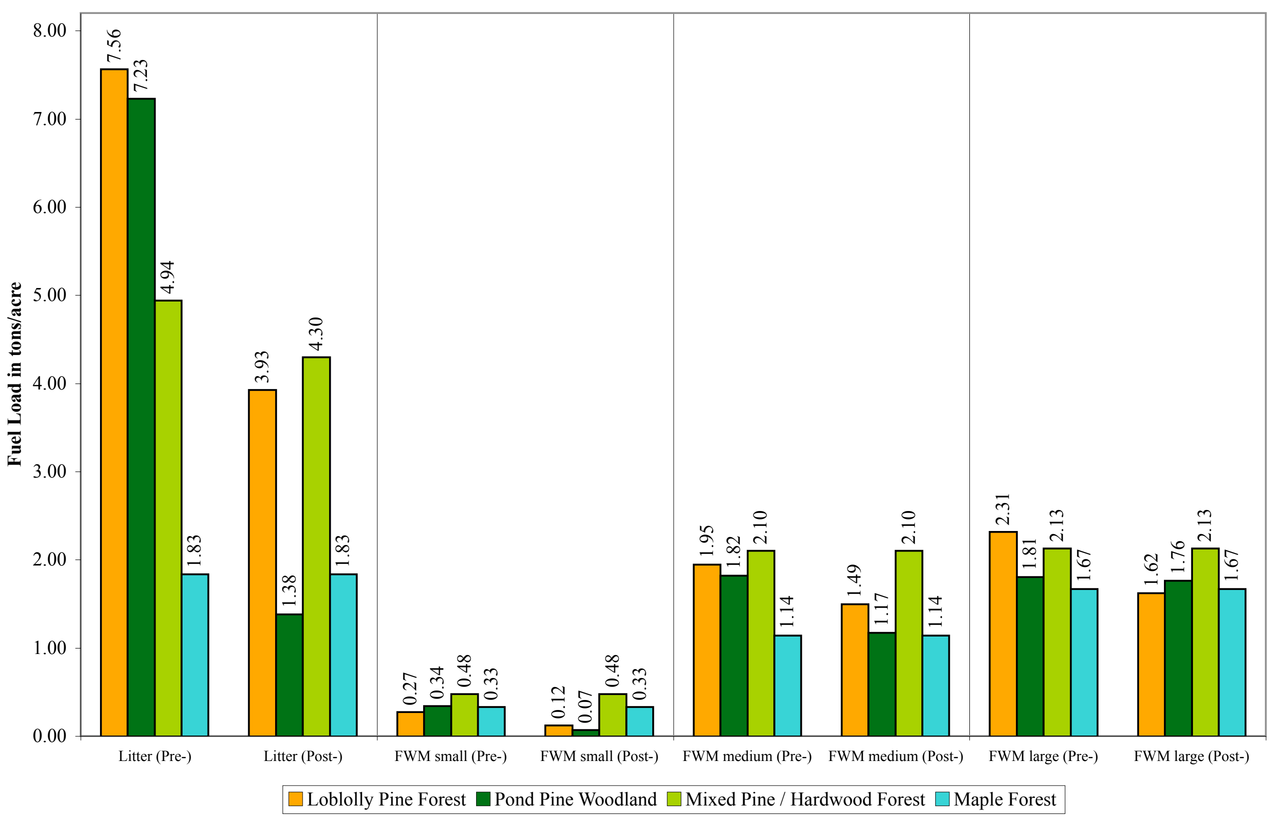


Figure 5—Pre- and postburn fuel loading by component in tons per acre. Colors correspond to the colors used on the vegetation map in figure 4.

Table 2—Consumed biomass by vegetation alliance.

Vegetation alliance	Tons/acre consumed					
	Total consumed	Litter	FWM small	FWM medium	FWM large	FWM total
Loblolly pine forest	4.94 (40.81%)	3.63 (48.07%)	0.15 (56.61%)	0.45 (23.24%)	0.69 (30%)	1.3 (28.69%)
Pond pine woodland	6.81 (60.86%)	5.85 (80.91%)	0.27 (79.53%)	0.65 (35.56%)	0.05 (2.56%)	0.96 (24.27%)
Mixed pine/hardwood forest	0.64 (6.66%)	0.64 (13.01%)	0	0	0	0
Maple forest	0	0	0	0	0	0

and small FWM classes. Fire consumed 6.81 tons/acre (60.9 percent) of the fuel load in the pond pine woodland alliance, including 80 percent of the litter and fine woody material classes. Litter consumption occurred on only one of the three plots in the mixed pine/hardwood forest alliance, removing 0.64 tons/acre. No consumption occurred in the maple forest alliance.

Discussion

The goals of the prescribed fire plan were to reduce accumulations of fine fuels, top-kill midstory shrubs encroaching into pine ecosystems, and top-kill encroaching hardwoods. Within the loblolly pine forest and pond pine woodland alliances, these conditions were met successfully. The litter and small fine woody material levels were reduced by 48 percent and 56 percent, respectively, in the loblolly pine forest. Litter and small FWM consumption was particularly high in the pond pine woodland alliance, where the canopy coverage was generally below 80 percent. The open canopy permitted sunlight to reach the forest floor, which combined with air circulation to desiccate the fine fuel classes and permit more active fire behavior. Within the pond pine woodland alliance, the fire consumed 81 percent of the total litter fuel load and 80 percent of the small FWM fuel load.

Light fuel loading and a variable fuel bed in the mixed pine/hardwood forest alliance limited fire activity. The encroaching hardwood bay (*Gordonia lasianthus / Persea borbonia*) midstory and dense overstory canopy inhibited fuel desiccation, which suppressed fire behavior and restricted the spread of fire. Future burns in this area may need to be conducted with lower relative humidity and 10-hour fuel moistures to successfully reduce fuel loads in this vegetation type.

The maple forest alliance burned poorly, as it contained little litter, areas of flooded soil, and a discontinuous fuel bed. This area would likely only burn under wind-driven wildfire conditions, when medium and large fine woody fuels, coarse woody fuels, and live canopy fuels could ignite. Under typical prescribed fire conditions, the maple forest serves as an effective fire barrier.

The mapping technique distinguished vegetation types that had different fuel loadings. The level of detail in the map was high enough to show the distribution of vegetation communities with differing fuel loads in the landscape. This information was useful for planning and implementing the prescribed burn. A distinction was drawn between high canopy coverage and low canopy coverage areas within the pond pine woodland alliance, due to appearances of different fuel loadings and fire behavior potential. This distinction did not reveal any actual differences in preburn fuel loading, but appeared to be more important for postburn fuel loading. This is likely due to increased drying from greater sunlight and wind reaching the fuels in the low canopy coverage areas. This illustrates the utility of mapping within-alliance distinctions in order to better anticipate fire behavior.

Comparison of our results to standardized fuel models was problematic because the maple forest and mixed/pine hardwood forest alliances could not be cross-walked to analogous Coastal Plain fuelbeds from the FCCS system. For the pond pine woodland alliance, the FCCS fuel loads underpredicted our measured values for total litter by 56 percent (table 3). This is likely due to site-specific variation from past fire suppression. Within the loblolly pine forest alliance, FCCS underpredicted litter by 27 percent and small FWM by 5 percent. Loblolly pine forests on saturated deep organic soils, such as those present on this research site, are somewhat atypical throughout much of the Southeastern United States and may not be accounted for in the FCCS model. Duff measurements were much higher than those reported by FCCS for the research unit due to the deep peat soil types typical of the Dare County peninsula.

Although detailed accuracy assessment was beyond the scope of this study, fuel loads for the pine-dominated ecosystems measured within the research unit were similar to those reported by Rosenfeld (2003) and Wendel and others (1962). The presence of two vegetation alliances that have no analogue in standardized fuel models suggests that detailed site-specific fuel loading measurements may be necessary for land managers with nonstandard vegetation types, or standard vegetation types growing on atypical sites.

Table 3—Comparison to fuelbed characterization classification system (FCCS).

	Measured biomass					FCCS				
Vegetation type	Duff	Litter	FWM small	FWM medium	FWM large	Duff	Litter	FWM small	FWM medium	FWM large
Loblolly pine forest	299.95	7.56	0.27	1.95	2.31	22.10	5.55	0.60	1.70	2.00
Pond pine woodland	405.20	7.23	0.34	1.82	1.81	56.00	3.15	1.00	1.50	1.50
Maple forest	263.11	1.83	0.33	1.14	1.67	N/A	N/A	N/A	N/A	N/A
Mixed pine/ hardwood forest	226.28	4.94	0.48	2.10	2.13	N/A	N/A	N/A	N/A	N/A

Conclusions

Fine-scale mapping of vegetation alliances and their associated fuel loads is a feasible technique for reducing or eliminating the limitations associated with standardized fuel models. Standardized fuel models may provide ballpark numbers that are, in many cases, appropriate for prescribed burn planning. However, site-specific differences that affect both fuel loading and fuel consumption can become apparent after direct measurements are compared to standardized models. These differences may be important to research and land management activities where smoke management and fuel reduction goals depend on using accurate fuel loadings.

Acknowledgments

Funding for this research project was provided by the Joint Fire Science Program (Project 04-2-1-80) and the U.S. Air Force Air Combat Command.

Reviewers Frank Koch (USDA Forest Service Southern Research Station), Dwight Otwell (IAVO Research and Scientific), and Candace Krull (USDA Forest Service Pacific Northwest Research Station) provided comments that substantially improved a draft of this paper.

References

Albini, F.A. 1976. Estimating wildfire behavior and effects. Gen. Tech. Rep. INT-30. Ogden, Utah: Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 92 p.

Anderson, H.E. 1982. Aids to determining fuel models for estimating fire behavior. Gen. Tech. Rep. INT-122. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 22 p.

Andrews, P.L.; Bevins, C.D.; Seli, R.C. 2005. BehavePlus fire modeling system, version 3.0: User's Guide. Gen. Tech. Rep. RMRS-GTR-106. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 144 p.

Avery T.E.; Berlin, G.L. 1992. Fundamentals of Remote Sensing and Airphoto Interpretation, fifth edition. New York: Macmillan Publishing Company.

Bailey, A.D.; Mickler, R.A. 2005. Vegetation Classification and Fuel Load Mapping Using Softcopy Photogrammetry. In: Proceedings of the 2005 American Society of Photogrammetry and Remote Sensing Annual Conference. Baltimore, MD: ASPRS.

Brown, J.K. 1974. Handbook for Inventorying Downed Woody Material. Gen. Tech. Rep. INT-16. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station.

Carey, H.; Schumann, M. 2003. Modifying Wildfire Behavior - The Effectiveness of Fuel Treatments. Santa Fe, NM: National Community Forestry Center.

Finney, M.A. 1998. FARSITE: Fire Area Simulator-model development and evaluation. Res. Pap. RMRS-RP-4. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 47 p.

Government Accountability Office. 2005. Wildland Fire Management: Important Progress Has Been Made, but Challenges Remain to Completing a Cohesive Strategy. GAO-05-147. Washington, DC: United States Government Accountability Office.

Graham, R.T.; McCaffrey, S.; Jain, T.B. (tech. eds.) 2004. Science basis for changing forest structure to modify wildfire behavior and severity. Gen. Tech. Rep. RMRS-GTR-120. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 43 p.

Grossman, D.H.; Faber-Langendoen, D.; Weakley, A.S.; Anderson, M.; Bourgeron, P.; Crawford, R.; Goodin, K.; Landaal, S.; Metzler, K.; Patterson, K.D.; Pyne, M.; Reid, M.; Sneddon, L. 1998. International classification of ecological communities: terrestrial vegetation of the United States, Volume I: The National Vegetation Classification System: development, status, and applications. Arlington, VA: The Nature Conservancy. 139 p.

Keane, R.E.; Burgan, R.; van Wagtendonk, J. 2001. Mapping wildland fuels for fire management across multiple scales: Integrating remote sensing, GIS, and biophysical modeling. International Journal of Wildland Fire 10:301-319.

Lavdas, L.G. 1996. Program VSMOKE—Users Manual. Gen. Tech. Rep. GTR-SRS-006. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 156 p.

McKenzie, D.; O'Neill, S.M.; Larkin, N.K.; Norheim, R.A. 2006. Integrating models to predict regional haze from wildland fire. Ecological Modelling 199(2006): 278-288.

Mickler, R.A.; Bailey, A.D. 2005. Quantifying Wildland Fire Fuel Loading and Fire Risk in Coastal Plain Forests. In: Proceedings of the 2005 American Society of Photogrammetry and Remote Sensing Annual Conference. Baltimore, MD: ASPRS.

O'Neill, S.M.; Ferguson, S.A.; Peterson, J.; Wilson, R. 2003. The BlueSky Smoke Modeling Framework (www.blueskyrains.org). In: 5th Symposium of Fire and Forest Meteorology. Orlando, FL: American Meteorological Society.

Ottmar, R.D.; Vihnanek, R.E. 2000. Stereo photo series for quantifying natural fuels, Volume VI: longleaf pine, pocosin, and marshgrass types in the southeast United States. PMS 835. Boise, ID: National Wildfire Coordinating Group, National Interagency Fire Center. 56 p.

Rosenfeld, B.J. 2003. Developing a New Fuel Load Mapping Strategy Using: Digital Photogrammetry; International Classification of Ecological Communities; USDA Forest Service, Forest Inventory and Analysis Protocols; and Disturbance History. Master's Thesis. Raleigh, NC: North Carolina State University.

Rothermel, R.C. 1972. A mathematical model for predicting fire spread in wildland fuels. Res. Pap. INT-115. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 40 p.

Sandberg, D.V.; Ottmar, R.D.; Cushon, G.H. 2001. Characterizing fuels in the 21st Century. International Journal of Wildland Fire 10:381-387.

Scott, J.H.; Burgan, R.E. 2005. Standard Fire Behavior Fuel Models: A Comprehensive Set for Use with Rothermel's Surface Fire Spread Model. Gen. Tech. Rep. RMRS-GTR-153. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Simpson, R.B.; Crews, T.G.; Montgomery, R.; Stratton, R.; Smith, S. 2004. Prescribed Fire Plan: North Navy Shell Compartment. Manteo, NC: U.S. Department of the Interior, Fish and Wildlife Service, Alligator River National Wildlife Refuge.

Wendel, G.W.; Storey, T.G.; Byrum, G.M. 1962. Forest fuels on organic and associated soils in the coastal plain of North Carolina. SFES Paper 144. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station. 46 p.

This page is blank on purpose

Presettlement Fire Regime and Vegetation Mapping in Southeastern Coastal Plain Forest Ecosystems

Andrew D. Bailey[1], Robert Mickler[1], and Cecil Frost[2]

Abstract—*Fire-adapted forest ecosystems make up 95 percent of the historic Coastal Plain vegetation types in the Southeastern United States. Fire suppression over the last century has altered the species composition of these ecosystems, increased fuel loads, and increased wildfire risk. Prescribed fire is one management tool used to reduce fuel loading and restore fire-adapted species, but little information exists on the presettlement extent and location of fire-dependent ecosystems at a level of detail useful to guide land management decisions at the local spatial scale. In an effort to close this knowledge gap, the principles of landscape fire ecology have been applied to develop a detailed presettlement fire regime map for ~200,000 acres of Coastal Plain ecosystems. Factors evaluated include the effects of fire compartment size in the original landscape, fire barriers, fire filters, prevailing wind direction during fire season, topographic and soil factors affecting fire intensity, fire frequency, fire spread, and fire effects on vegetation. The fire regime map was then combined with remnant fire-adapted vegetation surveys, historic aerial photography, digital elevation models, and soil survey information to create a map of presettlement vegetation. This map is being used to develop prescribed burning plans that restore original fire regimes, guide the use of prescribed fire as a management tool, restore fire-adapted vegetation structure and understory species diversity for threatened and endangered species, and enhance ecosystem sustainability.*

Introduction

Ninety-five percent of the forest, shrubland, and grassland ecosystems of the Southeastern United States Coastal Plain have been shaped by the occurrence of fire (Frost 1995). Many of the plant species that inhabit these ecosystems are adapted to either withstand fire by growing rapidly to take advantage of reduced competition following fire events, or regenerate rapidly after fire. Longleaf pine (*Pinus palustris*) / wiregrass (*Aristida stricta*) is the most frequently cited example of a fire-adapted Coastal Plain forest ecosystem. Of the estimated 60 to 90 million acres of presettlement forests dominated by longleaf pine in the Southeast, less than 4 million acres of poor-quality second growth longleaf pine forest remain in the region (Harper and others 1997). Many of these continue to decline due to lack of prescribed fire, or prescribed fire applied at an inappropriate frequency.

In contrast to the mineral soils that support longleaf pine ecosystems, the Lower Coastal Plain of the Southeast has extensive areas of deep organic soil types that support marshes, canebrakes, pond pine (*Pinus serotina*) pocosins (evergreen shrub bogs with pond pine), Atlantic white cedar forests (*Chamaecyparis thyoides*), and nonriverine swamps (Fussell and others 1995). Fire is important in these ecosystems, and the range of fire intensities and

In: Butler, Bret W.; Cook, Wayne, comps. 2007. The fire environment—innovations, management, and policy; conference proceedings. 26-30 March 2007; Destin, FL. Proceedings RMRS-P-46CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 662 p. CD-ROM.

[1] Associate Biologist and Program Manager, respectively, with Alion Science and Technology, Durham, NC. Lead author adbailey@AlionScience.com

[2] Adjunct Faculty, Ecology, University of North Carolina – Chapel Hill, Chapel Hill, NC.

frequencies is often much wider than those found in upland longleaf pine savannas. The effects of fire suppression in these lowland fire-adapted ecosystems are similar to those in other areas of the Southeast: conversion to less fire-adapted ecosystems; a loss of threatened, endangered, and other rare endemic species; and increased fire risk due to increasing fuel loads (Robertson and others 1998).

Many of these ecosystems occur on Federal lands, where land managers are expected to simultaneously provide wildlife habitat preservation and enhancement, endangered species protection, and wildland fire protection. In addition, Federal lands in the Departments of the Interior (USDI) and Agriculture (USDA) are required to manage lands for multiple uses that include recreation, grazing, forestry, and historic and cultural values. Department of Defense properties must be managed for the military mission. Forced to manage within these constraints, land managers can gain insight for the development and implementation of management strategies by examining the fire history of their land.

Several strategies have been applied successfully in parts of the United States to reconstruct fire history, including fire scar analysis and charcoal sediment analysis (NOAA 2007). Fire scar analysis is of limited usefulness in Southeastern Coastal Plain ecosystems on deep organic soils, because natural fire regimes in these locations began to deviate early after settlement (~1600 AD), predating any surviving tree. Typically, these ecosystems have experienced either catastrophic stand-replacing fires or clear-cut harvesting, destroying the old trees needed for fire history reconstruction. Charcoal sediment analysis is not accurate enough to determine fire regimes in frequent fire regions, and fire regimes detected by this method cannot be mapped spatially at a scale small enough for local management.

A third technique for determining fire history is to apply the principles of landscape fire ecology at a local scale. Using available local data sets, weather patterns, and current knowledge of fire behavior, the local landscape may be broken up into a series of fire compartments. A fire compartment is a unit of the landscape with no natural firebreaks, such that an ignition in one part would be likely to burn the whole unit unless there was a change in the weather or fuel conditions. Within each fire compartment on the landscape, an associated mean fire interval and range of variation may be determined (Frost 1995). Factors such as fire barriers, prevailing wind direction, topography, hydrology, and vegetation determine this interval and range within a specific compartment. Using field surveys for remnant vegetation, historical land survey documents, and photography, maps can be developed at a fine level of detail depicting the most likely distribution of fire regimes and fire-adapted vegetation communities in the presettlement landscape (Frost 2000). These maps may be used to guide land management decisions, determine areas for threatened and endangered species recovery, establish ecological endpoints, or guide ecological restoration efforts. Here, we apply the principles of landscape fire ecology to map the presettlement fire regimes and vegetation of Dare County, North Carolina.

Methods

Site Description

The mainland of Dare County, North Carolina, provides an outstanding example of several fire-adapted ecosystems in proximity to one another. Nearly 200,000 acres in Dare County are managed by the U.S. Fish and

Wildlife Service and the U.S. Air Force. The Dare mainland is a peninsula, 14 miles across, bordered on the north by the Albemarle Sound, on the east and south by the brackish Pamlico and Croatan Sounds, and on the west by the freshwater Alligator River. The long axis of the peninsula extends 29 miles from north to south. The Outer Banks barrier island chain provides protection from the Atlantic Ocean some 20 miles to the east. Though there are two small tidal creeks on the peninsula, there is virtually no relief, and elevations range from slightly below sea level to 4 ft above sea level. Areas below sea level are typically located in and around agricultural fields. The absence of topography means that the vegetation on the Dare mainland is shaped primarily by two major natural factors: fire and salinity.

Soils

A digital soil data layer for Dare County was obtained from the USDA Natural Resource Conservation Service (NRCS). These data layers are digital representations of USDA county soil surveys that contain a soil classification established through field work and aerial photography. Each polygon in the data layer is associated with detailed information describing physical characteristics of the soil, the type of terrain it is commonly found in, as well as potential vegetation types. The soil layer becomes the base map for classifying presettlement vegetation.

Remnant Vegetation

Vegetation survey information for fire adapted plant species and communities were grouped by soil series in the Southeastern United States, including Dare County (Frost 2000). This survey information was used for preliminary mapping of vegetation. Special attention was afforded to vegetation species that are considered to be highly fire adapted, or plant species that are remnants of fire-adapted vegetation communities displaced by fire suppression, such as pitcher plants (*Sarracenia* ssp.), wiregrass (*Aristida stricta*), and canebrake (*Arundinaria gigantea*). In some cases, downed logs and plant remains that have been buried in organic soil are preserved and can be identified. These provide clues to determine what vegetation may have previously occupied a converted site. On rare occasions, old individual trees may have fire scars that can be used to age past fires.

A second source used to delineate presettlement vegetation is a series of aerial photography taken in 1932 depicting the entire Dare County mainland. Because effective fire suppression was not possible in Dare until after the establishment of internal roads in the 1960s, these images are representative of the fire-shaped landscape. The photo series was digitized using a high-quality desktop scanner and orthorectified using a second-degree polynomial rectification procedure. Images were then stitched together to form a seamless mosaic of the peninsula. From this mosaic, vegetation types and fire patterns were identified and used to further refine the base map. Finally, all vegetation data were recorded by soil type and then plotted on a map for a rough first draft of presettlement vegetation. Using information from the soil map, vegetation plots, and historical photography, a first draft of presettlement vegetation was digitized into a GIS database.

Historical Maps

A third source of information was historical timber surveys and older maps collected from former forest industry owners and the U.S. National Archives. These maps have descriptions of the forest landscape and show the locations of remnant timber stands and place names that include natural history clues.

Topography

Digital Elevation Models (DEMs) for eastern North Carolina were developed beginning in 2000 using Light Detection and Ranging (LiDAR) technology, a highly accurate method of measuring elevations on Earth's surface. These models were used to develop a topographic map showing 1 ft isopleths of elevation change across the peninsula (fig. 1). Because elevation corresponds closely with moisture regime and vegetation type, these data were used to further refine the presettlement vegetation map.

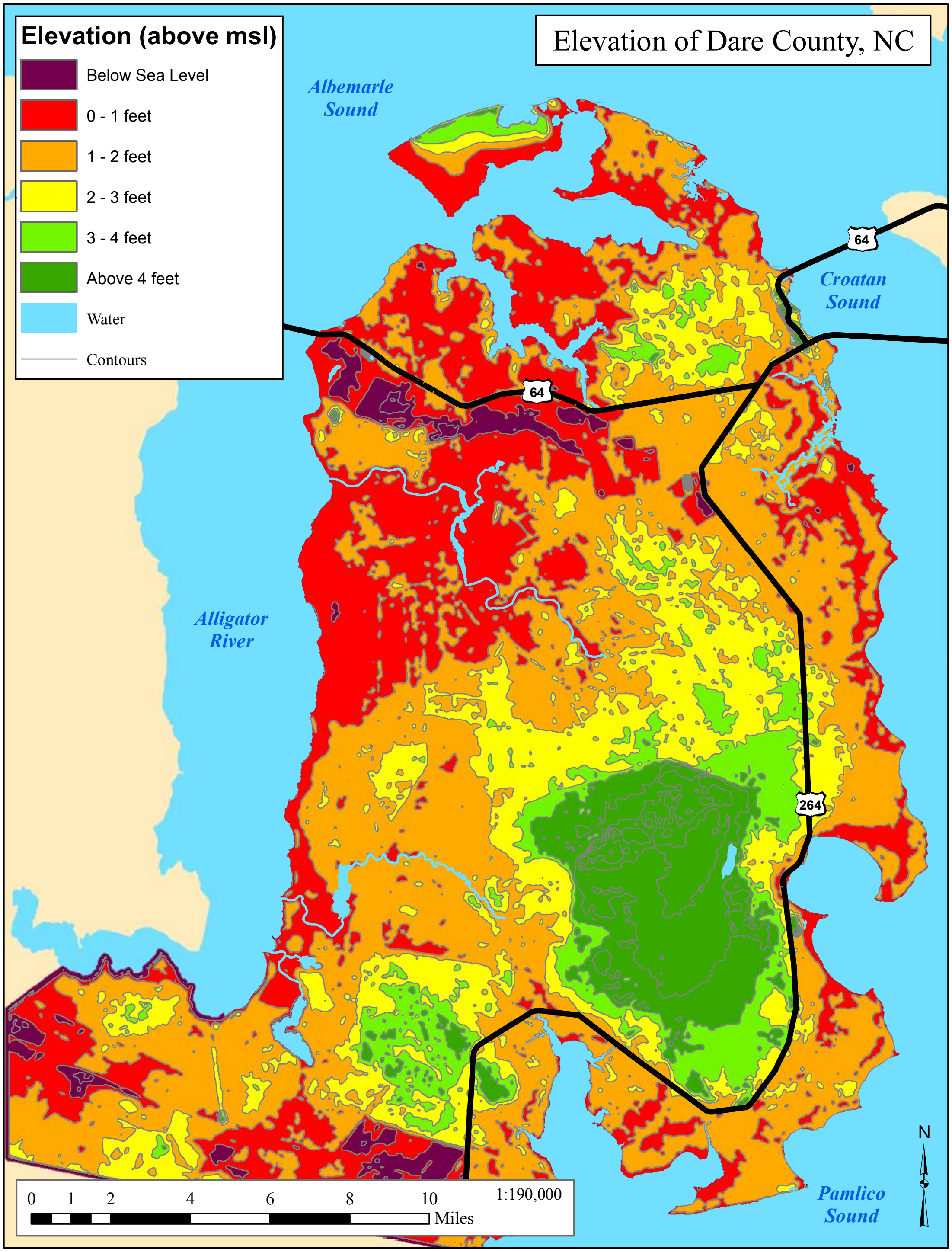


Figure 1—Color-coded topographic map for Dare County. Nearly the entire county is below 5 ft above sea level. The low pocosin dome (dark green), an area where peat has built up over time to rise slightly above the surrounding land, is clearly visible in the southeast.

Fire Regime Map Creation

All fire indicator species and communities were plotted over the soil map to generate a first draft of presettlement fire regimes. In areas where data were scarce, it was useful to construct general fire frequency gradients over a larger area that included the study area. Because vegetation and fire interact in a complex mechanism of feedback, frequent fire plant communities and infrequent fire plant communities are rarely found to abut one another directly; usually a gradient exists between extremely different communities. Landscape features that affect the spread of fire were determined and considered with respect to the prevailing winds during fire season. Hydrology data were used to identify barriers to fire spread, including nonflammable vegetation types and bodies of water. This knowledge is used to delineate isopleths between areas of similar fire frequency, where the lines form the boundaries between compartments with equal fire frequencies. The effect is similar to that of a contour map; the contours represent different fire-return intervals rather than elevation.

Feedback into Vegetation Map

The vegetation and fire frequency maps were compared, and areas were identified that needed further investigation. These included areas where fire-infrequent species were identified in fire-frequent compartments, or areas where gradients between infrequent fire and frequent fire appeared very steep. Collaborative discussions between the authors were used to resolve discrepancies when they were found, and both maps were adjusted using GIS editing tools.

Historical Document Validation

Final examination of the maps was done using historical documents from multiple sources. For Dare County, these sources included land grant documents from the 18th century and early survey plats (fig. 2) with witness trees and descriptions of vegetation. Personal accounts and newspaper articles were collected describing logging work from the late 19th century. In several cases these sources were used to adjust vegetation and fire frequency polygons.

Results

Presettlement fire regimes are displayed in figure 3. The largest fire frequency class had a mean fire interval of 4 years, and comprised 63,468 acres (32.5 percent) of the Dare County mainland where frequent-fire marsh vegetation along the eastern shoreline promoted the spread of fire into the peninsula interior under hot, dry conditions. The second-largest fire frequency class had a mean fire return interval of 25 years, and covered 35,116 acres (18 percent) of deep, wet peat soils toward the western interior portion of the peninsula. Transition areas are represented by the 6-year and 9-year fire return interval classes. These areas were narrow when wet soils forced a steep fire gradient and were wider where broad lenses of mineral soil promoted drier conditions. The smallest fire frequency class had a mean fire return interval of 2 years, and occurred on 1,192 acres (0.6 percent) of upland in the northeast of the county, where drier upland fuels and continuity with large areas of frequent-fire marsh, canebrake, and pocosin upwind to the south and southwest combined to raise fire frequency. All presettlement fire frequencies are listed in table 1.

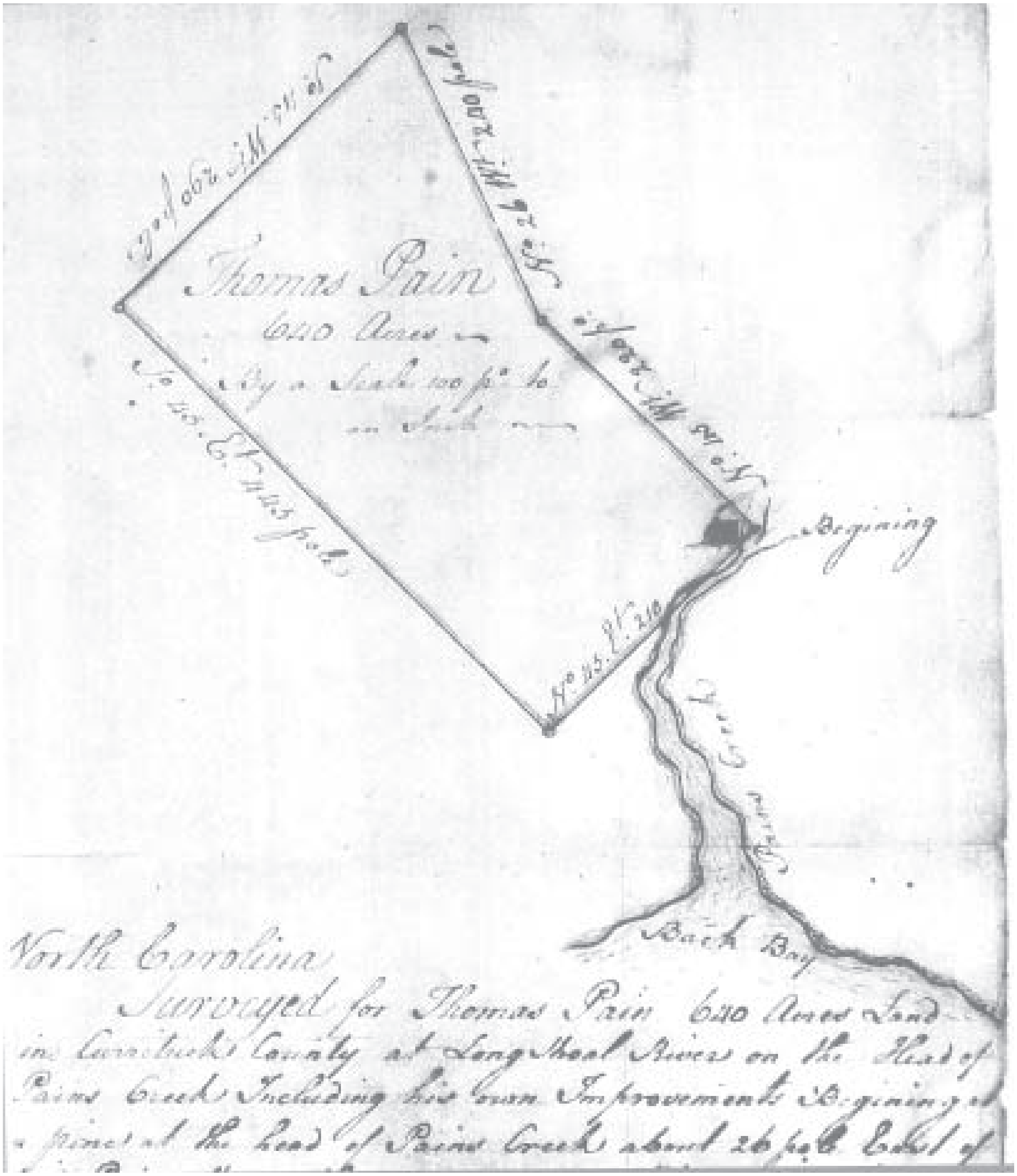


Figure 2—1765 land grant survey for Thomas Pain, the first settler on Pains Bay, southeastern Dare County, just north of Long Shoal River. The portion of interest for agriculture was a pine ridge near the center of the tract. Beyond the pine ridge to the northeast, the land was described as "the Desart," referring to treeless canebrake and pyrophytic (fire-maintained) low pocosin with sparse pond pine. Sea level rise over the intervening 240 years have converted the original house site to a brackish marsh today.

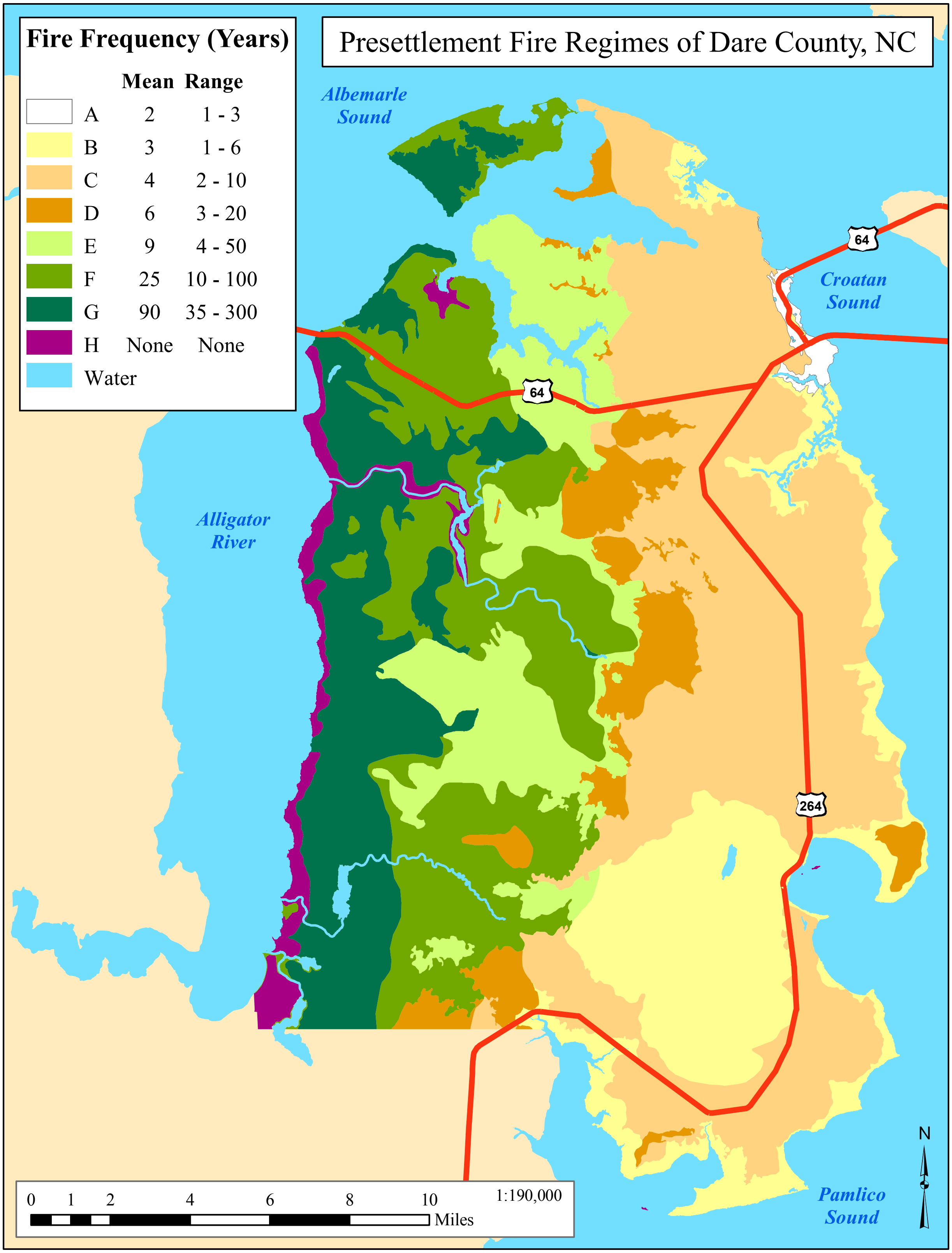


Figure 3—Fire regime maps, using cool colors to represent long fire intervals and warm colors for more frequent fire intervals (roads superimposed for reference).

Presettlement vegetation is displayed in figure 4. The largest two classes were the fire-frequent canebrake (33,823 acres) and pond pine pocosin (38,445 acres) vegetation types, which occur on the eastern portion of the peninsula. These are fire-dependant vegetation communities with similar, sparse pond pine overstories. Pocosin vegetation refers to an understory dominated by the shrubs little gallberry (*Ilex glabra*), big gallberry (*Ilex coriacea*), fetterbush (*Lyonia lucida*), and pepperbush (*Clethra alnifolia*). Canebrake refers to an understory dominated by the herbaceous giant cane (*Arundinarea gigantea*). Typical pond pine/canebrake is found in parts of the peatland landscape where fire frequency runs from 2 to 6 years. With fire intervals between 7 and 12 years, some pocosin shrubs become established, and the community consists of alternating canebrake and pocosin, with cane dominant for a few years after a fire and pocosin shrubs becoming increasingly prominent toward the end of the interval. With longer fire intervals, pond pine/canebrake is replaced by pond pine/pocosin. Fire-infrequent vegetation classes Atlantic white cedar (26,681 acres) and peatland long fire interval pyromosaic (31,349 acres) dominate on the western side of the peninsula under fire interval classes F (10 to 100 years) and G (35 to 300 years). Position in the fire landscape along with less flammable litter-layer fuels contribute to a reduction in fire frequency in these areas. Fires carried easily by the frequent fire fuel types

Table 1—Presettlement fire frequencies of Dare County.

Fire frequency class	Mean fire interval (years)	Estimated historic range of variation (90% of fires) (in years)	Acres	Percent of total
A	2	1 - 3	1,192	1
B	3	1 – 6	28,727	15
C	4	2 – 10	63,468	32
D	6	3 – 20	12,484	6
E	9	4 – 50 depending upon vegetation type and location in the landscape	21,993	11
F	25	10 – 100 depending upon vegetation type and location in the landscape	35,116	18
G	90	35 – 300+ depending on landscape position along the fire frequency gradient	26,357	14
H	None	Nonflammable, tidal cypress-tupelo swamp	4,712	2
W	Water		1,239	1

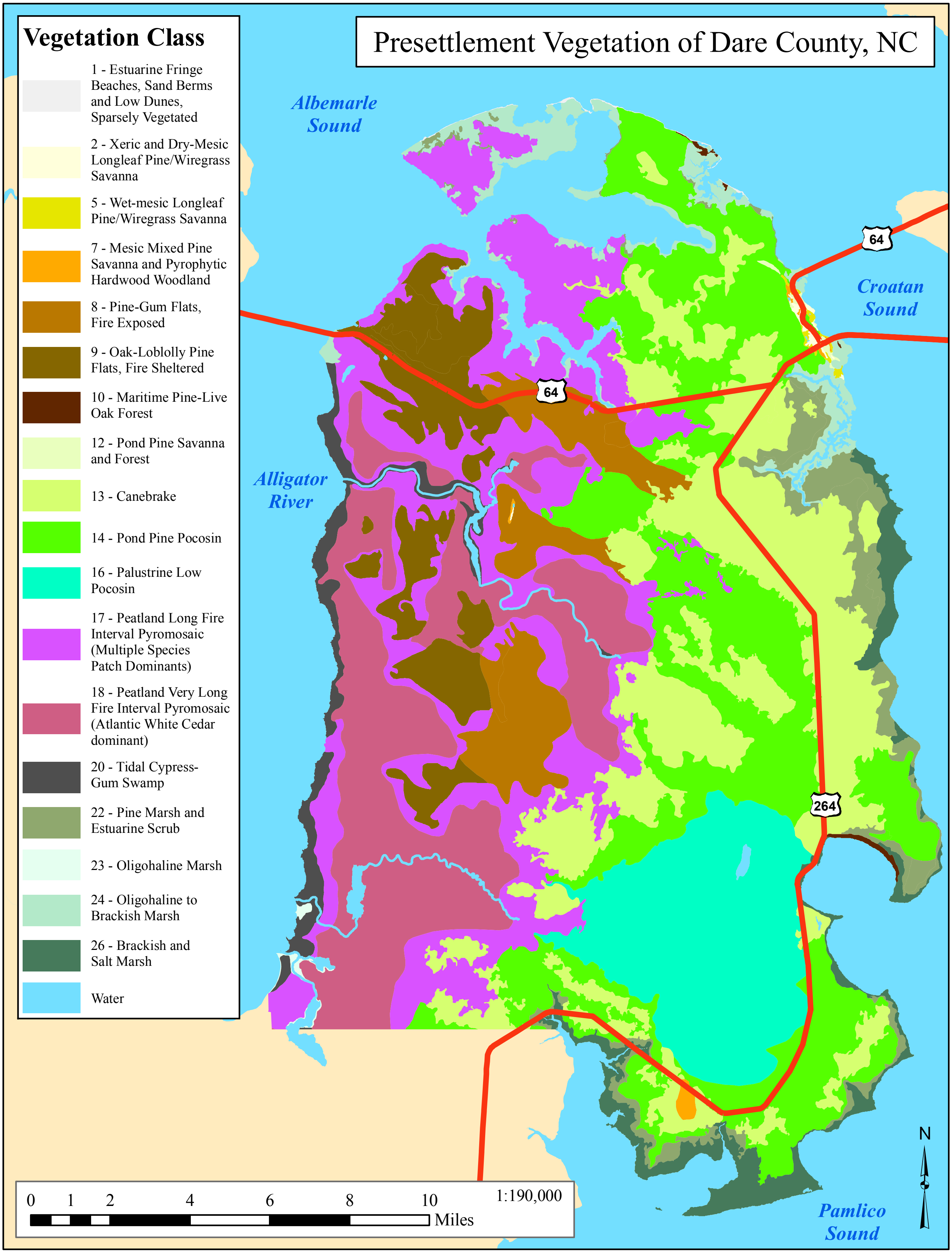


Figure 4—Presettlement vegetation map. Frequent fire vegetation types form bands along the eastern side of the peninsula, with vegetation becoming less frequently burned from east to west (roads superimposed for reference).

on the eastern side of the peninsula have little access to the western forests. Fires can approach only from the east and southeast, while any fires carried on the prevailing southwest winds are blocked by small lakes, streams, and the nonflammable band of cypress-gum along the Alligator River. Moderate fire return interval vegetation types such as oak-pine flats (11,977 acres) and pine-gum flats (9,756 acres) occur at the transition zones between frequent and infrequent fire regimes. These vegetation communities are largely missing in the current landscape due to site conversion for plantation forestry and agriculture. All presettlement vegetation types are listed in table 2.

Discussion

The pronounced east-west fire frequency gradient on the Dare County peninsula is driven by salinity. The brackish water along the eastern margin sustains flammable saltmeadow cordgrass (*Spartina patens*) / saltgrass (*Distichlis spicata*) and black needle rush (*Juncus roemarianus*) marshes, which form a continuous wide shoreline band stretching some 50 miles (80 km) from the Albemarle sound, down the length of mainland Dare, to the Pamlico sound at the bottom of the peninsula. This fire corridor graded into flammable canebrake immediately to the west. The boundary between brackish marsh and salt-intolerant canebrake likely occurs at the western limit

Table 2—Presettlement vegetation of Dare County.

Vegetation type	Acres	Percent
Estuarine fringe beaches, sand berms and low dunes, sparsely vegetated	130	0.1
Xeric and dry-mesic longleaf pine/wiregrass savanna	197	0.1
Wet-mesic longleaf pine/wiregrass savanna	161	0.1
Mesic mixed pine savanna and pyrophytic hardwood woodland	347	0.2
Pine-gum flats, fire exposed	9,756	5.0
Oak-loblolly pine flats, fire sheltered	11,977	6.1
Maritime pine-live oak forest	223	0.1
Pond pine savanna and forest	160	0.1
Canebrake	33,823	17.3
Pond pine pocosin	38,445	19.7
Palustrine low pocosin	18,560	9.5
Peatland long fire interval pyromosaic	31,349	16.1
Atlantic white cedar	26,681	13.7
Tidal cypress-gum swamp	3,726	1.9
Pine marsh and estuarine scrub	6,812	3.5
Oligohaline marsh	288	0.1
Oligohaline to brackish marsh	5,387	2.8
Brackish and salt marsh	6,023	3.1
Water	1,247	0.6
Total	**195,291**	

of storm overwash. In contrast, on the west side, nonpyrophytic cypress-gum swamp fringes the fresh waters of the Alligator River in a narrow band. The short fire interval marsh and cane communities of the eastern side and the nonflamable river swamp on the west comprise the extremes of a cross-peninsula fire frequency gradient. Between these extremes, a kilometer wide swath of canebrake graded into pocosin vegetation where fire frequency was low enough to allow the development of a dense shrub understory. To the west of the pocosin vegetation, a large-scale patch mosaic of wooded wetland ecotypes occurred at decreasing fire intervals. This mosaic was made up of pocosin, pond pine forest, black gum (*Nyssa biflora*) forest, pond cypress (*Taxodium ascendens*), loblolly bay (*Gordonia lasianthus*) forest, and Atlantic white cedar. Fire-exposed pine-gum and fire-sheltered oak-pine forests occurred on mineral soil lenses in the peninsula's interior. The patch mosaic was bounded on the west by a relatively narrow band of cypress-gum swamp, only 100 to 300 m wide, along the Alligator River.

A certain amount of uncertainty is inherent in the construction of presettlement maps. The polygons delineated represent our best estimate of the locations of specific fire-adapted communities and fire regimes. In many cases these estimates are confirmed by 1934 aerial photography, land grant documents, and historic maps, but it is important to realize these sources have limited spatial accuracy. This form of mapping does not lend itself to quantitative accuracy assessment, and the resulting maps should not be regarded as truth. Instead, they represent a snapshot of the many likely fire and vegetation patterns that have existed since these communities became dominant nearly 5,000 years ago.

No ecosystem is static, and many things have changed over the 400 years since European settlement, including extensive logging of Atlantic white cedar and loblolly pine, conversion of hardwood forests on mineral soils to agricultural fields, widespread alteration of hydrology, changing climate, and rising sea level. The changes dictate that these presettlement vegetation and fire regime maps should not be used to demonstrate what the current landscape should look like, but rather used as background information for managing existing vegetation. For example, special attention may be appropriate for the oak-pine and pine-gum forest types. These forest types occupied a moderate-frequency fire niche in the landscape that is currently not replicated by fire or management activity in Dare County. Frequent-fire vegetation communities such as low pocosin and canebrake are much smaller than they would have been in the presettlement landscape. At the present, 43 percent of presettlement extent of low pocosin and no pure canebrake communities remain. On the western portion of the peninsula, fire-intolerant vegetation types are now encroaching into what were once areas of low- and mid-frequency fire. This encroachment reduces habitat for threatened and endangered species, particularly the red-cockaded woodpecker, which inhabits open, frequently burned pond pine woodland ecosystems. Active management to increase the acreage of pond pine woodland burned would benefit these species.

These techniques may be useful throughout the Southeastern United States, where other techniques for establishing presettlement fire regimes and vegetation composition have proven less useful. The GIS datasets used in this analysis are freely available through online Federal data distribution Web sites, and historic documents may typically be obtained from State and Federal archives. Other sources of information, including historic aerial photography and maps, may be obtained from local land management offices, former landowners, and local history societies.

Conclusions

The principles of landscape fire ecology were applied to construct a map of presettlement fire regimes and presettlement vegetation in Dare County, North Carolina. In an area of the country where traditional fire history reconstruction techniques such as fire scar chronologies are not available, these techniques provide a method to create a useful product for the land manager. These presettlement maps should serve as a useful guide for prescribed fire management, restoration ecology, and ecosystem management planning for the current and future ecosystems of Dare County.

Acknowledgments

Funding for this research project was provided by the Department of Defense Legacy Resource Management Program (Project 05-252).

Reviewers Dwight Otwell (IAVO Research and Scientific), David Bailey (NCDOT Project Development and Environmental Analysis Branch), and Jennifer Costanza (UNC Landscape Ecology and Biogeography Group) provided comments which substantially improved a draft of this paper

References

Climate Assessment for the Southwest. 2007. Fire History Analysis Using Tree Rings. [Online] 1p. Available: http://www.ispe.arizona.edu/climas/learn/fire/history.html [March 1, 2007].

Frost, C.C. 1995. Presettlement Fire Regimes in Southeastern Marshes, Peatlands, and Swamps. In: S.I. Cerulean and R.T. Engstrom, ed. Fire in wetlands: a management perspective. Proceedings of the Tall Timbers Fire Ecology Conference, No 19. Tallahasee, FL: Tall Timbers Research Station; 39-60

Frost, C.C. 2000. Studies in landscape fire ecology and presettlement vegetation of the Southeastern United States. Doctural Thesis. Chapel Hill, NC: University of North Carolina.

Fussell, J.O.; Webster, W.D.; Hall, S.P.; LeGrand Jr., H.E.; Schafale, M.P. 1995. Ecosystem Survey of Dare County Air Force Range, North Carolina. NC Natural Heritage Program.

Harper, M.; Trame,A.; Fischer, R.A.; Martin, C.O. 1997. Management of Longleaf Pine Woodlands for Threatened and Endangered Species. USACERL Technical Report 98/21.

NOAA. 2007. A Brief Introduction to Fire History Reconstruction. [Online]. 1p. Available: http://www.ncdc.noaa.gov/paleo/impd/impd_data_intro.html [March 1, 2007].

Robertson, K.; Harper, M.G.; Woolery, M. 1998. Management of Peatland Shrub- and Forest-dominated Communities for Threatened and Endangered Species. USACERL Technical Report 99/08. Washington, DC: U.S. Army Corps of Engineers.

Fuels Management on the National Forests in Mississippi after Hurricane Katrina

Danny Bryant[1] and Jay Boykin[2]

Abstract—*On August 29, 2005, Hurricane Katrina made landfall in southern Mississippi. As the storm passed through Mississippi, it maintained hurricane force winds through the northern part of the State affecting all of the Forests. The eye of the storm passed within a few miles of the De Soto Ranger District, the Forest's southern-most district. Much of the District received moderate to heavy damage to timber and facilities. The De Soto Ranger District had historically prescribed burned 60,000 acres per year. In the 5 years prior to hurricane Katrina, the District had increased its prescribed fire program to an average of 94,000 acres per year. While Hurricane Katrina created a serious large fuel loading, the fact that most of the District has been regularly prescribed burned, prevented the problem from being exacerbated by having the new fuels being piled atop the new growth of volatile brush, which is common in the lower coastal plains. The National Forests in Mississippi developed an aggressive three-pronged strategy to deal with the sudden increase in fuel loading and the subsequent potential for catastrophic wildfire: (1) remove the large, downed material as quickly as possible, through conventional salvage operations; (2) establish fuel breaks in critical Wildland Urban Interface (WUI) areas; and (3) reestablish landscape scale prescribed fire treatments immediately.*

Introduction

The National Forests in Mississippi (MNF) consist of 1.2 million acres of public lands located in six Forests across Mississippi. These Forests are diverse ranging from coastal plain pine to upland hardwood stands. Within these lands there are over 2,000 acres of lakes and ponds and 600 miles of streams that are open to the public for fishing.

We have 14 wildlife management areas that are operated by Mississippi Department of Wildlife, Fisheries and Parks. In these areas, emphasis is placed on intensive management of games species such as white-tailed deer, wild turkey, and bobwhite quail.

On some of the forested lands, as we manage for healthy tree stands, we are also able to provide a sustainable harvest to meet the demands of you, our constituents, for lumber, paper, and other wood products. Forested areas are also managed to provide unique habitats for wildlife and opportunities for people to experience primitive natural surroundings.

The Supervisor's office, which is located in Jackson, MS, supports the activities on all the Districts.

The MNF has a very aggressive prescribed burning program. For the last 5 years, with the exception of 2006, MNF Districts have accomplished over 235,000 acres per year. As far back as our burn data goes (1963) Mississippi has consistently averaged over 100,000 acres per year. With the approximate number of "burnable" acres around 1,000,000 we are on a consistent 3 to 5 year rotation.

In: Butler, Bret W.; Cook, Wayne, comps. 2007. The fire environment—innovations, management, and policy; conference proceedings. 26-30 March 2007; Destin, FL. Proceedings RMRS-P-46CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 662 p. CD-ROM.

[1] Assistant Fire Management Officer, U.S. Department of Agriculture, Forest Service, National Forests in Mississippi, Jackson, MS. dannybryant@fs.fed.us

[2] District Fire Management Officer, U.S. Department of Agriculture, Forest Service, National Forests in Mississippi, De Soto Ranger District.

The MNF has a fulltime fire organization in the Supervisor's office as well as on all the Districts including fire managers, air and fire specialists, fuel technicians, engine crews, tractor plow crews, and firefighters. During the prescribed burning season, generally from January through May, we use personnel from other resource areas within the Districts and pull in detailers from all over the country. We usually have two to four helicopters on the Forest also.

Leading the way in this accomplishment is the De Soto Ranger District, MNF's southern-most ownership. The De Soto contains 378,538 acres including Camp Shelby military base, several communities and municipalities, and many wildland-urban interface issues. In spite of these challenges, the De Soto averages 94,000 acres of prescribed burning each year, which is by far, the largest program on the MNF. Just to the northeast of the De Soto lies the Chickasawhay Ranger District. The "Chick" consists of 122,153 acres and burns an average of 35,000 annually. On August 29, 2005, these two areas took the brunt of Hurricane Katrina's force.

Hurricane Katrina Impacts to the De Soto Ranger District

On August 29, 2005, the De Soto Ranger District was in the unfortunate position of being in the northeastern quadrant of Hurricane Katrina. Although the southern portion of the District lies within 8 miles of the Gulf, the western side of the District suffered the most damage. The eye of the storm passed within 5 miles of the western boundary of the Forest. Winds on the District were estimated between 100 and 140 mph and were sustained for several hours. Damage to homes, facilities, and timber ranged from moderate to near catastrophic.

Impacts to Employees

The De Soto Ranger District is a large complex District with more than 55 employees. Most employees rode out the storm at home. Fortunately there were no injuries. Those that evacuated had trouble returning due to roads being blocked. Every District employee had damage to homes, vehicles, or property. Three employees lost their homes. One employee lost every possession. Even 18 months after the storm, employees were still doing repair work and dealing with insurance companies.

Impacts to District Facilities

Practically all Forest Service facilities were damaged. The District Office sustained major roof damage, causing leaks throughout the building. Temporary offices were utilized during the repair. Work centers had only minor damage. Some of the fleet vehicles were not so lucky. All of the District's 18 recreation areas were heavily damaged. Over 170 miles of trails were made impassable or nearly obliterated. Every recreational or administrative facility became unsafe for use due to leaning trees and trees with broken tops and limbs. All roads (Forest Service, county, and State) were blocked by fallen trees. No form of communication was functional after the storm, including telephones, cellular phones, radios, and e-mail.

Impacts to Timber

The De Soto Ranger District's annual timber target was around 15 million board feet prior to Hurricane Katrina. The storm changed the timber program for the foreseeable future. Approximately 30 percent of sawtimber sized trees were blown over or broke off. Virtually all the young plantations are permanently bent over. The District estimates that 3 to 5 years of regular rotation timber sales will have to be suspended. Through salvage sales, hazardous fuel removal was completed on 99,000 acres. Final salvage volume (218 MMBF) harvested during 12 months represents 14.5 years of annual average De Soto Ranger District timber offered target.

Impacts to Threatened and Endangered Species

There were more than 150 Red-Cockaded Woodpecker (RCW) cavity trees on the De Soto. Around half of these cavity trees were blown over or snapped in-two by the hurricane. At least two RCWs died in the storm.

The Federally threatened gopher tortoise faired well because they burrow under ground. However, the amount of timber blown down could have restricted gopher tortoise movements for foraging and reproduction.

On a positive note, in preparation for salvage sales, approximately 48,200 acres of Threatened and Endangered Species surveys were completed. Close to 4,000 new gopher tortoise burrows were located and flagged to protect.

Impacts to Fuels

Since Hurricane Katrina, dead fuel loadings are obviously a great concern. The 1hr, 10hr, 100hr, and 1000hr fuel loadings have all increased dramatically, especially the 1000hr. The forest could be considered "jack-strawed" in many areas. Prior to the storm, no fuel models 11, 12, and 13 existed. Now these models are present in large areas. The open canopy has drastically increased the amount of solar radiation to the fuel bed. This has caused dead fuels to dry out more rapidly. This has also caused an increase in the mid flame windspeeds. The increase in available fuel has increased the source for spotting and therefore increased the spotting potential. In addition, the more open canopy will enhance the growth of common volatile understory brush species such as ti ti, gallberry, and yaupon. This combination of dense, volatile live fuels and the dramatically increased dead fuel loadings will be a concern for several years.

Another critical issue that has impacted mainly the area closest to the coast is salt damage to vegetation. Most of the needles have remained on the trees, so torching or crowning is an increased possibility. Areas with a heavy combination of brush and dead needles will most likely prove to be the most dangerous. These fuel types will have a heavy dead component to the understory and allow fire to move rapidly into the crowns.

The rate of fire spread has slightly increased due to more open canopies. The added fuel loading has increased the flame length and intensity in all areas. Spotting due to accumulations of debris and numerous snags has increased.

Prescribe burning has proven to be difficult and hazardous due to the volatile nature of the fuels. Prescribe burning has also produced higher concentrations of smoke and large particulate matter due to the above normal amount of dead and live fuel.

Fire Occurrence and Severity

The increased fuel loading caused by the hurricane, combined with a moderate to severe drought in the months after the hurricane has greatly increased southern Mississippi's fire danger. The combination of drought and fuel loading resulted in the following suppression figures for the De Soto Ranger District in the 18 months following the hurricane:

- 244 – fires suppressed
- 29 – fires over 100 acres
- 20,800 – acres burned
- 4 – Type 3 fires
- 11 – lightning caused fires

Forest Response

After Katrina made landfall, the first and foremost concern of the Forest and District staff was the wellbeing of District employees. Locating our employees and confirming that they (and their families) were safe were difficult tasks. Phone lines (including cell phones) were down all across the southern end of the State. Some employees had moved inland with family or friends. But eventually all employees either were contacted by or made contact with their supervisors.

The next concern of the Forest was to reopen Forest roads for emergency and essential travel. Over 1,300 miles of Forest roads were totally or partially blocked due to fallen trees and other debris. The Forest brought in two Type 2 Incident Management Teams to accomplish this task. Over the next 2 weeks, using chainsaws and mechanized equipment, personnel opened more than 1,000 miles of roads. It was only then that we realized the magnitude of Katrina's fury.

The fuel loading on the two Districts had gone from around 1 ton per acre to upwards of 60 tons per acre. We knew this new fuel had to be removed quickly due to the rapid rate of decay for wood products in the South. If this fuel was not salvaged, it would become available to burn within 1 or 2 years.

Use of the Healthy Forest Restoration Act (HFRA) authority was critical in meeting the time sensitive issue of salvaging these 1000 hr fuels. Proactive collaboration played a critical role in expediting the process. Key collaborators included U.S. Fish and Wildlife Service, The Nature Conservancy, Mississippi Department of Wildlife Fisheries and Parks, and forest industry. Weight scale authority was granted to expedite removal of downed timber. Salvage sale preparation was conducted concurrently with the National Environmental Protection Act process in order to expedite offering of merchantable timber.

All sales prepared were sold. Over 1.2 million tons or 276 MBF on 109,828 acres on the Chickasawhay and De Soto were removed.

Because of all the new fuel on the ground, access through the Forest was difficult if not impossible. We knew it was critical to establish fuel breaks between the Forest and adjoining private lands, especially those in Wildland Urban Interface (WUI) areas. The lines were needed not only to prevent wild fires from spreading onto private land from the Forest, but more often to prevent the spread into the Forest of fires started by the adjoining landowners as they were cleaning up debris. Using existing District resources, detailers, and contract resources, the Forest constructed more than 600 miles of WUI lines. While we knew that these lines would not stop an approaching wildfire on its own, they would serve as fuel breaks, provide access routes into areas where we needed to position suppression resources, and serve as escape routes if needed. It was not long before we began to see just how valuable the WUI lines were. On the Burnt Dog fire, the WUI line put in between the Forest and some private houses made it possible for our resources to make a stand and save the homes.

With the additional fuel loading, the District was reluctant to try any prescribed burning at first. It was actually after a wildfire or two that they realized they could conduct prescribed fires without doing resource damage, causing excessive smoke issues or creating a situation for extreme fire behavior. It turned out that what we had thought to be the case all along was actually true. Previous years of aggressively burning the Forest had reduced the fuels to such a level that, even with tons of fuel added to the forest floor, it was still manageable. The District successfully burned more than 14,000 acres but then, the Forest made a difficult decision. To concentrate all efforts and resources on assisting with the mechanical removal of fuels that were already sold. While the entire Forest burned only 91,000 acres that year, we were able to count an additional 112,000 acres as mechanical fuel reduction. This year, 2007, the De Soto jumped right back into their normal burning routine. At the time of this writing, they have successfully burned 74,017 acres with no plans to let up. The cost of burning is higher now due to additional preparation and holding resources needed but that will go down as time goes on.

Lessons Learned, and Our Plans

There are several lessons that we can learn from the events surrounding Hurricane Katrina. We know that a quick, organized response was vital to the success of our mission. Using HFRA and other agreements that were already in place, getting the support of our cooperators and other parties, and the aggressive, dedicated attitude of our employees made all of this possible.

At the time, the National Forests in Mississippi's Fire Staff Officer was a Type 1 Incident Commander. His background and experience played an important role in getting much of this started. After his retirement, he came back on contract and helped us put together a hurricane response plan that we can use for future events like this.

The aggressive fuels program that has been in place on the Forest was essential. Having much of the District in a condition class 1 made it possible for our resources to get back on the ground sooner because the new fuel was not piled on top of existing fuels and new growth of volatile brush that is common in the lower coastal plains.

Our plans include using supplemental Katrina funds to bring in additional resources during the burning season and purchase larger equipment that can get through the blow-down. We developed a 3-year plan to use these funds on the De Soto and several other Districts.

The first year or two after Katrina, our main goal has been to reduce the fuel loading as much as possible, but we plan to return to more of a growing season rotation, eventually bringing the De Soto and Chickasawhay back to where they were pre-Katrina.

Acknowledgments and References

This presentation was developed by Danny Bryant, Forest Assistant Fire Management Officer for the National Forests in Mississippi and Jay Boykin, District Fire Management Officer on the De Soto Ranger District.

We thought it would be beneficial to the whole fuels community to see how Mississippi and the entire agency pulled together to address and overcome what could have been a crippling event. Thanks to Katrina Incident Commander David Carter and all the Forest Service employees who were involved with this crucial event.

Most of the data came from weekly reports and updates submitted by the Incident Management Team (IMT) on the incident, David Carter Incident Commander. Reports are posted on the Hurricane Katrina Recovery Internet site, which is linked to the Mississippi National Forests home page: http://fsweb.ms.r8.ffs.fed.us/. Contact us at National Forests in Mississippi, 100 West Capitol Street, Suite 1141, Jackson, MS 39269 (601) 965 1600

References for this paper are:

Boykin, Jay. DFMO De Soto Ranger District

Bryant, Danny. FAFMO MNF

Carter, David. District Ranger, Bienville RD

Smith, Ron. District Ranger, De Soto RD

Calculating Accurate Aboveground Dry Weight Biomass of Herbaceous Vegetation in the Great Plains: A Comparison of Three Calculations to Determine the Least Resource Intensive and Most Accurate Method

Ben Butler[1]

Abstract—*Obtaining accurate biomass measurements is often a resource-intensive task. Data collection crews often spend large amounts of time in the field clipping, drying, and weighing grasses to calculate the biomass of a given vegetation type. Such a problem is currently occurring in the Great Plains region of the Bureau of Indian Affairs. A study looked at six reservations in the Great Plains region to compare three methods of calculating aboveground dry weight biomass to determine the least resource-intensive method. Data were collected in the six agencies using a modified FIREMON plot layout that included plot description (PD), fuel loading (FL), and cover frequency (CF). Additionally, grasses were clipped and weighed on ten 20 inch X20 inch frames per plot. Analyses were performed on the plot data to calculate the dry weight biomass of each plot using three common methods. The first method, considered to be the most accurate, calculated biomass using the ECODATA clip-and-weigh (CW) protocol where the dry weight of the vegetation is converted to pounds/acre based on the frame size of 20 inches X 20 inches. The second method used the FIREMON bulk density constant of 0.8 kg/m^{3,} which is multiplied by average height and percent cover of the vegetation and was applied to the FL and CF data. Last, a regional bulk density constant was established using the CW data. The study then compares the accuracy of both the FIREMON bulk density constant and the regional constant to the CW method. The results of this study provide a regional bulk density constant that can be used to generate accurate biomass calculations, which eliminates the need for the resource-intensive CW method.*

Introduction

Proper management of grasses through the use of fire and other methods promotes healthy grassland that is free from nonnative, invasive shrub and tree species encroachment. Accurate estimations of aboveground dry weight biomass are crucial to the management of native grassland and prairie ecosystems. Fire, as a management tool, relies on fuel readily available for consumption. When the biomass of herbaceous vegetation reaches a desirable level, managers are able to effectively use prescribed fire as a tool to promote new growth of native grasses and forbs. An increase in biomass often leads to increased litter production by herbaceous vegetation which in turn causes a decrease in forgeable grass production rates; therefore, timing is critical when burning grasslands.

Gathering biomass data is important for predicting the most effective time to use prescribed fire as a tool and to help explain postfire effects for a given fuel treatment. However, the gathering of this data is often time- and

In: Butler, Bret W.; Cook, Wayne, comps. 2007. The fire environment—innovations, management, and policy; conference proceedings. 26-30 March 2007; Destin, FL. Proceedings RMRS-P-46CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 662 p. CD-ROM.

[1] Program Manager, Student Conservation Association, Boise, ID. bbutler@thesca.org

resource-intensive, leading to a decrease in accurate measurements for a given management area. The clip-and-weigh (CW) method is the most time consuming; however, it yields the most accurate biomass value. The FIREMON cover frequency (CF) and fuel load (FL) methods allow data collection crews to make estimations of cover and height to be recorded for calculations. These estimations allow the crew to function at a much faster pace, which in turn results in less consumption of time and resources. A field comparison by the data collection crew used to gather the data for this study shows that the CW method uses 100 percent more time to derive a biomass value when compared to the FIREMON CF and FL methods.

The overall goal of this study is to generate a regional bulk density constant that can be used to calculate accurate aboveground dry weight biomass values. The regional constant was created in an effort to rely more heavily on the CF and FL methods outlined in the FIREMON methods (Lutes and others 2006) as the field protocol for generating biomass values within the Great Plains region of the Bureau of Indian Affairs (BIA).

Study Sites

Study sites were in the Great Plains region of the BIA in North Dakota, South Dakota, and Nebraska (fig. 1). Six reservations were sampled throughout summer 2006 by placing plots within nine preestablished burn units (table 1). Plot locations were determined randomly using a standard GIS protocol to ensure minimal bias. All plots were placed in burn units that consisted of the mixed grass prairie vegetation type.

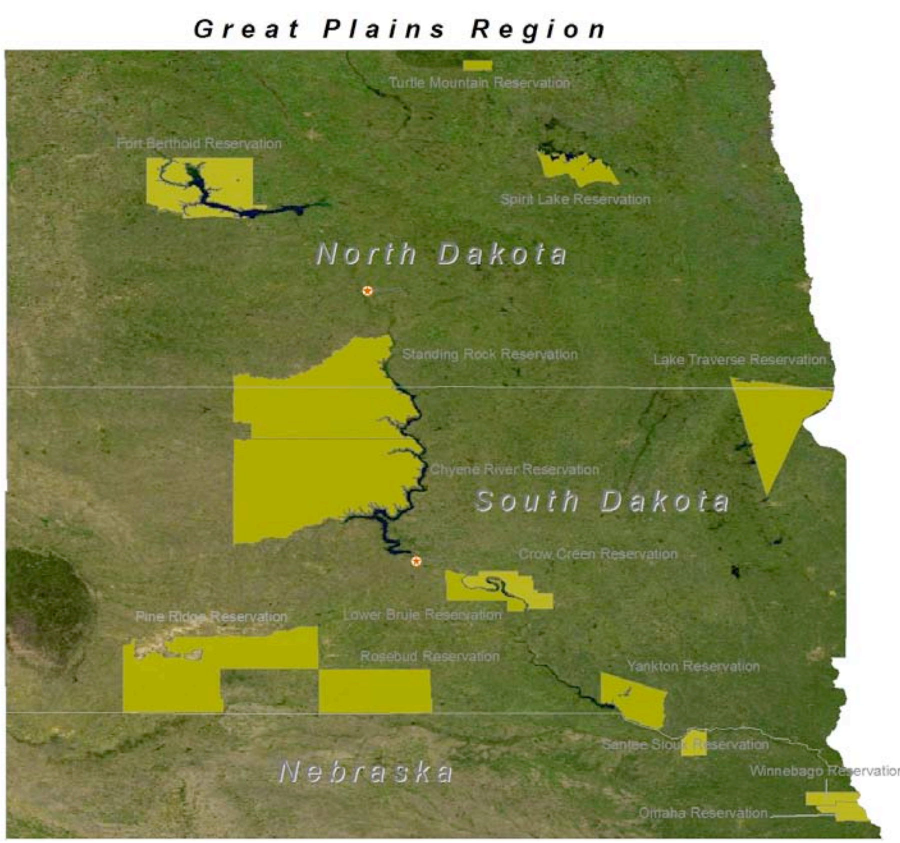


Figure 1—Map showing the Great Plains Region of the BIA and the reservations sampled.

Table 1—Summary of plots sampled by reservation and corresponding burn unit.

Reservation	Burn unit	Number of plots	CF quadrats	FL veg. cylinders	CW quadrats
Crow Creek	Carpenter	8	200	32	80
Fort Berthold	North School	8	200	32	80
	Wild Boar Ridge	6	150	24	60
Omaha	600/599	8	200	32	80
	Altmt. 125	5	125	20	50
	S. Harlan	3	75	12	30
Winnebago	148-149	4	100	16	40
Ponca	East Pen	13	325	52	130
Santee	ST Bar	17	425	68	170
Totals		**72**	**1800**	**288**	**720**

Field Measurements

Field sampling was performed by a team of four Student Conservation Association (SCA) interns and one SCA field staff member. The team was assisted by one or more Tribal staff members who provided local expertise. All team members were trained in standard FIREMON and ECODATA methods to ensure consistency in data collection techniques.

The plot design employed the FIREMON cover frequency (CF) and fuel load (FL) methodologies (Lutes and others 2006) and the ECODATA clip-and-weigh (CW) methodologies (Jensen and others 1993). CF and CW data were collected using a baseline running in an upslope direction from plot center and transects running perpendicular to that baseline across the slope (fig. 2). There were five transects running from the baseline upon which quadrats were located to sample vegetation data. Each transect contained five CF quadrats located on the upslope side of the line. Data were then collected in each frame and included cover estimates and the average height of each species rooted in the frame.

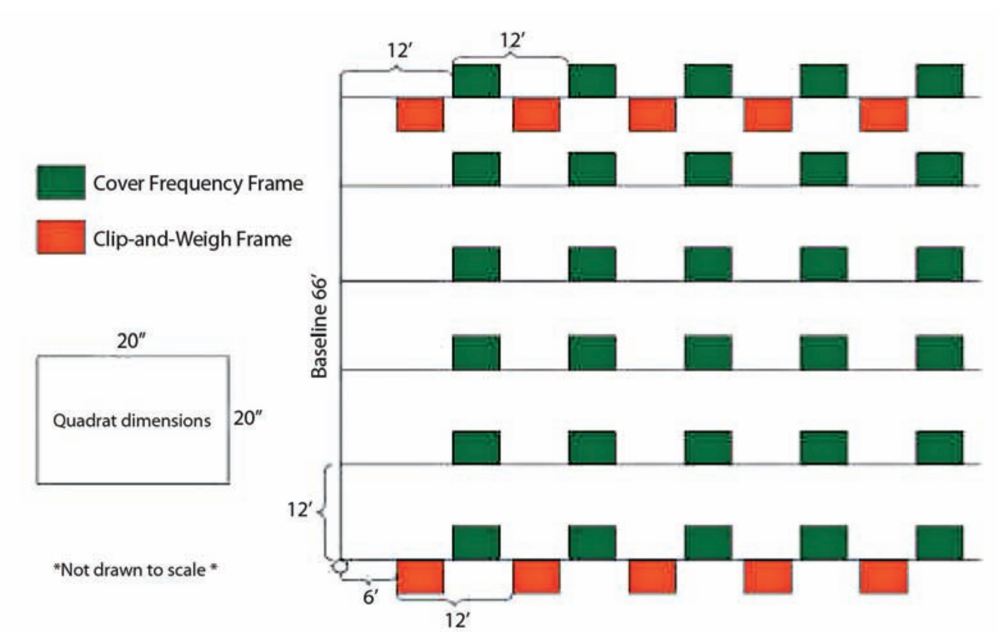


Figure 2—Plot design showing location and number of clip-and-weight quadrats and cover frequency quadrats.

Five CW quadrats were placed on the down slope side of the first and fifth transect. Herbaceous vegetation was clipped in each frame, and the average height of the vegetation was recorded. Tree and shrub species were not clipped to ensure the sample was comparable to the CF and FL methods.

The FL data were collected along transect lines running from plot center. Each transect followed one of the cardinal compass directions and contained two sampling cylinders. The sampling cylinders measured 6 inches in diameter and height and were located at the 45 foot and 75 foot mark on the transects (fig. 3). The average height of dead and live herbaceous vegetation, and the total cover were recorded for each cylinder using FIREMON cover classes (Lutes and others 2006).

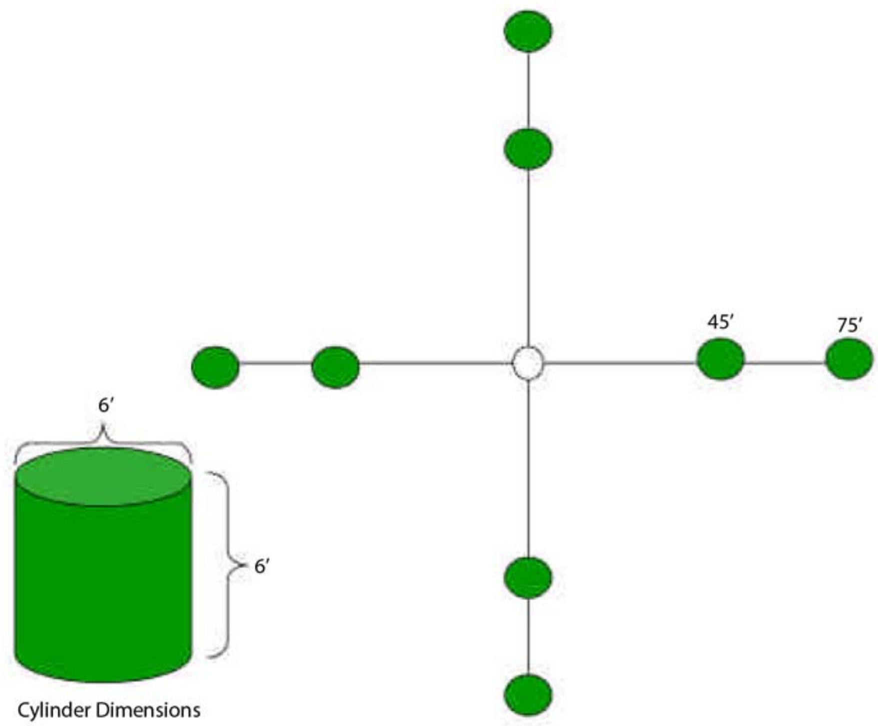


Figure 3—Plot design showing location and number of fuel load vegetation cylinders.

Data Analysis and Exploration

Weights were recorded for each CW quadrat sampled throughout the study area. Each sample was dried for 1 week or until the sample weight stabilized and then weighed to the nearest 0.1 gram. The dry gram weights were converted to pounds by multiplying by 0.0022 resulting in a pounds/20 inch x20 inch frame. Next, the values were multiplied by a 15681.6 conversion factor to generate a resulting tons/acre value for each quadrat. The individual quadrat biomass values were then averaged for each plot to generate a biomass value recorded in tons/acre.

FL vegetation cylinders were used to calculate the biomass values of herbaceous vegetation per plot. The FIREMON v. 2.1.2 software was used to perform this calculation (Lutes and others 2006). The software generated a biomass value for both the live and dead herbaceous component and these values were summed to generate a total biomass value for each plot. Again, the individual quadrat biomass values were averaged, resulting in an average biomass value for the study area recorded in tons/acre.

For the CF frames a biomass value was calculated for each herbaceous species inventoried by using the FIREMON bulk density equation B=H*C*BD (where H = average height, C = average cover, BD = bulk density (.8 kg m^3), and B = biomass) (Lutes and others 2006). The biomass values of each individual species rooted in the quadrat were then summed resulting in a kg/m^2 biomass value for the plot. The values were then multiplied by a 4.46 conversion factor to generate a resulting tons/acre biomass value for each plot. The plot values were then averaged to generate a biomass value for the study area.

The FIREMON biomass equation (B=H*C*BD) was also used to generate a regional bulk density constant. The CF data were used to calculate the values for the equation. The cover estimates for each plot were summed and the plot totals were averaged resulting in 12 percent as the average cover estimate for the study area. The height estimations from the CF data were averaged resulting in 0.48m as the average height of vegetation in the study area. Finally the average biomass of 0.397 kg/m^2 was determined from the CW data. The results produced a regional bulk density constant of 6.89 kg/m^3.

The regional bulk density constant was then used in the FIREMON biomass equation (B = H*C*BD) and calculations were performed on the CF and FL (resulting biomass values noted as CF-R, FL-R). Biomass values for the CF plots were calculated for each species rooted in a plot quadrat. The individual biomass values were then summed resulting in a biomass value for each plot. Calculations were also performed on the FL data set using the regional bulk density constant. Two biomass values were calculated for each plot (live herbaceous and dead herbaceous) using the FIREMON bulk biomass equation. The two biomass values were then summed to calculate the total biomass of each plot.

Results and Discussion

The relationship between CW, CF, and FL biomass values was consistently poor for each burn unit in the study area. The CW method produced an average of 1.773 tons/acre for the entire study area with the CF and FL methods averaging 0.325 and 0.308 tons/acre respectively (fig. 4). There was noted to be an average difference of 1.448 tons/acre difference between the CW and CF method and a 1.462 tons/acre difference between the CW and FL methods. The FIREMON bulk density constant of 0.8 kg/m^3 therefore proved to be an inaccurate constant when compared to the CW data set.

A comparison of the biomass values calculated using the regional bulk density constant was also performed. The average biomass values were calculated for the CF-R and FL-R datasets and were noted to be 2.655 tons/acre and 1.50 tons/acre, respectively (fig. 5). When compared to the biomass value of 1.773 recorded from the CW method the relationship proved to be much improved.

It was determined that further investigation of the poor performance of the FIREMON method's data set was needed to confirm the CW values. The three average biomass values (CF, FL, CW) were compared to the Natural Fuels Photo Series (Ottmar and Vihnanek 1999). Volume V was used as a compari-

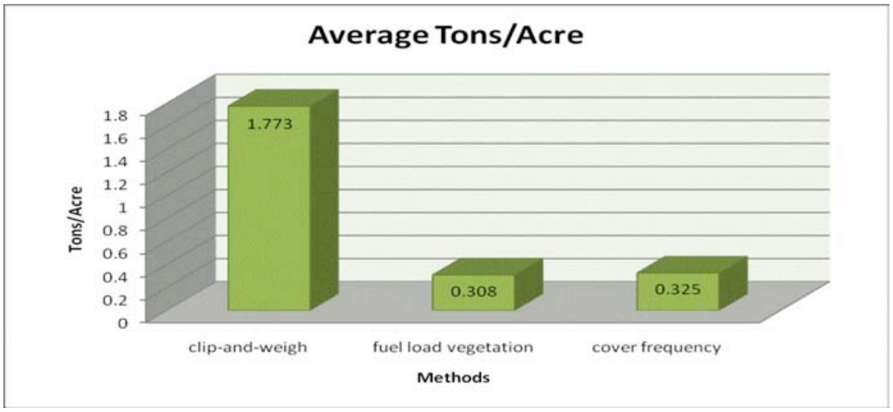


Figure 4—Comparison of the CW method to the FL and CF.

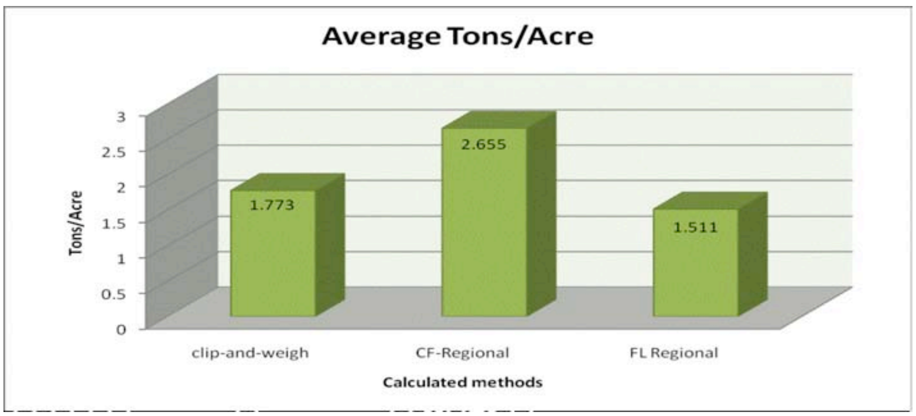


Figure 5—Comparison of the CW method to the CF-R and FL-R.

son to validate the CW biomass value. The northern tall grass prairie photo series was used and the area was determined to be most closely related to the TP 5 photo. The photo series provides a total biomass value of 1.718 tons/acre when subtracting the surface fuel and shrub components. This value compared well with the average CW biomass of 1.773 for the reservation, however, when compared to the CF and FL biomass values of 0.325 and 0.308 respectively, the relationship proved once again to be poor.

Cover estimates were examined as a possibility of the seemingly low biomass values yielded through the CF and FL methods. An average of 12 percent herbaceous vegetation cover was recorded by the field crew for the study area. Examination of photo documentation from the field crew solidified their cover estimates for each quadrat (fig. 6). Crew precision did not prove to be a factor in the FIREMON biomass calculations.

The bulk density constant used in the FIREMON calculations (0.8 kg/m^3) was questioned as a potential influence in the low biomass values. This constant was compared to Brown's *Bulk Densities of Nonuniform Surface Fuels and Their Application to Fire Modeling* (Brown 1981), which lists a bulk density constant of 0.8 kg/m^3 for upright surface strata located in the grass-shrub vegetation type. Being that the constant used in the FIREMON calculations was the same, the constant was considered to be accurate. Both constants, however, rely on forest vegetation types and do not necessarily represent the mixed grass prairie ecosystem.

Figure 6—Documentation showing quadrat before clipping (left) and after clipping (right).

The excellent relationship between the FL-R value and the CW value proves to be one of significance and it was therefore determined to be the most accurate, least time consuming method of producing biomass values.

Summary and Conclusions

The data clearly show a poor performance of the 0.8kg/m^3 bulk density constant when applied to the FIREMON CF and FL. Exploration into possible causes of this poor performance leads to the fact that national bulk density constants make poor predictors of actual biomass values when reduced to a smaller scale. This is noted in the loose relationship between the CW, CF, and FL methods when applying the national bulk density constant. The creation of local constants is essential to calculating accurate biomass values for a given ecosystem.

Accuracy of data collection crews also proves important when determining biomass in grasslands. The creation of a regional constant cannot be completed without accurate cover and height estimates, and therefore crew calibration is necessary in the early stages of sampling design.

The regional bulk density constant of 6.89 kg/m^3 proves to be a sound value and displayed a consistent relationship with the CW data when applied to the FL data set. Further analysis will be performed on the data set to examine the loose relationship between the CF and CW methods when applying the regional bulk density constant. Additional comparisons will also be performed in the future with the project set to be reexamined throughout summer 2007, with the overall goal still being to provide the most accurate bulk density constant possible for use by fire professionals throughout the Great Plains region of the BIA.

Acknowledgments

I thank Duncan Lutes and John Caratti for their advice and assistance during the project development and data analysis stages. The project was greatly enhanced by Morgan Beverage and all of the coordinators located in the Great Plains region and I thank them for their continued support. I also thank the members of the 2006 SCA FIREMON Great Plains crew, under the direction of Thomas Hanson, for their tireless data collection efforts in the field. Finally, I thank Jill Kolodzne and Mary Taber for their support and funding of this project from its conception to the final results.

References

Brown, J.K. 1981. Bulk Densities of Nonuniform Surface Fuels and Their Application to Fire Modeling. Forest Science. Vol. 27. No. 4: 667-683.

Jensen, M.E.; Hann, W.; Keane, R.E.; Caratti, J.; Bourgeron, P.S. 1993. ECODATA—A multiresource database and analysis system for ecosystem description and evaluation. In: M.E. Jensen and P.S. Bourgeron, ed., Eastside Forest Ecosystem Health Assessment, Vol. II, Ecosystem Management: Principles and Applications. National Forest System Information Report. Washington, DC: U.S. Department of Agriculture, Forest Service: 249-265.

Lutes, D.C.; Keane, R.E.; Caratti, J.F.; Key, C.H.; Benson, N.C.; Sutherland, S.; Gangi, L.J. 2006. FIREMON: The fire effects monitoring and inventory system. Gen. Tech. Rep. RMRS-GTR-164-CD, U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO. 1 CD.

Ottmar, R.D.; Vihnanek, R.E. 1999. Stereo photo series for quantifying natural fuels, vol. V: red and white pine, northern tall grass prairie, and oak/hickory in the Midwest. PMS 834. Boise, ID: National Interagency Fire Center, National Wildfire Coordinating Group. 99 p.

Testing the Modeled Effectiveness of an Operational Fuel Reduction Treatment in a Small Western Montana Interface Landscape Using Two Spatial Scales

Michael G. Harrington[1], Erin Noonan-Wright[2], and Mitchell Doherty[2]

Abstract—*Much of the coniferous zones in the Western United States where fires were historically frequent have seen large increases in stand densities and associated forest fuels due to 20th century anthropogenic influences. This condition is partially responsible for contemporary large, uncharacteristically severe wildfires. Therefore, considerable effort is under way to reduce the potential for extreme wildfire behavior and effects, especially near communities, by manipulating canopy and surface fuels using mechanical thinning and/or prescribed burning. Treatment effectiveness, however, has been difficult to quantitatively assess, but methods are now available for estimating stand-level canopy and surface fuels with which fire behavior can be more accurately modeled and compared among different fuel treatments. The Sheafman Fuels Reduction Project was recently conducted by the Bitterroot National Forest incorporating various fuel treatments to reduce the probability of high intensity crown fire impacting a watershed adjacent to Pinesdale, MT. Detailed sampling of stand conditions was conducted before and after two treatments: overstory thinning with understory cutting, and understory cutting only. Both were followed by slash burning. Surface fuel loadings were estimated from intercept data, and canopy fuels were estimated from tree data using the FuelCalc program. Pre- and posttreatment fuels data were used to model surface and crown fire behavior using the NEXUS program. A comparison was made between fire behavior computed from treatment mean fuels data and individual plot fuels data. Results indicate that because surface fuels and estimated mid-flame wind speeds increased modestly with treatments, surface fire behavior was not greatly altered until 20-ft wind speeds exceeded 20 mph. Treatment effects on canopy base heights and canopy bulk densities within the small landscape determined the level of estimated treatment effectiveness. Both treatments reduced the probability of crown fire initiation by raising canopy base heights. The likelihood of crown fire spread was appreciably reduced only in the overstory thinning treatment. An examination of plot scale surface and crown fire behavior gave a more detailed assessment of treatment effectiveness than average treatment values.*

Introduction

A large proportion of the forested regions in the Western United States, which historically were exposed to frequent, low intensity wildfire (Arno and others 1997; Everett and others 2000), are currently represented by altered stand structure and composition compared to pre-European settlement (Cooper 1960; Parsons and others 1979). An alteration of historical disturbance trends, from regular fire occurrence to general fire exclusion and tree harvesting, is the supposed cause for these forest changes. These changes are generally characterized by large numbers of trees, typically with a considerable proportion of shade tolerance (Hartwell and others 2000),

In: Butler, Bret W.; Cook, Wayne, comps. 2007. The fire environment—innovations, management, and policy; conference proceedings. 26-30 March 2007; Destin, FL. Proceedings RMRS-P-46CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 662 p. CD-ROM.

[1] Research Forester, U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Missoula, MT. mharrington01@fs.fed.us

[2] Fire Ecologist and Forestry Technician, respectively, Systems for Environmental Management, Missoula, MT.

and often with significant amounts of dead vegetation litter (Pyne and others 1993; Arno and others 2000). Therefore, across many low to mid-elevation forested landscapes, large amounts of both living and dead biomass have accumulated. Furthermore, wildland fires of uncharacteristically high intensity and severity are now common, in part because of this condition, and because communities and many recreational activities occur within or close to this forest type, the fire risk is high (Skinner and Chang 1996; Hardy 2005). In addition, because historically these ecosystems were defined by low to mixed severity rather than high severity systems, they have developed little resilience, and postfire recovery to some acceptable condition is uncertain (Barrett and others 1991; Brown and others 1994).

A large effort is currently under way to lessen this hazard by manipulating canopy and surface fuel characteristics to reduce the probability of severe wildfire behavior and impacts (USDA, USDI 2004; http://www.healthy-forests.gov/accomplish-report_2004.pdf). Most fuel reduction treatments use mechanical thinning, prescribed burning, or a combination to reduce horizontal and vertical fuel quantities and homogeneity (Agee and Skinner 2005). Ideally, areas with high probability of severe fire because of a fuel hazard can be delineated for active management consideration (GAO 2003). Whereas techniques for assessing surface fuel characteristics and surface fire behavior have been available for some time, canopy fuel treatment prescriptions and their assumed effects on crown fire initiation and spread have been, until recently, qualitatively assessed, typically by expert opinion. This was primarily due to the inability to accurately quantify canopy fuels and crown fire spread (Scott and Reinhardt 2001).

The Sheafman Fuels Reduction Project was recently conducted by the Bitterroot National Forest incorporating various canopy and surface fuels treatments in a dense forest condition to reduce the probability for high intensity crown fire impacting the watershed and community of Pinesdale, MT. This study evaluates pre- and posttreatment fuels and models the change in anticipated fire behavior following two treatments across this small, interface landscape. Predicted fire behavior is compared at two scales: the more traditional average treatment-level scale, and a more detailed plot-level scale.

Methods

Treatment History

In May 2001, The Bitterroot National Forest signed a Decision Notice to conduct the Sheafman Fuels Reduction Project within a 475-acre area adjacent to and west of private property in the community of Pinesdale, MT, with several hundred rural homes. The Purpose and Need statement from the document (Bitterroot National Forest 2001) reports:

> Breakup the existing fuel continuity on National Forest System lands near the town of Pinesdale by reducing the density of trees. This will decrease the probability that a future wildland fire would develop into, or be sustained as, a stand replacing or crown fire, and increase the probability of being able to defend life and property within the wildland/urban interface from wildland fire.

Based on existing fuels and site conditions, a series of units were established by the National Forest for either prescribed burning only (not discussed in this paper), understory cutting with prescribed fire, or overstory thinning with understory cutting and prescribed fire. The silvicultural prescription for the overstory thinning treatment called for leaving a single or two-story semiopen stand with 50 to 80 trees per acre favoring ponderosa pine with a heavy reduction of understory trees. In the understory cutting treatment, trees less than 7 inches diameter breast height (dbh at 4.5 ft) were cut and piled for burning, mostly on slopes steeper than 45 percent, where equipment for overstory thinning could not safely operate.

Field Methods

In 2002, sample plots were established in six locations within the Sheafman treatment area. Five plots were established for sampling surface fuels, stand structure, and other site attributes in four locations and 10 plots in the remaining two locations for a total of 40 plots. Throughout the project area, the final decision between overstory thinning (OT) or understory cutting (UC) was made by the forest operator with the most liberal treatment, OT, preferred. Therefore, 32 plots received the OT treatment and eight received the UC treatment (fig. 1).

a

b

Figure 1—Examples of Sheafman fuel treatments: pre (a) and post (b) overstory thinning, and pre (c) and post (d) understory cutting.

c

d

The first plot at each location was randomly located, and subsequent plots were systematically located along a previously selected azimuth and distance. At each plot, two or three 50-ft transects were laid out at previously chosen azimuths to measure surface fuel characteristics according to FIREMON protocols, version 2.1.1 (Lutes 2006) in which intercepts of down and dead woody fuels were counted by size class; canopy cover and height of shrub and herbaceous vegetation were measured; and forest floor depth measurements were made separating litter and duff. The intercept, canopy cover/height, and litter/duff depth data were used in standard algorithms to calculate loadings by fuel type. Note that posttreatment shrub characteristics could not be measured on 30 of 40 plots because of dormancy. Therefore, because shrub canopy cover and heights on the 10 measured plots were similar between pre- and posttreatment, pretreatment values were used in the posttreatment analysis for those 30 plots. Also at each plot, the following measurements were made for all trees > 4.5 ft tall within a 1/10th-acre circular subplot: species, dbh, height, height to live crown base, and crown class (dominant, codominant, intermediate, and suppressed). Few trees <4.5 ft tall occurred at this site. Tree data were used in the FUELCALC program, Beta version (Reinhardt and others 2006) to compute canopy fuel attributes, such as loading by fuel size class, canopy bulk densities, and canopy base heights. Crown class adjustment factors that were most appropriate for the Sheafman site were used in the calculations. Pretreatment sampling took place in 2002 and 2003, overstory thinning, understory cutting and pile burning occurred between 2002 and 2004, and posttreatment sampling took place in 2004.

Fuel and Fire Behavior Modeling

Modeled fire behavior—namely surface fire spread rate and flame length along with the torching and crowning indices—was used to evaluate the pre- and posttreatment level of wildfire hazard and assess the effect of the fuel treatments. In this analysis, we compared pre- and posttreatment stand conditions, surface and canopy fuel characteristics, and the resulting fire behavior in the 32 plots with overstory thinning/understory cutting (OT) and the eight plots with understory cutting (UC) only. Fire behavior modeling was conducted at two scales for comparison: using average treatment-level fuels data and using individual plot-level fuels data. In the first method, the surface and canopy fuels data for all plots within a treatment were averaged resulting in one custom fuel model per treatment each for pre and post conditions. These single custom fuel models were used to predict single values for each surface and crown fire behavior attribute by treatment before and after thinning. This method is commonly reported when assessing treatment effectiveness (Raymond and Peterson 2005; Stephens and Moghaddas 2005). In the second method, custom fuel models were developed for each plot from plot-level surface fuel characteristics and canopy fuel attributes. These plot-level models were used to estimate surface and crown fire behavior for each plot to assess a distribution of predicted fire response within a treatment. Therefore, this is an assessment of scale, examining surface and crown fire behavior at the larger treatment scale and at the smaller plot scale, which may be the fuel environment level at which fire actually responds. Fulé and others (2002) also reported that average stand conditions fail to represent canopy fuel variability, reducing the chance of predicting real crown fire behavior.

The 95th percentile fire weather and computed fuel moistures used in the wildfire scenario and representing a very high level of fire danger were retrieved using the Fire Family Plus 3.0 program with data from the Smith Creek Remote Automatic Weather Station (#242912) 7 miles north and at a similar elevation and aspect as the fuel treatment site. Data were analyzed for the 7 years the station has been in operation and covered May 1 to Oct. 30, 2000 to 2006. The fuel moisture scenario used in fire behavior calculations for both pre- and posttreatment was 1-hr = 3 percent, 10-hr = 4 percent, 100-hr = 6 percent, live woody = 70 percent, herbaceous = 30 percent, foliar = 100 percent. Because winds are inherently transient, they were modeled at four 20-ft wind speeds (10, 20, 30, and 40 mph) and across slope, which is the most likely wind direction in the Sheafman area. Stand height, crown ratio, and canopy cover were used to derive the wind adjustment factor for calculation of the mid-flame wind speeds (Albini and Baughman 1979). Both the treatment-level or plot-level custom surface fuel models, canopy fuel attributes, and slopes along with the 95th percentile computed fuel moisture values as well as the selected 20-ft wind speeds were used for fire behavior modeling at the treatment or plot level using the NEXUS 2.0 program (Scott 1999). Note that, even though crown fire behavior values are computed by NEXUS, only fire behavior from surface fire is reported because the focus of this assessment is whether or not crown fire will initiate and spread, not how intense the crown fire will be.

Crown fire terminology used in this paper comes from Scott and Reinhardt (2001):

- Passive crown fire occurs as individual or small groups of trees torch out but lateral crown fire spread is not necessary.
- Active crown fire occurs as the entire fuel complex from surface to canopy is burning and the crown fire is dependant on the surface fire.
- Conditional surface fire occurs when passive crown fire requirements are not met but crown fire spread requirements are.
- Torching index is the 20-ft wind speed at which crown fire activity can initiate.
- Crowning index is the 20-ft wind speed at which active crown fire is possible.

Results

Much of the Sheafman treatment area had been heavily logged, most likely a century earlier, leading to dense Douglas-fir stands that occupied the site at the beginning of this project. Before treatment, the overstory thinning plots (OT) averaged about 580 trees/acre and 140 ft^2/acre basal area, with individual plots ranging from 230 to 1770 trees/acre (fig. 2). Tree density and basal area averaged just under 380 trees/acre and 125 ft^2/acre in the understory cutting plots (UC) with a much narrower range than the OT plots.

Thinning reduced the average OT plot tree density by 87 percent (73 trees/acre) and basal area by 63 percent (53 ft^2/acre) compared to 59 percent (154 trees/acre) and 17 percent (102 ft^2/acre) reductions, respectively, for the UC plots (fig. 2). The relatively high stand densities resulted in substantial mean canopy bulk density (CBD) values, and the range of plot values was large, 0.06 to 0.54 kg/m^3 for the OT plots and 0.06 to 0.27 kg/m^3 for the UC

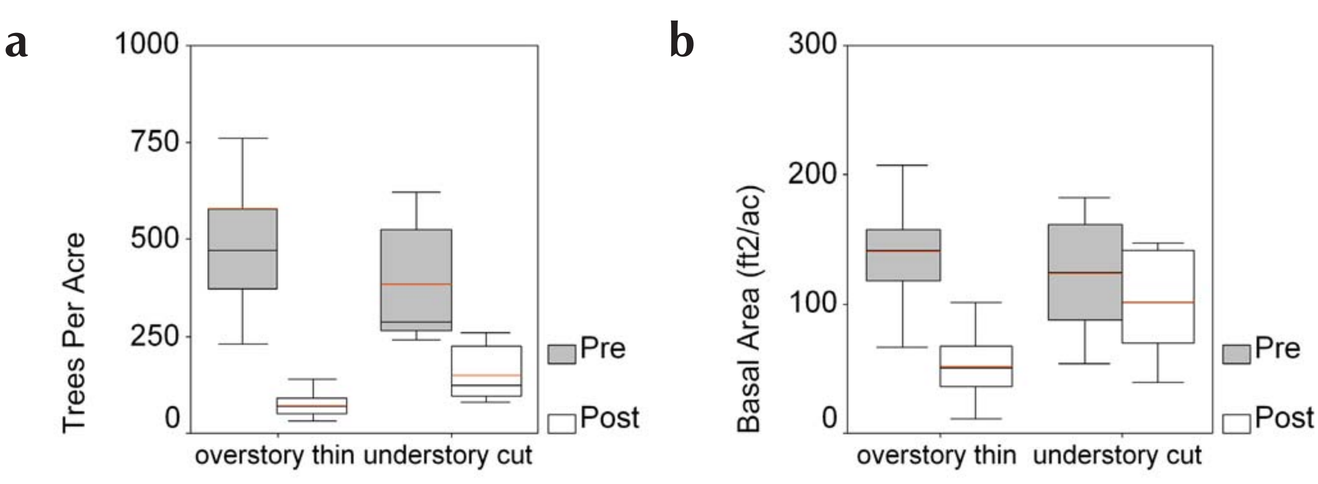


Figure 2—Box plot of trees per acre (a) and basal area (b) grouped by treatment, overstory thin (n=32) and understory cut (n=8) and status, pretreatment or posttreatment. The box portion of the box represents the interquartile range (25th to 75th percentile). The red line is the mean; the black line is the median. The lines extending from the bottom and top of the box represent the minimum and maximum values, respectively. Outliers are not shown.

plots (fig. 3). The canopy base height (CBH) mean was moderately high for pretreatment conditions, again with a large range for individual OT plots (4 to 39 ft). Thinning in the OT plots resulted in a 74 percent average CBD reduction (from 0.20 to 0.05 kg/m^3) and 88 percent average increase in CBH (from 17 to 32 ft). In the UC plots, mean CBD decreased by only 13 percent (from 0.14 to 0.12 kg/m^3) and CBH increased by 58 percent (from 12 to 19 ft) (fig. 3). A more detailed examination shows that all plots experienced an expected decrease in CBD with the exception of one UC plot which had no change. Postthinning CBD values ranged from 0.01 to 0.10 kg/m^3 in the OT plots and 0.05 to 0.21 kg/m^3 in the UC plots. CBH predictably rose in all plots, with increases ranging from 3 ft to over 40 ft with the most substantial increases occurring in the OT plots.

Surface fuel loadings were similar in the two treatments prior to thinning with fine dead fuels (1-, 10-, 100-hr, litter) averaging about 4 tons/acre with a three to four fold range in individual plot values (fig. 4). UC plot shrub fuel loads were roughly double those in the OT plots, but herbaceous fuels were equally low in both treatments. With thinning treatments, which were followed by pile burning, average fine fuel loads in the UC plots rose by about 30 percent to 5 tons/acre, whereas those in the OT plots increased by

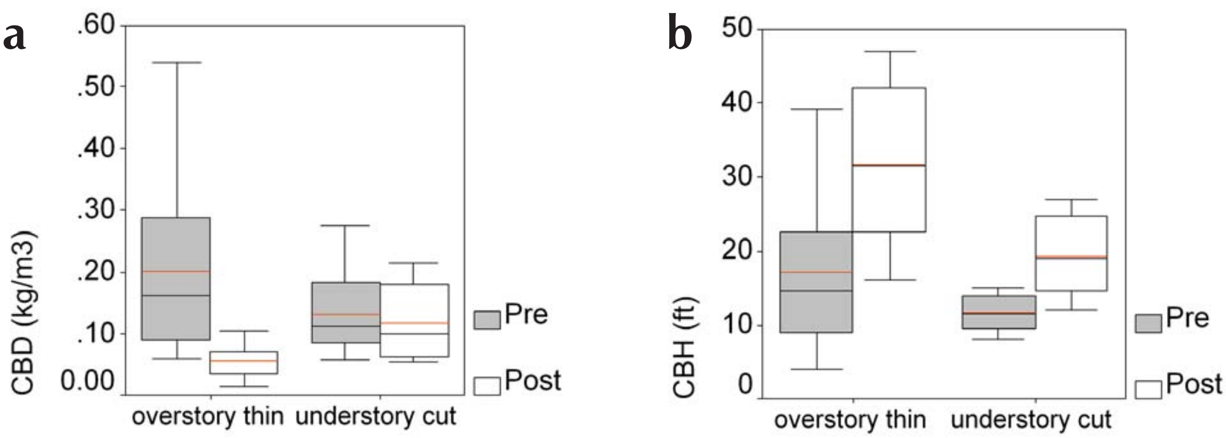


Figure 3—Box plot of canopy bulk density (a) and canopy base height (b) grouped by treatment, overstory thin (n=32) and understory cut (n=8) and status, pretreatment or posttreatment. The box portion of the plot represents the interquartile range (25th to 75th percentile). The red line is the mean; the black line is the median. The line extension represents the minimum and maximum values. Outliers are not shown.

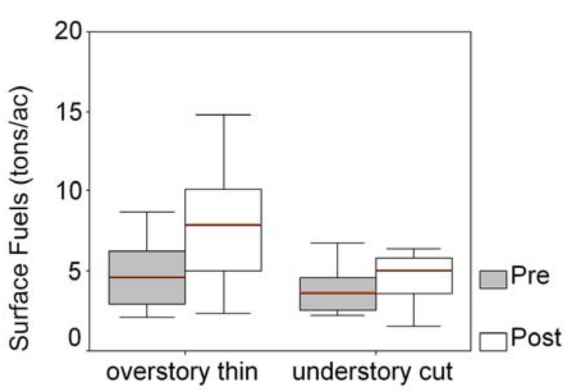


Figure 4—Box plot of downed, surface fuels including litter (needles, vegetative plant parts, and so forth) and 1-hr, 10-hr, 100-hr woody fuels grouped by treatment, overstory thin (n=32) and understory cut (n=8) and status, pretreatment or posttreatment. The box portion of the plot represents the interquartile range (25th to 75th percentile). The red line is the mean; the black line is the median. The line extension represents the minimum and maximum values. Outliers are not shown.

almost 70 percent to 8 tons/acre. These fuel loading increases were primarily due to added 10-hr and 100-hr woody biomass. Live herbaceous fuels changed little, and shrub loads were similar in the analysis, primarily because pretreatment shrub biomass was used for posttreatment in 30 of 40 plots as described in the methods.

Effective mid-flame wind speeds are also expected to increase with higher wind adjustment factors resulting from the more open posttreatment stand features. The wind adjustment factor as computed using Albini and Baughman (1979) averaged about 0.12 in both treatments before thinning but almost doubled (0.22) in the OT plots with thinning compared to only a 25 percent increase (0.15) in the UC plots. The range of wind adjustment factors across pretreatment OT plots was predicted to reduce a 20 mph, 20-ft wind to 2 to 3 mph at mid-flame height but would increase to 3 to 6 mph after thinning. UC plot mid-flame wind speed range would also be 2 to 3 mph pretreatment and would only increase to 2 to 4 mph posttreatment.

To repeat from the Fuels and Fire Behavior Modeling section above, two methods were used to compute and summarize the fire behavior outputs. In the first method, treatment-level fire behavior values were computed from the NEXUS model using a single mean custom fuel model for each treatment, for pre and post conditions. The second method used plot-level outputs that were the distribution of fire behavior values from NEXUS-produced custom fuel models for each plot. Treatment-level predicted surface fire spread rates and flame lengths are compared in table 1 for pre- and postthinning for the two treatments under four wind speeds. Postthinning treatment-level spread rates and flame lengths were similar to prethinning values in the OT plots at lower wind speeds but increased more rapidly with increasing wind speeds. The ranges of plot-level spread rates and flame lengths broadened to higher maximums after treatment and at wind speeds higher than 20 mph.

Table 1—Rates of surface fire spread and flame lengths at four 20-ft wind speeds pre- and posttreatment in the Overstory Thinning and Understory Cutting treatments. Treatment-level (trt-level) values are computed from mean fuel loadings, slopes, and wind speeds. Plot-level values include the maximum and minimum values computed from individual plot fuel loadings, slopes, and wind speeds.

20-ft wind speed (mph)	Rate of fire spread (chains/hour)							
	Overstory thinning				Understory cutting			
	Pretreatment		Posttreatment		Pretreatment		Posttreatment	
	Trt-level	Plot-level	Trt-level	Plot-level	Trt-level	Plot-level	Trt-level	Plot-level
10	6	2-23	5	2-24	15	3-31	11	4-23
20	7	3-39	9	4-53	17	6-34	14	7-30
30	10	4-52	16	8-96	22	9-48	20	11-45
40	14	6-73	25	12-148	30	14-67	29	17-66

20-ft wind speed (mph)	Flame length (feet)							
	Overstory thinning				Understory cutting			
	Pretreatment		Posttreatment		Pretreatment		Posttreatment	
	Trt-level	Plot-level	Trt-level	Plot-level	Trt-level	Plot-level	Trt-level	Plot-level
10	3	2-10	3	2-10	6	2-9	5	2-8
20	4	2-10	4	2-11	6	3-9	6	3-9
30	4	2-11	5	2-14	7	3-10	7	4-11
40	5	2-12	6	3-18	8	4-12	8	5-13

The treatment and plot-level rates of fire spread and flame lengths in the UC plots were predicted to change little as a result of the thinning (table 1). Looking at individual plots, figure 5 shows that a general increase in fire behavior after treatment is predicted for a growing number of plots as wind speed rises. With winds at or above 20 mph, rates of fire spread and flame lengths after the OT treatment are expected to increase in over 60 percent of the plots. Increases in fire spread and flame length are predicted to occur posttreatment in over 50 and 35 percent of the UC plots, respectively, with wind speeds 30 mph and greater.

The treatment-level torching index for plots in the OT treatment was quite high for both pre- and posttreatment, exceeding 80 mph (table 2). Plot-level indices were expansive because of the broad range of CBH values (fig. 3). For the UC treatment, the treatment-level torching index rose from 27 mph pretreatment to almost 50 mph posttreatment. The treatment-level

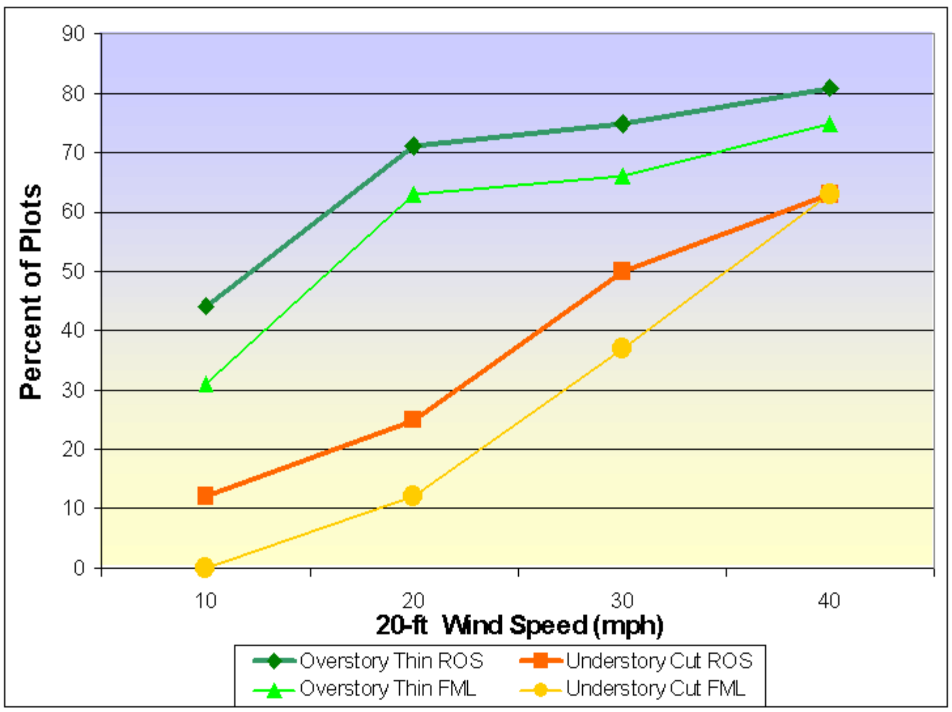


Figure 5—Percent of plots with increasing surface rates of spread (ROS) and flame lengths (FML) following the overstory thinning and understory cutting treatments.

Table 2—Torching and crowning indexes in miles/hour winds speed pre- and posttreatment for the overstory thinning and understory cutting treatments. Treatment-level (trt-level) values are computed from mean fire behavior values, CBD, and CBH. Plot-level values include the maximum and minimum values computed from individual plot fire behavior values, CBD, and CBH.

Index (mph)	Overstory thinning				Understory cutting			
	Pretreatment		Posttreatment		Pretreatment		Posttreatment	
	Trt-level	Plot-level	Trt-level	Plot-level	Trt-level	Plot-level	Trt-level	Plot-level
Torch	89	0-469	118	21-392	27	0-95	49	10-99
Crown	12	4-32	34	21-89	17	8-32	19	11-34

crowning index almost tripled in the OT plots from 12 to 34 mph with thinning as did the range, but changed minimally in the UC treatment. This reflects the relative changes in CBD by treatment shown in figure 3. Figure 6 shows the percent of plots with torching potential under four wind speeds. Throughout the tested wind speed range, 6 to 28 percent of the OT plots were predicted to torch before treatment, which was reduced to a maximum of 13 percent at 40 mph winds after thinning. Between 25 and 75 percent of the UC plots were initially predicted to torch with 10 to 40 mph winds. These values were reduced approximately in half with treatments, indicating that some crown fire initiation was still predicted at all wind speeds in the UC plots after thinning.

Combining active and conditional crown fire potential, 31 percent of the OT plots were predicted to support crown fire spread at a 20-ft wind speed of 10 mph before treatment, up to 100 percent with winds at 40 mph (fig. 7). After thinning, no plots were expected to support crown fire at winds below 20 mph, but with 30 to 40 mph winds, 34 and 63 percent of plots were predicted support crown fire. In the UC plots before treatment, the range of plots predicted to sustain crown fire spread ranged from 13 to 100 percent within the tested wind speed range. With understory tree cutting, these percentages decreased by only 13 percent with winds at or below 30 mph, and remained at 100 percent with a 40 mph wind speed.

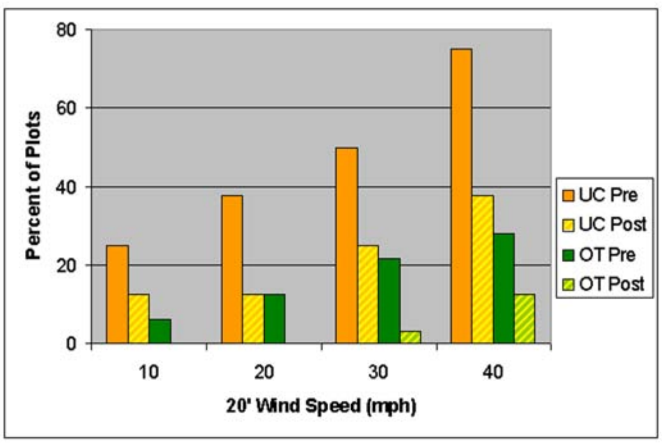


Figure 6—Percent of plots in the overstory thinning (n=32) and understory cutting (n=8) treatments in which crown fire initiation is predicted before and after treatment at four wind speeds.

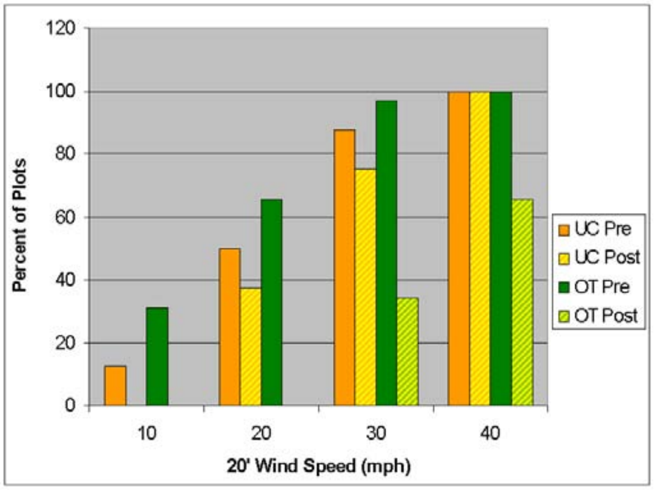


Figure 7—Percent of plots in the overstory thinning (n=32) and understory cutting (n=8) treatments in which crown fire spread is predicted before and after treatment at four wind speeds.

Summary and Discussion

The purpose of the Sheafman Fuels Reduction Project as stated in the Decision Notice (see Methods section) was to breakup fuel continuity through tree density reduction thereby lessening the probability of stand replacement crown fire. The monitoring and analysis reported here quantified the surface fuel status and the assumed canopy fuel continuity, determined the effect of thinning on fuel structure, and modeled the predicted fire behavior before and after fuel reduction treatments. We presented average values for surface fuel loadings and canopy fuel structure before and after thinning and also treatment-level predicted surface and crown fire behavior based on these average fuel characteristics and a specified wildfire weather/fuel moisture scenario for the two treatments implemented in the project area. These average values offer an assessment of general fuel conditions within treatments as well as broad generalization of predicted fire behavior, which is standard reporting procedure.

An additional evaluation features a comparison of pre- and posttreatment fire behavior on a plot scale with the assumption that fire response is more closely tied to small scale surface and canopy fuel characteristics than to larger stand scale average conditions and therefore, perhaps, more informative. Because surface fire behavior at any particular site depends on the quality and quantity of available fuels, spatial variability in fuels should lead to variable fire behavior. Further, because surface fire behavior and canopy base height are the primary factors controlling crown fire initiation, quantifying the plot-level coincidence of these two factors should provide a more accurate assessment of the spatial probability of torching than do treatment averages. Additionally, plot-level canopy bulk density values, which may exceed or fall short of wind speed thresholds for crown fire spread, should provide a more detailed picture of the potential variability of crown fire behavior across a treatment area than does an average CBD value, representing the entire treatment.

The initiation of crown fire is determined by the relationship between surface fire intensity and adjoining canopy base height. The fire intensity input variables that were affected by the thinning treatments were primarily fuel loadings and mid-flame wind speed through the wind adjustment factor. Average surface fuel loading (fig. 4) and wind adjustment factor increased by about 70 and 100 percent in the OT plots, respectively, and 30 and 25 percent and the UC plots, respectively. However, predicted posttreatment spread rates and flame lengths, as indicators of fire intensity, remained similar to pretreatment values until 20-ft wind speeds exceeded 20 mph in the OT plots and at all wind speeds in the UC plots (table 1). The torching index computed from treatment-level fire intensity and CBH was very high for the OT plots before (89 mph) and after (118 mph) treatment (table 2), implying that crown fire initiation in either case would be highly unlikely. However, with a plot-level assessment, there clearly are individual plots predicted to initiate crown fire at lower wind speeds than predicted by treatment-level values. Before treatment, the percent of plots with torching potential ranged from 6 percent at 10 mph winds to 28 percent at 40 mph (fig. 6). After treatment, torching was not predicted in OT plots with winds below 30 mph but could be expected in 13 percent with 40 mph winds. In the UC plots, the torching index computed from treatment-level fire intensity and CBH was moderately low at 27 mph before treatment, but rose to 49 mph with thinning. At the plot scale, torching was predicted in 25 percent of the plots at 10 mph and up to 75 percent at 40 mph (fig. 6). With thinning, these percentages were reduced in half, 13 to 38 percent, with the same wind speeds, indicating that the torching potential, even though lessened, is still apparent because CBH values were significantly raised in only a portion of the plots relative to variable plot-level changes in surface fire intensity.

Crown fire spread is primarily determined by canopy bulk density and wind speed once the transition from surface to crowns has occurred (active crown fire) or once the crown fire has moved in from an adjacent stand (conditional surface fire) (Scott and Reinhardt 2001). Using average CBD values for each treatment, the crowning index for the OT plots is predicted to rise from 12 mph to 34 mph (table 2) with thinning which reduced CBD by almost 74 percent (fig. 3). In the UC plots, the modest 13 percent decrease in average CBD resulted in an inconsequential change in crowning index from 17 to 19 mph. Figure 7 illustrates percent of plots in which sustained crown fire spread is predicted as either active or conditional crown fire under four wind speeds. With 10 mph winds, a modest percentage of pretreatment UC and OT plots, 10 and 30 percent, respectively, would have sufficient CBD to support crown fire spread. With incrementally higher winds, the percentage of pretreatment plots with expected crown fire spread increases rapidly, including 90 percent of the plots or greater in both treatments at 30 to 40 mph winds. Because the UC plots had significantly less CBD reduction than the OT plots, the former continues to support high proportion of crown fire after thinning, with 40 to 100 percent of plots still capable of crown fire spread at wind speeds between 20 and 40 mph. No crown fire spread is predicted in the posttreatment OT plots until 30 mph wind speeds are reached, but 63 percent still have that potential with 40 mph winds.

It should be pointed out that when a fuel reduction treatment is implemented the expected result is an anticipated reduction in fire behavior. Figure 5 shows a predicted increase in surface fire behavior after treatment due to increased fuel loads and mid-flame wind speeds. This seems to be a reasonable tradeoff for the significant reduction in probability of crown fire initiation and spread (fig. 6 and 7), since management options for response to crown fire are greatly limited compared to surface fire.

In their concluding remarks, Scott and Reinhardt (2001) state: “Spatial and temporal variability in the fire environment leads to higher crown fire activity than predicted using average conditions.” The sampling and analysis reported here captures the spatial variability of a portion of the fire environment, specifically, surface and canopy fuel structure, slope, and predicted mid-flame wind speed. Using this spatially variable data provides more detail for predicted fire behavior than that from average values. For example, where crown fire initiation was not predicted from treatment-level values, a certain percentage of plots were predicted to torch based on that smaller scale assessment. This should give managers of the Sheafman Fuels Reduction Project a better appraisal of crown fire probability. It should be noted that the appropriate size of a plot-scale fuels assessment has not been determined, and the plot size used in this analysis is, at this point, only for illustration.

References

Agee, James K.; Skinner, Carl N. 2005. Basic principles of forest fuel reduction treatments. Forest Ecology and Management 211: 83-96.

Albini, F.A.; Baughman, R.G. 1979. Estimating wind speeds for predicting wildland fire behavior. Res. Pap. INT-221. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 12 p.

Arno, S.F.; Smith, H.Y.; Krebs, M.A.1997. Old growth ponderosa pine and western larch stand structures: influences of pre-1900 fires and fire exclusion. Res. Pap. INT-RP-495, Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 20 p.

Arno, Stephen F.; Parsons, David J.; Keane, Robert E. 2000. Mixed-severity fire regimes in the Northern Rocky Mountains: consequences of fire exclusion and options for the future. In: Cole, David N.; McCool, Stephen F.; Borrie, William T.; O'Loughlin, Jennifer, comps. Wilderness science in a time of change conference, Volume 5: Wilderness ecosystems, threats, and management; May 23-27, 1999. Proceedings RMRS-P-15. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 225-232.

Barrett, S.W.; Arno, S.F.; Key, C.H. 1991. Fire regimes of western larch-lodgepole pine forests in Glacier National Park, Montana. Canadian Journal Forestry Research 21:1711-1720.

Bitterroot National Forest. 2001. Sheafman Fuel Reduction Project: Environmental Assessment. On file: Stevensville Ranger District, 88 Main, St., Stevensville, MT. 130 p.

Brown, J.K.; Arno, S.F.; Barrett, S.W.; Menakis, J.P. 1994. Comparing the prescribed natural fire program with presettlement fires in the Selway-Bitterroot Wilderness. Int. Journal of Wild-land Fire 4:157-168.

Cooper, C.F. 1960. Changes in vegetation, structure and growth of southwestern pine forest since white settlement. Ecological Monographs 30: 129-164.

Everett, R.L.; Schellhaas, R.; Keenum, D.; Spurbeck, D.; Ohlson, P. 2000. Fire history in the ponderosa pine/Douglas-fir forests on the east slope of the Washington Cascades. Forest Ecology and Management 129: 207-225.

Fulé, Peter Z.; Covington, W.; and others. 2002. Comparing ecological restoration alternatives: Grand Canyon, Arizona. Forest Ecology and Management 170: 19-41.

Hardy, Colin C. 2005. Wildland fire hazard and risk: Problems, definitions, and context. Forest Ecology and Management 211: 73-82.

GAO. 2003. Additional actions required to better identify and prioritize lands needing fuels reduction. Report to Congressional Requesters GAO-03-805. Washington, DC: United States General Accounting Office.

Lutes, D.C. 2006. FIREMON: fire effects monitoring and inventory system. Gen. Tech. Rep. RMRS-GTR-164-CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Parsons, D.J.; DeBenedetti, S. 1979. Impact of fire suppression on a mixed-conifer forest. Forest Ecology and Management 2:21-33.

Pyne, S.J.; Andrews, P.L.; Laven, R.D. 1996. Introduction to wildland fire. New York: John Wiley and Sons. 769 p.

Raymond, Crystal L.; Peterson, David L. 2005. Fuel treatments alter the effects of wildfire in a mixed-evergreen forest, Oregon. Canadian Jour. Forest Research 35: 2981-2995.

Reinhardt, E.; Lutes, D.; Scott, J. 2006. FuelCalc: A method for estimating fuel characteristics. In: Andrews, P.; Butler, B., comps. 2006. Fuels Management—How to Measure Success: conference proceedings. 28-30 March 2006; Portland, OR. RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 273-282.

Scott, J.H. 1999. NEXUS: a system for assessing crown fire hazard. Fire Management Notes 59(2): 20-24.

Scott, J.H.; Reinhardt, E. 2001. Assessing crown fire potential by linking models of surface and crown fire behavior. Res. Pap. RMRS-RP-29. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 59 p.

Skinner, C.N.; Chang, C. 1996. Fire regimes, past and present. In: Sierra Nevada Ecosystem Project: Final report to Congress, vol. II chap. 38. Davis, CA: University of California, Centers for Water and Wildland Resources.

Stephens, Scott L.; Moghaddas, Jason J. 2005. Experimental fuel treatment impacts on forest structure, potential fire behavior, and predicted tree mortality in a California mixed conifer forest. Forest Ecology and Management 215: 21-36.

USDA, USDI. 2004. Achieving Healthy Forests and Rangelands: National Fire Plan Performance Update 2004. Washington, DC: U.S. Department of Agriculture and U.S. Department of the Interior. http://www.healthyforests.gov/accomplish-report_2004.pdf

Role of Fire in Restoration of a Ponderosa Pine Forest, Washington

Richy J. Harrod[1], Richard W. Fonda[2], and Mara K. McGrath[3]

Abstract—*Ponderosa pine forests in the Eastern Cascades of Washington support dense, overstocked stands in which crown fires are probable, owing to postsettlement sheep grazing, logging, and fire exclusion. In 1991, the Okanogan-Wenatchee National Forests began to apply long-term management techniques to reverse postsettlement changes in ponderosa pine forests. For 9 years, the effects of thinning and burning in a ponderosa pine/pinegrass forest were evaluated, using prescribed fire in fall 1997 in forest stands that had been thinned in 1996. Thinning and burning had little effect on the canopy layer of ponderosa pine, western larch, and Douglas-fir, but small grand fir trees, and nearly half of the saplings of all species, were killed. Shrubs in the middle forest layer were top-killed, but resprouted during the first postfire growing season, and increased dramatically after 3 years and 9 years. Frequency and cover maintained or increased for species in the lower forest layer in postfire years 1, 3, and 9. The thinning and fire treatments reduced the middle layer of small trees and shrubs in the first postfire year, but by the third and ninth postfire years tree seedlings, especially grand fir and ponderosa pine, and small shrubs were abundant in the understory. Thinning trees and removing excess fuels, coupled with low intensity late season prescribed burns, offers a promising management strategy for restoring the presettlement structure of the ponderosa pine/pinegrass community in Beehive Forest.*

Introduction

Historically, ponderosa pine (*Pinus ponderosa*) dominated forests depended on periodic fire to maintain or increase the frequency and density of low-growing plants (Armour and others 1984; Campbell and others 1977; Covington and others 1997; Leege and Hickey 1971; Old 1969; Ruha and others 1996; Tveten and Fonda 1999; Wilson and Shay 1990). In pre1900 fire regimes of the Eastern Cascade Mountains, Washington, ponderosa pine forests supported frequent low intensity fires (Agee 1993; Everett and others 1996, 2000; Weaver 1943, 1951, 1961, 1967). The periodic surface fires in these dry forests maintained an open, parklike structure of expansive, grassy understories and uneven-aged overstories formed by even-aged patches of trees <0.4 ha in area (fig. 1; Harrod and others 1999; Everett and others 1996, 2000). These disturbances resulted in a mosaic of pine stands on the landscape (Everett and others 2000), a pattern that was disrupted only when the patches became senescent or when diseased or insect-infested trees torched (Agee 1994).

The presettlement fire regime in the Eastern Cascades produced pine forests with three layers. Mature pine trees formed the upper layer, the discontinuous canopy of the forest that ranged from 15 to 30 m high (fig. 1). In contrast to forests in wetter regions, dry forests in the Eastern Cascades

In: Butler, Bret W.; Cook, Wayne, comps. 2007. The fire environment—innovations, management, and policy; conference proceedings. 26-30 March 2007; Destin, FL. Proceedings RMRS-P-46CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 662 p. CD-ROM.

[1] Deputy Fire Management Officer, U.S. Department of Agriculture, Forest Service, Okanogan-Wenatchee National Forests, Wenatchee, WA. rharrod@fs.fed.us

[2] Biology Professor Emeritus, Western Washington University, Bellingham, WA.

[3] Botanist, Ecological Services, Inc., Longview, WA.

Figure 1—Ponderosa pine stand on the Okanogan-Wenatchee National Forests in the early 1900s (Forest Service photo). The parklike structure consists of widely spaced trees in the canopy layer, few shrubs in the middle forest layer, and grasses and forbs in the lower forest layer.

had large gaps among the groves of ponderosa pine maintained by periodic fire (Harrod and others 1999; Everett and others 1996). Although mature pines resisted fire, small pines often were killed by fire. Well-maintained pine stands had few saplings (Everett and others 2000). Little information is available on the structure of the middle layer, ~2 to 4 m high. It may have been a fragmentary mix of shrubs, most likely bitterbrush (*Purshia tridentata*), spirea (*Spiraea* spp.), and mountain balm (*Ceanothus velutinus*) (Franklin and Dyrness 1988; Weaver 1951). The mostly continuous lower layer, ~1 to 2 m high, was formed by grasses, forbs, and low-growing shrubs. Pinegrass (*Calamagrostis rubescens*), elk sedge (*Carex geyeri*), Idaho fescue (*Festuca idahoensis*), lupines (*Lupinus* spp.), hawkweeds (*Hieracium* spp.), and roses (*Rosa* spp.) were common members of the lower layer (Franklin and Dyrness 1988; Weaver 1951).

Fire suppression in ponderosa pine forests in the Okanogan-Wenatchee National Forests (OWNF) began about 1910, and in the intervening years the fire regime changed from frequent, low intensity surface fires to infrequent, high intensity crown fires (Everett and others 1996, 2000). For example, two fires in OWNF, the Dinkleman fire in 1988 (22,275 ha) and the Tyee fire in 1994 (56,700 ha), burned with greater intensity and covered more area than they would have under presettlement fire regimes (Everett and others 1996, 2000). After nearly a century of fire exclusion, the forests now are ~10 to 12 fire-free intervals removed from historical conditions (Everett and others 2000), forest composition has shifted away from fire resisters and endurers (Agee 1993; Fonda and others 1998; Fonda 2001; Rowe 1983), and forest structure has shifted toward denser stocking of smaller understory trees in a dense, multicanopy arrangement (Everett and others 1996; Weaver 1961, 1967). Fire exclusion has had two consequences: (1) a continuous middle forest layer was created in an otherwise open forest by invading, drought sensitive trees (Everett and others 1996), which (2) died a decade or two after germination, adding to the total fuel loadings (Harrod and others 1999).

Weaver (1943, 1951, 1961, 1967) advocated management fires in these dry forests to reverse the changes in forest structure and composition. Using fire to reduce density of overstory species, however, presents challenges that must be managed carefully during the burn (Kilgore and Curtis 1987). Many ponderosa pine stands in the Cascades have dense canopies and continuous ladder fuels, so that torching of trees, spotting, and crown fires are possible. Thus, in today's forests prescribed surface fires might erupt into devastating crown fires (Everett and others 1996), unless the middle layer saplings and high density overstories are thinned to lower crown bulk density and remove ladder and dead woody fuels. Prefire management tactics that thin small trees to remove ladder fuels to the canopy and reduce fire intensity have come to be viewed as necessary in burning programs to restore presettlement forest structure (Agee 1991, 1996; Covington and others 1997; Scott 1998; Swezy and Fiedler 1996).

In 1991, the Leavenworth Ranger District of OWNF formed an interdisciplinary team to apply management techniques to dry forest stand to reverse postsettlement changes. The decision to thin and burn 865 ha in the Beehive Reservoir area was signed in December 1993. This project had six objectives: (1) improve forest health and develop stands of timber tolerant of disease, insect attack, drought, and wildfire; (2) develop/maintain park-like stands of ponderosa pine on slopes north of Beehive Reservoir; (3) maintain natural fire-dependent plant communities; (4) maintain/improve the health of large mature trees; (5) promote the development of wildlife habitats that require larger tree structure; and (6) use excess trees. The data in this study were gathered in conjunction with this forest management project, specifically objectives 2 and 3. In sum, the project was designed to rehabilitate and mitigate past disturbances that included sheep grazing from the 1880s to 1940, extensive logging in the 1920s and 1930s, and fire exclusion that became effective in the 1930s (Harrod and others 1999). The objectives above were expected to be achieved over a long period of forest management to restore forest structure to approximate the historical low intensity, low severity fire regimes described in many papers (Agee 1993; Everett and others 1996, 2000; Harrod and others 1999; Weaver 1943, 1951, 1961, 1967).

The first stages in the sequence to reach the desired future condition of the forest north of the Beehive Reservoir began with thinning in 1996. Our research began in September 1997 with the objective of assessing the first stages of the project. We wanted to know if a combination of thinning and burning could shift community structure toward parklike stands while maintaining composition of native species.

Materials and Methods

Study Site

The study site for this research was located in OWNF, 13 km southwest of Wenatchee, Washington, near Beehive Reservoir, in a ponderosa pine/pinegrass community that we call Beehive Forest for convenience (fig. 2). The overstory was dominated by large diameter ponderosa pine with clumps of small diameter Douglas-fir and grand fir. Western larch saplings were scattered throughout. The understory was dominated by grasses and forbs, namely pinegrass and broadleaf lupine (*Lupinus latifolius*). Bitterbrush, Scouler willow (*Salix scouleriana*), bittercherry (*Prunus emarginata*), and oceanspray (*Holodiscus discolor*) were important shrubs in the matrix of herbaceous species. The study site has a northeast aspect and gentle topography with 7° slopes. The site averages 590 mm of precipitation annually, with most falling as winter snow (Franklin and Dyrness 1988). Snow cover accumulates up to 3 m. Cumulative summer rain averages 44 mm, mostly from thunderstorms. Diurnal air temperatures fluctuate by more than 20 °C in the summer. Beehive Forest and the surrounding area (fig. 2) are part of the Wenatchee formation, which was created by fluvial and lacustrine processes in the lower Oligocene (Glesens and others 1981). Soils are Andisols (Meurisse and others 1991), and are derived from shale, siltstone, and sandstone (Glesens and others 1981).

Forest Restoration

This study comprised burned and unburned treatments. Before the fire, all stands were treated to approximate historical stand structure and composition as described in the management plan. Stands were thinned in a range of size classes, but the treatment focused on the understory to reduce density and vertical fuel structure. Litter was raked from the bases of large trees, lower branches were pruned to remove ladder fuels, and logging slash was scattered. Mechanical harvesting units were used to thin trees more than ~1 m of snow, which prevented damage to understory plants and soil. Stands in the unburned treatments had been unburned for >20 years. After thinning, the stands fit fire behavior fuel model SB1, in which spread rate is moderate and flame length low (Scott and Burgan 2005). We selected a 14-ha unit in the thinned part of Beehive Forest for the unburned treatment.

The prescribed burn was intended to enhance the growth of large, fire-resistant trees, kill ~95 percent of all saplings <10 cm dbh, improve the vigor of grasses and forbs, and reduce surface fuel loadings. Fifteen ha of Beehive Forest, comprising the burn treatment, were underburned on 22 September 1997. The prescribed burn was a relatively low intensity surface fire with flame lengths generally <1.5 m. Approximately 80 percent of the area burned was blackened, and ~25 percent of the area consisted of white ash, suggesting higher burn intensity and complete litter consumption.

Vegetation Sampling

Postfire data for trees in the upper and middle forest layers, and taller shrub species in the middle forest layer, were gathered on six 20 x 50 m macroplots in each treatment. Two lines parallel to the 50-m side of the macroplot were located at the 5 m and 15 m marks on the 20-m side. Data on species in the lower forest layer were gathered on 20 1 x 1 m microplots placed every 5 m along these two 50-m lines. Data were gathered on the unburned plots in

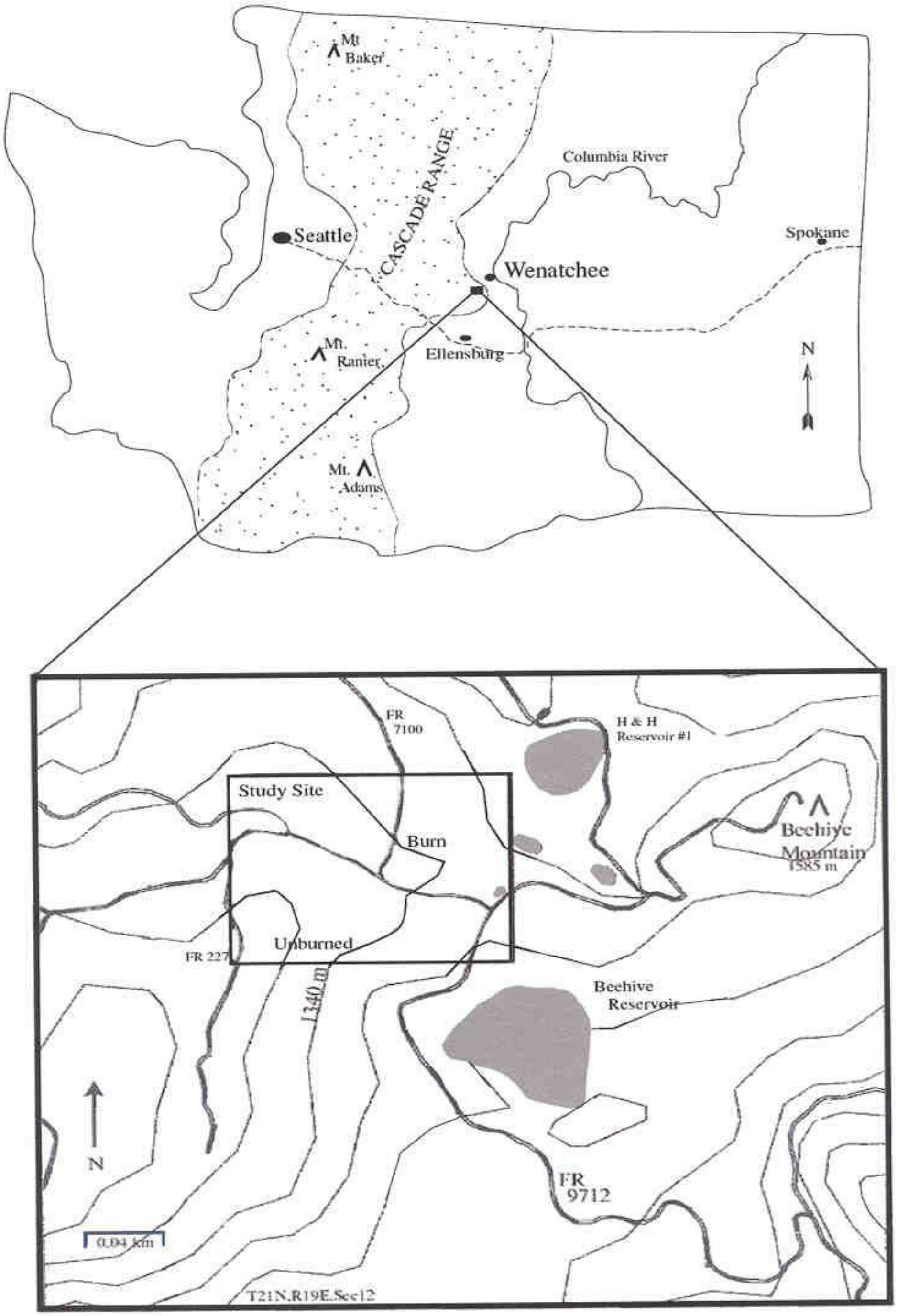


Figure 2—Location of the study site, ~13 km southwest of Wenatchee, WA. The area north of the Beehive Reservoir was thinned in 1996, and the burn treatment was applied in 1997.

summer 1998, and on the burned plots in summer 1997 (preburn), 1998 (burn +1), 2001 (burn +3), and 2006 (burn +9). The unburned plots were burned in October 1998, and thus were unavailable afterwards.

Density, basal area, and fire response (alive or dead) were recorded in 1998, 2001, and 2006 for all tree species >2 cm dbh on the macroplots. All tree seedlings were tallied on the macroplot. Crown scorch volume (CSV), the best indicator of postfire survivability/mortality (Peterson 1985, Wyant and others 1986, Ryan and Reinhardt 1988), was scored for each tree in 1998 using scorch classes: <1 percent, 1-5 percent, 6-25 percent, 26-50 percent, 51-75 percent, 76-99 percent, 100 percent. Mean CSV was calculated using midranges of each scorch class. Scorch evidence was gone by 2001.

Density of taller shrubs in the middle layer was recorded on the microplots. Fire response of the taller shrubs (alive/unharmed; top-killed/resprouted; or, dead) was tallied in 1998 on the macroplots. Because the trees and taller shrubs are woody, prefire density was easily reconstructed. We knew that all woody plants were alive before the fire, thus skeletons of dead and top-killed plants were created by fire.

Percent frequency and cover of herbaceous species were recorded on the microplots. Cover was scored to the nearest 1 percent for each species. Postfire data for herbaceous species were compared to the unburned plots because no prefire data were collected for herbaceous species on the burned plots. We judged fire responses according to the same frequency categories used by Tveten and Fonda (1999). Species whose frequency changed by <10 percentage points, compared to the unburned treatment, were maintainers. Those whose frequency changed by >10 percentage points, compared to the unburned treatment, were increasers or decreasers.

Four hawkweed species were present in the study site and could not be distinguished when young; their data were combined and reported as hawkweed spp. Likewise, the data for taxonomically and ecologically similar bristly Nootka rose (*Rosa nutkana* var. *hispida*) and baldhip rose (*R. gymnocarpa*) were combined and reported as rose spp. Botanical nomenclature follows Hitchcock and Cronquist (1973). Voucher specimens are deposited in the Biology Department Herbarium (WWB), Western Washington University.

Data Analysis

This research was designed as a Randomized Complete Block ANOVA, with the significance level set at 0.05 before the research began. The years relative to fire constituted the treatments in the analysis: 1997 (preburn), 1998 (burn +1), 2001 (burn +3), and 2006 (burn +9). The six macroplots constituted the blocks. Because the postfire treatments were defined by a numerical component (+1, +3, +9), the data also could be analyzed by Linear Regression to identify possible functional relationships among the data with time since fire. We used ANOVA and Linear Regression to analysis relationships among percent cover in the lower layer, shrub and seedling density in the middle layer, and tree density and basal area in the tree layer.

Results

Overstory Response

Ponderosa pine was well represented on the burned plots in all prefire and postfire diameter classes, with the most young and mature trees of any species (fig. 3). Mean height of the canopy layer was 20 m. Douglas-fir, western larch, and grand fir were absent from diameter classes >40 cm. Douglas-fir was concentrated in the 11 to 40 cm diameter classes preburn and burn +1 year, but more trees were present in the <4-10 cm diameter classes after burn +3 and burn +9 years. Western larch was concentrated in the 11 to 40 cm diameter classes in all years. Grand fir had fewer trees in the smallest diameter classes after burn +1, but had a substantial increase in <4 cm trees

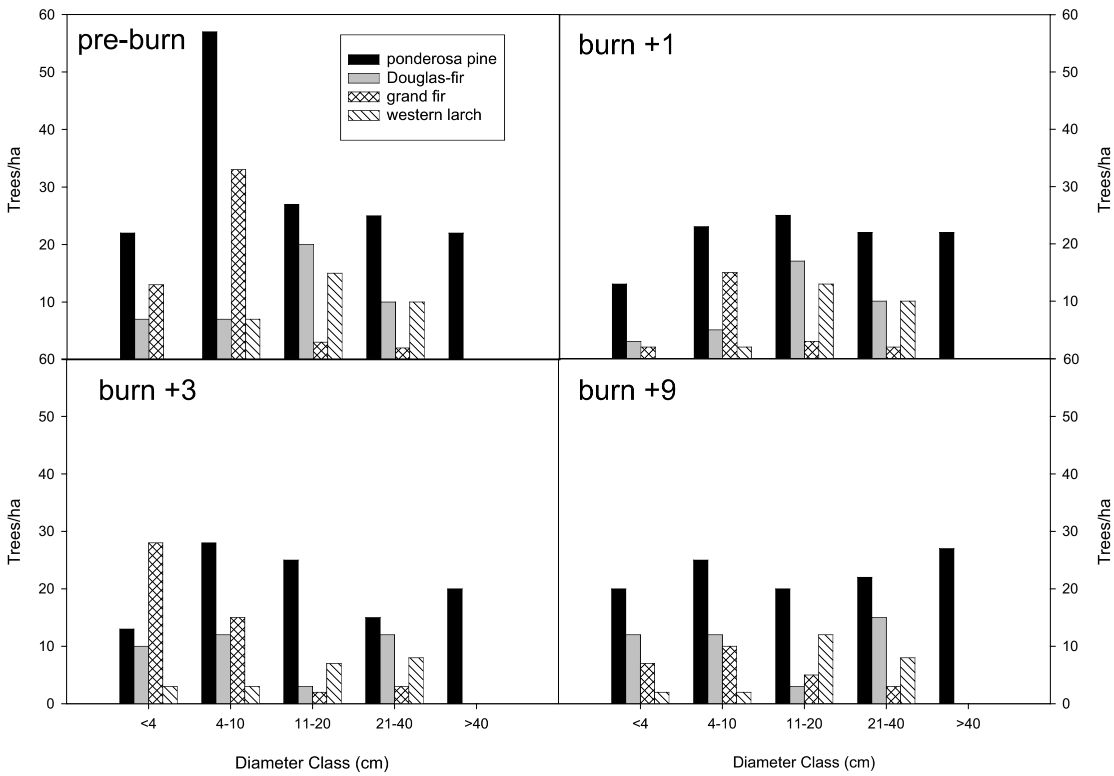


Figure 3—Prefire and postfire mean diameter distribution (trees/ha) for trees >2 cm dbh.

after burn +3. However, these trees were not maintained into burn +9 years. Few trees >11 cm of any species were killed by fire (fig. 3), but the smaller trees in the middle layer were most affected. Young trees of all species in the <4 cm diameter class were reduced by 43 percent by the fire.

Fire had little effect on density and basal area for total trees (table 1). The small trees killed by fire resulted in lower density, but these differences were not significant for any species across years. In addition, there were no significant differences among species for any postfire year, except in burn +9 year ponderosa pine was significantly greater than any other species (table 1). Ponderosa pine clearly dominated the canopy layer with significantly greater

Table 1—Mean tree density (trees/ha) and mean basal area (m^2/ha) at Beehive Forest, from 1997 (preburn), 1998 (burn +1), 2001 (burn +3), to 2006 (burn +9). No significant differences for a species across years for density and basal area and only ponderosa pine significantly different in burn +9 (in bold) when comparing species density.

	Preburn	Burn +1	Burn +3	Burn +9
Density				
Ponderosa pine	153	105	101	**114**
Grand fir	51	22	48	25
Douglas-fir	44	35	37	42
Western larch	32	25	21	24
Total	280	187	207	205
Basal area				
Ponderosa pine	7.84	7.60	8.05	8.73
Grand fir	0.26	0.22	0.06	0.09
Douglas-fir	1.06	1.00	0.64	1.25
Western larch	1.01	0.96	0.69	0.92
Total	10.17	9.78	9.44	10.99

basal area in each of the treatment years compared to grand fir, Douglas-fir, and western larch (table 1). Grand fir, Doulgas-fir, and western larch were not significantly different from each other in the preburn year or any postfire year. Basal area for a given species was not significantly different across the treatment years.

Trees <4 m had generally greater CSV than trees >4 m (table 2). Grand fir had greater CSV than any other tree species, and the differences among the larger ponderosa pine, Douglas-fir, and western larch were trivial.

Table 2—Postfire mean crown scorch volume (CSV) for all trees >2 cm dbh on the burned plots. Species are listed by order of increasing CSV in the >4 m tall category.

Species	>4 m tall	<4 m tall
Ponderosa pine	21	72
Western larch	23	1
Douglas-fir	45	53
Grand fir	80	86

Middle Layer Response

The most dramatic change in community structure was represented by new tree seedlings (<4 cm dbh) in burn +3 and burn +9 years (table 3). In 1998, two ponderosa pine seedlings (= 3/ha) were tallied postfire on the six macroplots in the burned treatment. No other species had individuals <2 cm dbh. By burn +3 years, seedlings of five species were present on the burned plots, with grand fir and ponderosa pine the most abundant, followed by Douglas-fir and western larch. After burn +9 years, ponderosa pine and Douglas-fir seedling density was not significantly different from burn +3 years, nor was there a significant change over time (table 3). Grand fir and western larch seedlings were not significantly different among sample years, but the increase over time was significant (regression coefficient for grand fir was b= 7.53 (that is, an increase of 7.53 seedlings per ha per year), and for larch b= 1.56).

Table 3—Composition of the middle layer, and changes by tree seedling and shrub density (per hectare) after fire. Means with the same superscript are not significantly different, by species.

Species	Postfire year 1	Postfire year 3	Postfire year 9	Regression relationship with time
Tree seedlings				
Ponderosa pine	3	410[a]	372[a]	Not significant
Douglas-fir	0	190[a]	125[a]	Not significant
Grand fir	0[a]	538[a]	713[a]	Significant
Western larch	0[a]	118[a]	150[a]	Significant
Total seedling density	3	1,256	1360	
Shrubs				
Shiny-leaf spirea	2,530[a]	870[a]	9982[a]	Not significant
Moutain balm	0	48[a]	57[a]	Significant
Oceanspray	15[a]	337[a]	238[a]	Not significant
Scouler willow	55[a]	63[a]	73[a]	Not significant
Bitterbrush	100[a]	87[a]	100[a]	Not significant
Serviceberry	0[a]	30[a]	48[a]	Not significant
Squaw currant	0[a]	7[a]	3[a]	Not significant
Total shrub density	615	617	10,501	

Shiny-leaf spiraea was the most abundant shrub species in the middle layer in all three postfire years (table 3). However, only moutain balm significantly increased density over time; postfire years +3 and +9 were significantly greater than the first postfire year. Other abundant postfire shrubs were oceanspray, Scouler willow, and bitterbrush, all of which readily resprouted in the first year postfire (78, 100, and 64 percent resprouted, respectively). Fewer than 14 percent of shrub individuals were killed on the burned plots, so shrub species were consider important endurers or maintainers.

Lower Layer Response

Although postfire responses of the lower forest layer components were pronounced on burned plots, the postfire community structure and composition did not change substantially compared to the unburned plots. Based on changes in frequency, most of these species responded as maintainers or increasers in an intact lower layer after burn +1, burn +3, and burn +9 years (table 4). Mean cover of each species was not significantly different among the unburned site and any postfire year. In fact, nearly all grasses, forbs, and shrubs were endurers. The understory dominant and fire maintainer, pinegrass, was uniformly distributed and had the highest cover of any understory species (table 4). One of the latest flowering understory species, pinegrass had abundant, tall flower stalks after burn +1 in August.

Broadleaf lupine was a uniformly distributed, dominant species and fire maintainer, but it had about half of the cover of pinegrass (table 4). Lupine flowered in early summer and set seed by mid-July. It was completely senesced by August when pinegrass became prominent. The remaining maintainers, with low frequency and cover, were structurally unimportant (table 4).

Table 4—Unburned and postfire percent frequency and mean percent cover of grasses, forbs, and shrubs in the lower forest layer. Species listed have at least 1 percent cover in one treatment. Mean cover for each species did not differ significantly among the four treatments.

	Frequency				Cover			
	Unburned	**Burn +1**	**Burn +3**	**Burn +9**	**Unburned**	**Burn +1**	**Burn +3**	**Burn +9**
Maintainers in all postfire years								
Pinegrass	86	81	84	84	23.3	23.3	26.8	20.7
Broadleaf lupine	82	75	75	73	12.1	13.8	14.4	8.4
Hawkweed spp.	43	41	53	38	3.8	1.4	3.0	1.7
Sharptooth angelica	13	16	6	12	0.6	<0.1	0.4	0.4
Yellow penstemon	12	15	10	16	0.9	1.0	0.6	0.8
Increaser by burn +9								
Kinnikinnick	26	21	31	37	8.1	3.8	7.0	10.3
Decreaser in burn +1 and burn +3, maintainer by burn +9								
Elk sedge	68	45	50	67	8.7	6.2	3.4	8.2
Decreasers by burn +9								
American vetch	26	28	20	10	3.0	2.8	1.0	0.1
Northwest sedge	18	28	13	1	2.5	1.5	0.3	0.2
Increaser in burn +1 and burn +9								
Heart-leaf arnica	22	37	18	33	2.3	4.1	0.9	1.0
Increaser in burn +1 and burn +3, decreaser by burn +9								
Fireweed	12	34	28	0	1.5	2.5	1.7	0
Increasers in burn +3								
Yarrow	53	58	68	63	5.2	3.9	3.2	1.9
Idaho fescue	9	14	27	3	0.6	1.5	1.5	0.2
Decreaser in burn +1 and burn +9								
Rose spp.	49	38	42	33	5.6	5.1	3.8	1.8

American vetch (*Vicia americana*) and northwest sedge (*Carex concinnoides*) were decreasers by burn +9 and contagiously distributed (Whittaker 1975) within the pinegrass-lupine matrix (table 4).

There were five increasers (table 4). Kinnikinnick (*Arctostaphylos uva-ursi*) commonly formed extensive mats, which contributed strongly to sustaining fire on the burned plots. Heart-leaf arnica (*Arnica cordifolia*) was an increaser after burn +1 and burn +9 years. Fireweed (*Epilobium angustifolium*) was an increaser in the first two postfire year measurements, but disappeared by burn +9. Yarrow (*Achillea millefolium*) and Idaho fescue were increasers into the third postfire year. They were prominent in late summer, often in flower with pinegrass.

Rose spp. response was variable over time, but were decreasers in burn +1 and burn +9 years. Elk sedge was a consistent decreaser in burn +1 and burn +3 years and cover for this species was less than 50 percent of the unburned cover. However, elk sedge was a maintainer by burn +9.

Discussion

The forest structure achieved by thinning and burning suggests that Beehive Forest approached the conditions established by the management objectives in the first postfire year. The data for postfire shrubs, however, indicate that more time and treatments will be needed before the forest reaches the structure depicted in figure 1. Few plants in Beehive Forest were completely killed by fire, and species composition, comprising maintainers and a few increasers, were stable after burning. This is a similar finding to thinning and burning treatments in ponderosa pine-Douglas-fir in northeastern Oregon, where understory vegetation was largely unchanged (Metlen and others 2004). As in the northeastern Oregon study, individual species response at Beehive to thinning and burning treatments was consistent their life history characteristics. Most grasses, forbs, and shrubs were endurers that maintained the low forest layer through rapid resprouting and postfire growth. Resisters and endurers commonly are maintainers, occasionally increasers, whose frequency or density does not change substantially after fire. The postfire responses of plant species in Beehive Forest were similar also to species on Fort Lewis, WA, where dominant species in fire-maintained Idaho fescue prairies and Garry oak (*Quercus garryana*) woodlands were maintainers whose frequency changed by <10 percentage points from prefire conditions (Tveten and Fonda 1999). Few native species on Fort Lewis or in Beehive Forest were increasers or decreasers.

Prefire thinning and burning initially opened the middle layer in Beehive Forest, primarily by top-killing at least 50 percent of taller shrubs and secondarily by killing sapling trees. About 13 percent of individual shrubs were killed by fire; all survivors were endurers that resprouted <6 weeks after the fire. Densities of smaller ponderosa pine and Douglas-fir, and grand fir of all sizes, in the middle layer were reduced by fire in the first postfire growing season. The current forest structure now fits fire behavior fuel model 2, in which low intensity surface fires are carried through fine herbaceous fuels (Anderson 1982). Developing and maintaining parklike stands by changing the structure of this middle layer with a combination of thinning and burning was a management objective. Third and ninth year data on tree seedlings and shrubs indicate that community structure has shifted only slightly toward parklike stands while maintaining native species on the site. The low percentage of total killed seedlings and shrubs indicates that more thinning and fire will be needed before the goal is achieved.

The canopy layer remained intact on the burn site. Mature ponderosa pine, western larch, and Douglas-fir were resisters. Mature Douglas-fir in the canopy layer resisted the direct effects of fire. If the desired forest structure requires lower Douglas-fir density, future management efforts may focus on mechanical thinning of Douglas-fir, rather than low intensity fires, to achieve that structure.

Prescribed fire objectives usually define acceptable values for overstory mortality. Because CSV of >80 percent invariably indicates mortality in conifers (Ryan and Reinhardt 1988), many burn programs use low intensity surface fires to avoid burning the canopy. For instance, mean flame lengths in a thinned stand of ponderosa pine in Arizona were ~15 cm, with occasional flareups to ~64 cm (Covington and others 1997), compared to 1 to 2 m flame lengths for Beehive Forest. The fires in Beehive Forest did involve the canopy, with good results. Mean CSV for grand fir (avoider) exceeded 80 percent, whereas ponderosa pine (resister) was <80 percent (table 2). Furthermore, successive fires enhance the resister strategy of ponderosa pine by raising the height to live crown, thereby reducing potential CSV and postfire tree mortality in the future.

Conclusions

The treatments in Beehive Forest have started the process to restore forests of widely spaced groves of large ponderosa pine trees with scattered western larch and Douglas-fir, a grassy understory with sporadic clumps of young trees, and light surface fuel loadings (Agee 1993; Everett and others 1996, 2000; Harrod and others 1999; Weaver 1951). Ponderosa pine forests in the Cascades have missed 10 to 12 fire episodes (Everett and others 1996, 2000), and one thinning and burning treatment will not restore presettlement conditions. The restoration process has started in Beehive Forests, and no counterindications exist that suggest management objectives cannot be achieved. Prescribed burning alone fails to restore ponderosa pine forests to presettlement conditions, since forest structure has changed so drastically with fire exclusion (Agee 1996; Covington and others 1997; Everett and others 1996, 2000; Fiedler 1996; Harrod and others 1999; Scott 1998; Swezy and Agee 1991). Consequently, thinning trees and removing excess fuels, coupled with low intensity late season prescribed burns, offers a promising management strategy for restoring the presettlement structure of the ponderosa pine/pinegrass community in Beehive Forest.

Acknowlegments

Josie Melton, James Dickinson, and Pete Ohlson assisted with the field work, and Jeannie Gilbert created figure 2. We thank the Wenatchee River Ranger District, Okanogan-Wenatchee National Forests, for implementing both the prescribed burning and thinning treatments. Funding was provided by the USDA Forest Service, Okanogan-Wenatchee National Forests.

References

Agee, J.K. 1993. Fire ecology of Pacific Northwest Forests. Covelo, CA: Island Press. 493 p.

Agee, J.K. 1994. Fire and weather disturbances in terrestrial ecosystems of the Eastern Cascades. Gen. Tech. Rep. PNW-GTR-320. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 52 p.

Agee, J.K. 1996. Achieving conservation biology objectives with fire in the Pacific Northwest. Weed Technology 10:417-421.

Anderson, H.E. 1982. Aids to determining fuel models for estimating fire behavior. Gen. Tech. Rep. INT-122. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 22 p.

Armour, C.D.; Bunting, S.C.; Neuenschwander, L.F. 1984. Fire intensity effects on the understory in ponderosa pine forests. Journal of Range Management 37:44-49.

Campbell, R.E.; Baker, M.B.; Ffolliott, P.F.; Larson, F.R.; Avery, C.C. 1977. Wildfire effects on a ponderosa pine ecosystem: an Arizona case study. Res. Pap. RM-191. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 12 p.

Covington, W.W.; Zule, P.Z.; Moore, M.M.; Hart, S.C.; Kolb, T.E.; Mast, J.N.; Sackett, S.S.; Wagner, M.R. 1997. Restoring ecosystem health in ponderosa pine forests of the southwest. Journal of Forestry 95:23-29.

Everett, R.L.; Schelhaas, R.; Anderson, T.A.; Lehmkuhl, J.F.; Camp, A.E. 1996. Restoration of ecosystem integrity and land use allocation objectives in altered watersheds. In: Proceedings on Watershed Restoration Management. Middleburg, VA: American Water Resources Association: 271-280. (McDonnel, J.J.; Stribling, J.B.; Neville, L.R.; Leopold, D.J., eds).

Everett, R.L.; Schelhaas, R.; Keenum, D.; Spurbeck, D.; Ohlson, P. 2000. Fire history in the ponderosa pine/Douglas-fir forests on the east slope of the Washington Cascades. Forest Ecology and Management 129:207-225.

Fiedler, C.E. 1996. Silvicultural applications: restoring ecological structure and process in ponderosa pine forests. In: The use of fire in forest restoration. Gen. Tech. Rep. INT-GTR-341. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station: 34-40. (Hardy, C.C.; Arno, S.F., editors).

Fonda, R.W. 2001. Burning characteristics of needles from eight pine species. Forest Science 47:390-396.

Fonda, R.W.; Belanger, L.A.; Burley, L.L. 1998. Burning characteristics of western conifer needles. Northwest Science 72:1-9.

Franklin, J.F.; Dyrness, C.T. 1988. Natural Vegetation of Oregon and Washington. Corvallis, OR: Oregon State University Press. 452 p.

Glesens, R.L.; Naeser, C.W.; Whetten, J.T. 1981. Stratigraphy and age of the Chumstick and Wenatchee Formations: tertiary fluvial and lacustrine rocks, Chiwakum graben, Washington: summary. Geological Society of America Bulletin 92:233-236.

Harrod, R.J.; McRae, B.H.; Hartl, W.E. 1999. Historical stand reconstruction in ponderosa pine forests to guide silvicultural prescriptions. Forest Ecology and Management 114:433-446.

Hitchcock, C.L.; Cronquist, A. 1973. Flora of the Pacific Northwest. Seattle, WA: University of Washington Press. 730 p.

Kilgore, B.M.; Curtis, G.A. 1987. Guide to understory burning in ponderosa pine-larch-fir forests in the Intermountain West. Gen. Tech. Rep. INT-233. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 39 p.

Leege, T.A.; Hickey, W.O. 1971. Sprouting of northern Idaho shrubs after prescribed burning. Journal of Wildlife Management 35:508-515.

Metlen, K.L.; Fiedler, C.E.; Youngblood, A. 2004. Understory response to fuel reduction treatments in the Blue Mountains of northeastern Oregon. Northwest Science 78: 175-185.

Meurisse, R.T.; Robbie, W.A.; Niehoff, J.; Ford, G. 1991. Dominant processes and properties in western-montane forest types and landscapes - some implications for productivity and management. In: Proceedings of the Symposium on Management and Productivity of western-montane forest soils. Gen. Tech. Rep. INT-280. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station: 7-19. (Harvey, A.E.; Neuenschwander, L.F., comps).

Old, S.M. 1969. Microclimate, fire, and plant production in an Illinois prairie. Ecological Monographs 39:335-384.

Peterson, D.L. 1985. Crown scorch volume and scorch height: estimates of postfire tree condition. Canadian Journal of Forest Research 15:596-598.

Rowe, J.S. 1983. Concepts of fire effects on plant individuals and species. In: The Role of Fire in Northern Circumpolar Ecosystems. New York, NY: John Wiley & Sons:135-154. (Wein, R.W.; MacLean, D.A., eds).

Ruha, T.L.; Landsberg, J.D.; Martin, R.E. 1996. Influence of fire on understory shrub vegetation in ponderosa pine stands. In: Proceedings of the Symposium on Shrubland ecosystem dynamics in a changing environment. Gen. Tech. Rep. INT-GTR-338. Odgen, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station: 108-113. (Barrow, J.R.; McArthur, E.D.; Sosebee, R. E.; Tausch, R. J., comps).

Ryan, K.C.; Reinhardt, E.D. 1988. Predicting postfire mortality of seven western conifers. Canadian Journal of Forest Research 18:1291-1297.

Scott, J.H. 1998. Fuel reduction in residential and scenic forests: a comparison of three treatments in a western Montana ponderosa pine stand. Res. Pap.-RMRS-RP-5. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 19 p.

Scott, J.H.; Burgan, R.E. 2005. Standard fire behavior fuel models: a comprehensive set for use with Rothermel's surface fire spread model. Gen. Tech. Rep. RMRS GTR-153. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 72 p.

Swezy, D.M.; Agee, J.K. 1991. Prescribed fire effects on fine-root and tree mortality in old growth ponderosa pine. Canadian Journal of Forest Research 21:626-634.

Tveten, R.K.; Fonda, R.W. 1999. Fire effects on prairies and oak woodlands on Fort Lewis, Washington. Northwest Science 73:145-158.

Weaver, H. 1943. Fire as an ecological and silvicultural factor in the ponderosa pine region of the Pacific slope. Journal of Forestry 41:7-15.

Weaver, H. 1951. Observed effects of prescribed burning on perennial grasses in the ponderosa pine forests. Journal of Forestry 49:267-271.

Weaver, H. 1961. Ecological changes in the ponderosa pine forest of Cedar Valley in southern Washington. Ecology 42:416-420.

Weaver, H. 1967. Fire as a continuing ecological factor in perpetuation of ponderosa pine forests. Advancing Frontier of Plant Sciences 18:137-153.

Whittaker, R.H. 1975. Communities and Ecosystems. New York, NY: MacMillan Publishing Company. 387 p.

Wilson, S.D.; Shay, J.M. 1990. Competition, fire, and nutrients in a mixed-grass prairie. Ecology 71:1959-1967.

Wyant, J.G.; Omi, P.N.; Laven, R.D. 1986. Fire induced tree mortality in a Colorado ponderosa pine/Douglas-fir stand. Forest Science 32:49-59.

This page is blank on purpose

Comparing the Effectiveness of Thinning and Prescribed Fire for Modifying Structure in Dry Coniferous Forests

Richy J. Harrod[1], **Nicholas A. Povak**[2], **and David W. Peterson**[2]

Abstract—*Forest thinning and prescribed fires are the main practices used by managers to address concerns over ecosystem degradation and severe wildland fire potential in dry forests of the Western United States. There is some debate, however, about treatment effectiveness in meeting management objectives as well as their ecological consequences. This study assesses the effectiveness of thinning and prescribed fire treatments, alone and combined, for modifying forest structure and potential fire behavior in the Eastern Cascade Mountains of Washington State. Treatments were applied to 12 management units (~10 ha each), with each treatment combination replicated three times (including untreated controls). Thinning modified forest structure by reducing overall tree stocking and canopy fuels to ≤50 percent of pretreatment values. Furthermore, thinning greatly reduced the modeled probability of severe wildfire and reduced stand densities to below critical levels for insect outbreaks. The prescribed fire treatment, conversely, did not appreciably reduce stocking levels or canopy fuel loadings, but was effective for raising canopy height and increasing the density of standing dead trees. Prescribed fire effects were more pronounced when used in combination with thinning. While thinning was a more reliable method for altering stand structure, the spring burns conducted in the experiment were cooler and spottier than were desired and may have led to results that downplay the efficacy of fire to meet forest restoration goals.*

Introduction

Structure is an important ecological aspect of dry, coniferous forests. Dry forests throughout the Interior West have increasingly become dense, closed-canopy stands of mostly small, fire-intolerant trees as compared to the more open, fire-tolerant, large-tree dominated stands of the past (Agee 1994; Covington and Moore 1994; Everett and others 2000; Harrod and others 1999). Dense overstories with continuous ladder fuels lead to high probabilities of torching and crown fires (Peterson and others 2005; Scott 1998; Scott and Reinhardt 2001) and increased vulnerability to many insects and diseases (Hessburg and others 2005). Understory diversity, composition, and abundance have been altered due to these modified structural conditions (Covington and others 1997; Hall 1977; Smith and Arno 1999). Wildlife are also affected as many dry forest species, such as the white-headed and hairy woodpeckers, lack suitable habitat (Gaines and others 2007). In general, changes in structure and composition have lead to an overall deterioration in forest ecosystem integrity and an increased probability of large, high-severity wildfires throughout the West (Dahms and Geils 1997; Patton-Mallory 1997; Stephens 1998; Weatherspoon and Skinner 1996).

In: Butler, Bret W.; Cook, Wayne, comps. 2007. The fire environment—innovations, management, and policy; conference proceedings. 26-30 March 2007; Destin, FL. Proceedings RMRS-P-46CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 662 p. CD-ROM.

[1] Deputy Fire Management Officer, U.S. Department of Agriculture, Forest Service, Okanogan-Wenatchee National Forests, Wenatchee, WA. rharrod@fs.fed.us

[2] Biological Science Technician and Research Forester, respectively, U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Wenatchee Forestry Sciences Laboratory, Wenatchee, WA.

The structure and composition of today's forests have been created by disturbance regimes that are very different from those of the past. Prior to Euro-American settlement, fire regimes characterized by high-frequency, low-severity fire promoted open structure with large trees, particularly ponderosa pine (*Pinus ponderosa*; Agee 1998; Hessburg and others 2005). Fire burned every 6 to 7 years in the Eastern Cascade Mountains (Everett and others 2000), acting as a natural thinning agent that selectively removed small trees while causing minimal overstory mortality (<20 percent of basal area; Agee 1990, 1993). Trees often grew in clumps, creating numerous canopy gaps. Canopy layering was minimal as shade-tolerant but fire intolerant species such as grand fir (*Abies grandis*) were limited by frequent fires (Harrod and others 1999; Hessburg and others 2005). Fire regimes were altered during the past century, however, by active fire suppression, land-use changes, and removal of fine fuels through heavy grazing by sheep and cattle (Agee 1994). In the absence of fire, dense forests developed, creating intense competition for light and water, greater tree mortality and increased hazards of severe wildfires. Past logging practices further altered forest structure and fire resistance by removing large, fire-resistant trees and promoting prolific regeneration of small trees (Habeck 1990). These changes are of great concern to forest managers because extensive crown fires have threatened lives and property, and fire suppression activities have proven to be costly. This paper focuses on forest restoration treatment options that modify forest structure, and their effectiveness in reducing crown fire hazard.

Forest restoration opportunities are constrained by available methods. Thinning and prescribed fire used alone or in combination are options available for modifying forest structure and reducing potential for severe wildland fire. However, there is disagreement about the appropriate balance among mechanical treatments and prescribed fire (Stephens 1998; van Wagtendonk 1996; Weatherspoon 1996) and whether or not the treatments can meet restoration objectives (Brown and others 2004). Thinning allows for control over species selection and size classes of material removed or retained. However, thinning can be problematic if the value of the wood removed does not offset treatment costs; if slash significantly increases surface fuel loads (Pollet and Omi 2002; McIver and Ottmar 2007); or if activities are limited by road access, slope steepness, or sensitive soils. Prescribed fire can be used to reduce surface and some ladder fuels and is less limited by road access, but does not allow for much control over species and size class selection and may produce secondary fire effects, such as bark beetle mortality (Ganz and others 2003; McHugh and others 2003). Prescribed fire may also kill large trees that are intended to be retained after treatment (Agee 2003). Thinning and prescribed fire may complement each other when used in combination, although empirical data are still lacking (Weatherspoon and Skinner 2002). Further, the added costs associated with completing both treatments may not be warranted if management objectives can be met with a single treatment.

The purpose of our study was to assess the effectiveness of thinning and prescribed fire alone and in combination for modifying overstory structure in dry forests with the purpose of restoring a low-severity fire regime. Data were collected from the Mission Creek Fire and Fire Surrogates site, which is part of a network of sites throughout the United States (Weatherspoon 2000), in which thinning and prescribed fire treatments were applied in factorial combinations. We asked the following research questions:

1. Can prescribed fire or thinning alone produce the structural changes necessary to restore a low severity fire regime?

2. If prescribed fire and thinning are used in combination, are the results additive or is there an additional benefit to combining treatments?
3. Which treatments reduce stand density sufficiently to reduce the risk of insect outbreaks?
4. How do treatments affect current snag inventories and future snag recruitment?

Methods

Study Area

The study was conducted in the Eastern Cascade Mountains of central Washington State within the Okanogan-Wenatchee National Forests. Forests within the study area are dominated by ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziesii*) with grand fir (*Abies grandis*) and western larch (*Larix occidentalis*) occurring at higher elevations. Plant associations include *Pseudotsuga menziesii/Calamagrostis rubescens, P. menziesii/Spirea betulifolia, P. menziesii/Carex geyeri, P. menziesii/S. betulifolia/C. rubescens, P. menziesii/S. albus, P. menziesii/ Symphoricarpos albus/C. rubescens, Pinus ponderosa/C. rubescens/Agropyron spicatum, Abies grandis/Mahonia nervosa,* and *A. grandis/S. albus/C. rubescens* (Lillybridge and others 1995).

Climate is continental due to the rain shadow produced by the Cascade Mountains. Annual precipitation averages 22 cm and occurs mostly as snow between November and April; mean January and July temperatures are –3 °C and 17 °C, respectively. Soils are stony, sandy loams (USDA 1995) and slopes vary from 30 to 40 percent. A more complete description of general site conditions will be found in Harrod and others (in progress).

Treatment Descriptions

Approximately 30 candidate stands were identified in 1999 in the Mission Creek watershed and other smaller watersheds immediately adjacent to the west. We constrained the search to eliminate units with (1) north aspects, (2) average slopes >40 percent (there are locally steeper slopes), (3) >10 percent rock or nonforest vegetation cover, and (4) known plant or animal species of concern. Twelve treatment units, each approximately 10 ha, were ultimately chosen for the study.

The treatments included: (1) thinning from below (thin only), (2) prescribed fire alone (burn only), (3) commercial thinning followed by prescribed fire (thin + burn), and (4) untreated control. Treatment combinations were assigned to the 12 study units, producing three replicates of each treatment combination. Treatment assignment was random except that four units were not considered for prescribed fire treatments due to access limitations.

The specific treatment objectives were to restore low-density dry forest stand structure, reduce ladder and surface fuels, reduce the risk of extensive bark beetle attack, and reduce the risk of high-severity fire. The overall objective of the Fire and Fire Surrogate Study was to achieve an 80 percent survival rate in codominant/dominant trees in the posttreatment stand for modeled wildfires under 80th percentile weather conditions (Weatherspoon 2000). The thinning treatment objectives on thin-only and thin + burn units were to reduce stand density and favor drought and fire resistant species (largely ponderosa pine or Douglas-fir). Target thin densities were designed to lower current stand density to the estimated upper management zone for low bark beetle risk (Cochran and others 1994), which is also the estimated historical density for this area (for example, stand density index = 263 for pine sites; Harrod and others 1999). Stands were thinned from below (largely understory trees) leaving the largest and most vigorous trees at irregular spacing. Treatments were tailored to individual forest stands, and target densities were dependent on the predominant plant association and site stockability. Thinning was accomplished with contract fallers in the winter of 2002/2003, and logs were yarded by helicopter to landings outside the study units. Unmerchantable tree tops and branches were left in the study units.

Prescribed burning was conducted on four of the six experimental units in spring 2004 and, because of lack of appropriate burning conditions, on the remaining two units in spring 2006. Ignition of units was by hand (drip torch) and helicopter with polystyrene spheres filled with potassium permanganate crystals, which are injected with ethylene glycol and dropped to the ground. Flame lengths ranged from 0.2 to 1.0 m and burns were generally patchy (20 to 50 percent area blackened) because of spring burning conditions.

Sampling Design

Preliminary reconnaissance of the treatment units was used to identify areas of continuous forest vegetation and to avoid sampling in areas dominated by nonforest vegetation. A series of six, 20x50m plots were permanently established within each unit in 2000 (prior to treatments), and plots were systematically stratified within the most abundant plant associations within each unit (Lillybridge and others 1995). Based on a preliminary analysis of adjacent forest stands we determined that six plots per treatment unit would adequately capture the within unit variability and provide an accurate estimate of vegetation characteristics.

Within each sample plot, all live and standing dead trees >7.62 cm d.b.h. were identified by species, permanently numbered and measured for diameter, total height, height to crown base (height from tree base to the intersection of the lowest live limb at the tree bole), bole scarring, and crown condition (Keen 1943; Hawksworth 1977). Saplings (height >1.37 m, diameter <7.62 cm) were also tallied. Canopy closure was measured in the center of the plot using a Lemmon Spherical Densiometer, Model-C. Slope, aspect, and elevation were also recorded for each plot.

In general, sampling occurred 1 year before and after the treatments were implemented; however, the actual years each unit was measured depended on the timing of the treatments (Harrod and others in progress). Upon reassessment of the units following treatment we noted that two plots located in burn units escaped the fire because they were located on the wrong side of the handline and had no possibility of being burned. These two plots were subsequently removed from all analyses.

Data Analysis

Data were averaged up from the plot-level to the experimental unit level for all analyses (Hurlbert 1984). Live trees and snags >7.62 cm, and saplings ($\geq$1.37 m tall and $\leq$7.62 cm d.b.h.) were analyzed separately. Response variables of interest included: density (ha^{-1}) and basal area ($m^2\ ha^{-1}$), quadratic mean diameter (cm), stand density index, canopy bulk density ($kg\ m^{-3}$), canopy fuel loading ($Mg\ ha^{-1}$), and canopy base height (m).

A two-factorial analysis of variance (ANOVA) was used on the pretreatment data to determine if there were significant differences in forest structural components between treatments prior to the experiment. Factors were burn (two levels, burn or no burn) and thin (two levels, thin or no thin). Of all the response variables tested in the pretreatment analysis, only snag basal area (BA) was significantly different among treatments. Even though there were largely no significant differences in pretreatment forest structure, there was enough variability among treatment units to warrant the use of a pretreatment covariate for the analysis of treatment effects. Therefore, to determine the treatment effects on stand structure, a two-factorial analysis of covariance (ANCOVA) was used with absolute change as the dependent variable (posttreatment – pretreatment) and the respective pretreatment condition included as a covariate in the model. This analysis was chosen because it (1) accounts for pretreatment variability in structural components, and (2) accounts for the repeated measures aspect of the experiment by analyzing the absolute change of the response variables rather than the posttreatment values.

Least square means were used to compare main treatment and interaction effects on stand structure, and the Tukey-Kramer adjustment for multiple comparisons was used to control the experiment-wise error rate. An error rate of 0.1 was chosen over the more traditional 0.05 level to (1) reduce the probability of Type II errors and (2) because a 90 percent success rate is favorable for most management decisions.

Because treatments were designed to remove trees based on their size, trees were grouped into four diameter classes for some analyses to elaborate upon the effects of treatments on different size classes of trees. Diameter classes included small (7.62 to 19.9 cm d.b.h.), medium (20.0 to 39.9 cm d.b.h.), large (40 to 59.9 cm d.b.h.) and very large (>60.0 cm d.b.h.).

Stand density index is a useful measure of competition in forest stands and has been applied to many forest types around the world (Shaw 2006). Originally developed for even-aged pure stands, SDI has since been applied to uneven-aged and mixed-species forests (Shaw 2000; Woodall and others 2003, 2005). Stand density index for each sample plot was calculated using the summation method following Cochran and others (1994) and Shaw (2000):

$$[1] \qquad SDI = \sum(D_i/25)^a$$

Where, D_i = individual tree diameter (cm), a = 1.77 for ponderosa pine and 1.51 for Douglas-fir and all others.

A variant of Reineke's maximum size-density model was used to construct Gingrich-type stocking charts, following the methods of Cochran and others (1994), for use in forest types similar to those in the current study. Average model parameters for Douglas-fir and ponderosa pine were calculated to determine tree density and basal area at full stocking over a range of average stand diameters:

$$[2] \qquad TPH = \exp^{[a-b(\log(Dq)]*(SDIf/SDIn)}$$

Where TPH = trees per hectare, Dq = quadratic mean diameter, a = 9.70 and b = 1.64, SDIf = stand density index at full stocking for our stands (777), and SDIn = average maximum SDI for self-thinning stands (922). Basal area (BA; m^2 ha^{-1}) was then calculated for each Dq as:

$$[3] \qquad BA = TPH*0.0000785398*Dq^2$$

While SDI is reportedly robust to changes in site quality and stand age, full-stocking values have been shown to vary by region and plant association (Woodall and others 2000). The (SDIf/SDIn) in equation 2 is an adjustment factor used in the model to tailor maximum size-density models to specific forests of interest. An SDIf value of 777 was calculated by averaging the SDI values for the individual plant associations (PA) in our study area (based on Lillybridge and others 1995) and weighting them by the total number of sample plots on which each PA occurred. An SDIn of 920 was used as an average maximum density for ponderosa pine and Douglas-fir over a wide range of plant communities as summarized by Cochran and others (1994). Upper and lower management zones were calculated as 75 and 50 percent of full stocking, respectively.

Canopy fuels were modeled at each time period using the Crown Mass® software in the Fuels Management Analyst 3® (FMA) package. Canopy bulk density, canopy fuel loading, and canopy base height were calculated using pre- and posttreatment, plot-level data for each unit. Canopy bulk density is the crown mass per unit volume in a forest stand and is an estimate of available fuel in the canopy. Crown Mass® calculates canopy bulk density as the maximum of the running mean estimates for 0.3048 m canopy segments on the basis that fires will most likely spread in the denser portions of the canopy. Canopy fuel loading is the crown mass per unit area and is calculated as the cumulative foliage, 1-hr live and dead timelag canopy fuel mass. Canopy base height is defined as the vertical distance from the ground to the lowest point in the canopy where bulk density is high enough to propagate fire into the canopy (0.011 kg m^{-3}; Scott and Reinhardt 2001).

Results

Treatment Effects on Tree Density and Stocking

The thinning treatment greatly reduced stand density over the course of the experiment, particularly in the small and medium size classes. Thinning significantly reduced total live tree density by >60 percent ($P<0.0001$), with similar declines found using thin only and thin + burn treatments (fig. 1A). Thinning removed over two-thirds of the trees in the small and medium size classes, and removed some trees >40cm d.b.h. (fig. 2). Residual trees were generally vigorous, with few signs of mistletoe or other insects or diseases. Less than 2 percent of the residual trees had signs of mechanical scarring related to the thinning treatment. The percentage of Douglas-fir stems increased slightly following thinning; however, all changes in species composition were <10 percent (by density) and no significant differences were found among treatment combinations ($P>0.5847$).

The burning treatment caused minimal tree mortality, most of which was restricted to the smaller diameter classes. Evidence of bole scorching was found on over half of the trees on plots that received only a burn; however, fires burned into the crowns of only 20 percent of the trees on these plots. The burn-only treatment caused only 8 percent mortality for all size classes of trees, which was not significantly different than the 1 percent background mortality observed on control plots ($P=0.5061$; fig. 1A). Burning alone removed 20 percent of small diameter trees and its effect on larger size classes was negligible, with more than twice as many trees in the 20 to 40cm d.b.h. class remaining on burned only units as compared to the thinned areas (fig. 2). Under the thin + burn treatment, fire scorched about two-thirds of the trees and fire-related mortality was higher under this treatment as compared to burning alone (fig. 2). The burn-only treatment had no effect on species composition with burning causing <2 percent increase in Douglas-fir on average ($P>0.6020$).

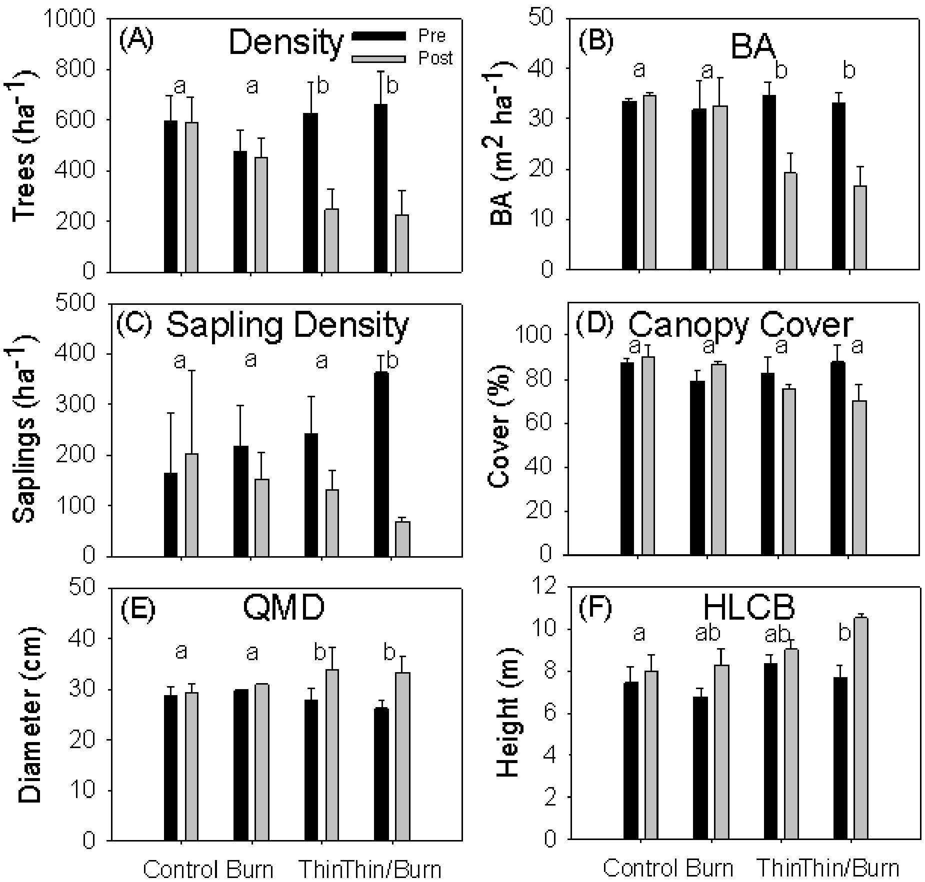


Figure 1—Changes in (A) live tree density, (B) live tree basal area, (C) sapling density, (D) canopy cover, (E) quadratic mean diameter, and (F) height to live crown base following treatments in dry-forests of central Washington. Error bars represent standard deviation. Treatments with the same letter indicate no significant differences between the absolute change in the attribute from pre- to posttreatment (P<0.1).

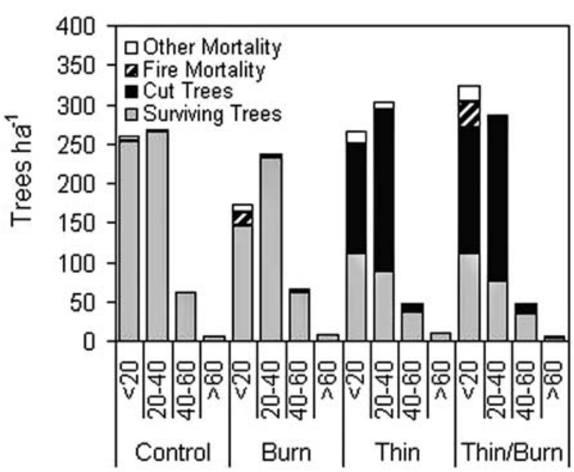


Figure 2—Causes of tree mortality by diameter class (cm) within each treatment combination. The full bars in each treatment are equal to the pretreatment diameter distribution for live trees and the bottom "surviving tree" bars are approximately equal to the posttreatment diameter distribution (actual posttreatment diameter distributions may differ due to tree recruitment into other diameter classes over the course of the experiment). The "other" mortality category includes trees that died of either unknown or natural causes not directly attributable to the experimental treatments.

All treatment combinations caused a decline in sapling densities over the course of the experiment. Thinning caused a ~45 percent decline in sapling density when used alone and >80 percent when used in combination with burning. The burn-only treatment also reduced sapling densities, but to a somewhat lesser extent (fig. 1C). The thin + burn treatment led to a drastic and significant decline in future tree recruitment compared to the control ($P=0.0809$), and thinning alone and burning alone had a similar yet lesser effect on reducing sapling densities.

Burning alone was not effective at reducing tree stocking, while thinning led to a marked reduction in basal area (BA) and an increase in average stand diameter. Prior to the experiment, most stands were at or near full stocking for their respective plant associations (as defined by Cochran and others 1994; see fig. 3). Basal area on burn-only units increased slightly over the course of the experiment, but was not significantly different than the trends observed on control units ($P=0.9986$; fig. 1B). The thin-only treatment reduced BA by almost half following treatment, which was significantly less than observed on control units ($P<0.0001$). The thin + burn treatment had a somewhat greater effect on reducing BA compared to the thin-only treatment; however, no significant differences were found between treatments ($P=0.8754$). Thinning, in general, reduced stocking to between 50 and 75 percent of full stocking, whereas burning alone led to an increase in stocking (fig. 3). Ponderosa pine dominated units responded similarly to the thin-only and thin + burn treatments and were well below 50 percent stocking following treatment. The decline in stocking levels on thin-only and thin + burn units led to a significant increase in average live tree diameter ($P<0.0001$; fig. 1E). Average diameter on burn-only units also increased following treatment; however, this change was not significant and mimicked control units where increases in stand diameter were a function of tree growth and suppressed tree mortality ($P=1.000$).

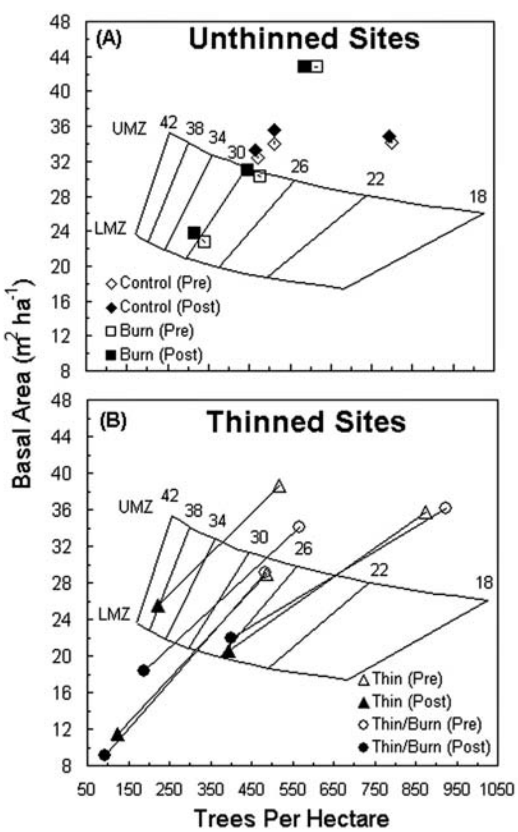


Figure 3—Pre- and posttreatment stocking for the 12 treatment sites located in central Washington. The dotted lines show the change in stocking for individual units following treatments. Upper management zone (UMZ) and lower management zone (LMZ) values are equal to 75 and 50 percent full stocking, respectively. Quadratic mean diameters (cm) are presented for each calculated stocking level.

Snag Dynamics Under Thinning and Burning Treatments

Burning and thinning treatments had dissimilar effects on snag density, and snag populations did not follow the same trends as live trees. The density of snags prior to treatment was highly variable between sites; however, no significant differences were found among treatments (P>0.3087). Pretreatment snag densities ranged from 8 to 83 ha^{-1} and averaged 47 ± 7 ha^{-1} across all units with a higher density of snags on control units and fewer snags on thin + burn units (fig. 4). About three-quarters of the snags in all treatments were <20cm d.b.h. with densities attenuating in sequentially larger size classes in a reverse-J pattern. Burning significantly increased snag densities on both burn-only and thin + burn units (P=0.0124). Increases in snag density on burn-only units were generally restricted to trees <20 cm d.b.h.; however, the thin + burn treatment created snags in all size classes (fig. 4). Thinning alone, conversely, led to a ~50 percent reduction in snag density, which was significantly different compared to the thin + burn (P=0.0286). Thinning alone removed snags in all diameter classes, with the largest reductions occurring in the <20 cm d.b.h. class.

Treatment effects on snag basal area differed somewhat from the changes observed in snag density. Pretreatment basal area of dead standing trees ranged from 0.2 to 2.9 m^2 ha^{-1} and averaged 1.6 m^2 ha^{-1} across all treatments. Thin-only units had the highest snag BA prior to the experiment, and was significantly different to the thin + burn treatment with the least amount of snag BA (2.4 and 0.8 m^2 ha^{-1}, respectively; P=0.0359). Snag BA remained relatively constant on both control and burn-only units, whereas the thin-only treatment reduced snag BA by >50 percent. Snag BA more than doubled under the thin + burn treatment, and had the most snag BA of all treatments by the end of the study. The main effect of burning was a significant increase in snag BA (P=0.0178); however, there were no significant differences found among treatments (P>0.1020).

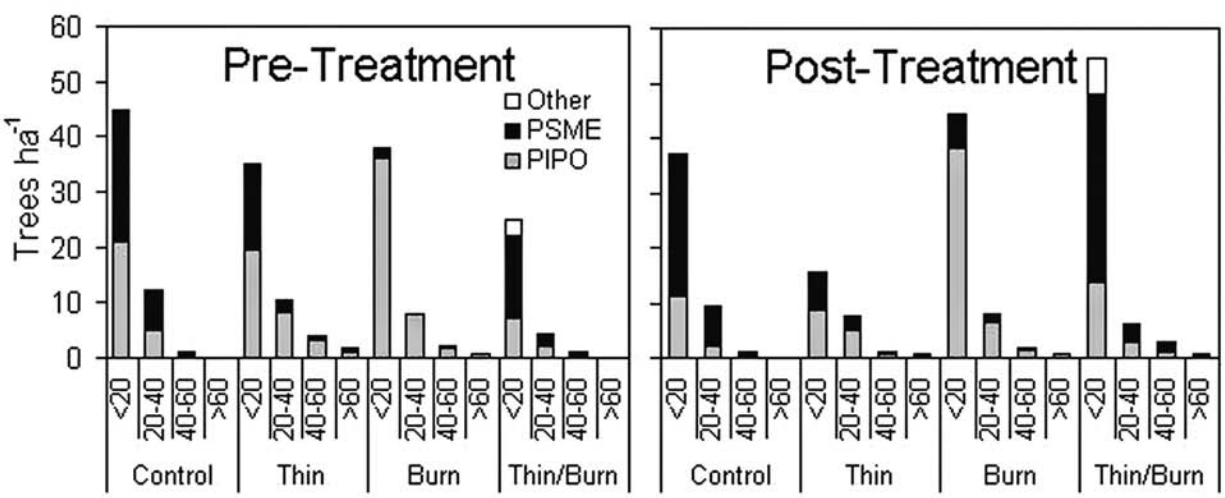


Figure 4—Diameter distribution (cm) and species composition of dead standing trees pre- and posttreatment in dry forests of central Washington. The "other" species category includes western larch and grand fir.

Changes in Canopy Structure Following Treatments

Canopy base height (CBH) increased over the course of the experiment under all treatment combinations; however, this increase was greatest under the thin + burn treatment. The burn only treatment raised CBH by ~1 m, but this was not significantly different as compared to the control (P=0.9208; fig. 1F). Thinning had a much larger effect on CBH, with the thin-only treatment and thin + burn treatment causing a ~3.5 and ~5.5 m increase in CBH, respectively. The rise in CBH on both thin-only and thin + burn treatments was significantly different compared to the control (P=0.0917, P=0.0101, respectively), and the thin + burn was significantly different compared to the burn-only (P=0.0232).

Canopy fuel loadings were greatly reduced by the thinning treatments, while burning was not effective at altering canopy structure. Canopy bulk density and canopy fuel loading remained relatively constant under the control and burn-only treatments, with values somewhat higher on control plots (fig. 5). The thin-only and thin + burn treatments both caused a significant two-fold reduction in canopy bulk density on average, compared to burn-only and control units (P=0.0006). Canopy bulk densities in both thin-only and thin + burn treatments were significantly different from burn-only and control treatments (P<0.0294). Similar trends were observed for canopy fuel loadings, with significant reductions occurring on thin-only and thin + burn units (P<0.0001). Both thin-only and thin + burn treatments led to significant declines in canopy fuel loadings as compared to the control treatment; however, the thin + burn treatment reduced canopy fuels by >6 Mg ha^{-1}, while thinning alone caused only a 3.5 Mg ha^{-1} decline. The greater reductions on thin + burn units may be due to greater pretreatment canopy fuel loading (fig. 5).

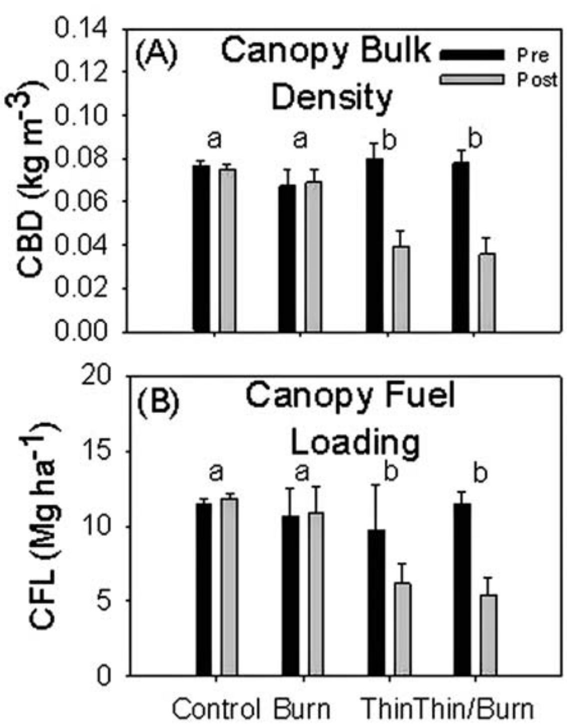


Figure 5—Changes in (A) canopy bulk density and (B) canopy fuel loading as calculated by Crown Mass®. Bars with differing letters are significantly different (P<0.1).

Canopy cover increased slightly when burning was used alone; while the reduction in canopy fuels on thin-only and thin + burn units led to a more open canopy. The minimal effect of burning alone on canopy cover was similar to the unmanaged control (P=0.9991, fig. 1D). However, thinning accounted for a 10 percent reduction in canopy cover on average over all thin-only and thin + burn units. This decline was significant compared to control and burn-only units (P=0.0363). No added benefit was found when thinning and burning were used in combination as compared to thinning alone (P=0.9662, fig. 1D).

Discussion

Tailoring Management Prescriptions Using Density Management Guidelines

Density management guidelines can be used to regulate forest stands to achieve a broad range of management objectives (Newton 1997). The natural range of variability (NRV) in forest density is often used to determine reference points in which to judge the ultimate success of restoration treatments. Using NRV to tailor management prescriptions is an attractive way to revert forest stands to previous structural conditions that were controlled by disturbance processes in place prior to the influence of Euro-Americans. Previous studies have identified a range of historic densities for forest types similar to our study (Avery and others 1976; Covington and Moore 1994; Harrod and others 1999; Morrow 1985). Harrod and others (1999) reconstructed stand structure in forests adjacent to our study site and found presettlement stocking varied between plant association groups (PAG) and ranged from 27 to 68 trees ha^{-1} and 10 to 22 m^2 ha^{-1}. In our study, thin-only and thin + burn units following treatment differed somewhat from historical forests, with densities and BA averaging 4.6 and 2.8 times greater than historical values, respectively. However, these values may not be directly comparable due to the relatively young age and early seral stage of development of our study forests. For instance, historical stands investigated by Harrod and others (1999) were dominated by trees nearly twice the average diameter of post-treatment stands in our study.

Insect populations are often dependent on host densities, with increasing tree densities leading to higher probabilities of insect outbreaks. Sartwell and Stevens (1975) studied mountain pine beetle (*Dendroctonus ponderosae*) outbreaks in ponderosa pine forests of the Interior Western United States and found beetle outbreaks to be appreciably increased in even-aged ponderosa pine forests with >34 m^2 ha^{-1} BA. In our study, none of the thin-only or thin + burn units exceeded the BA threshold following treatment; however, seven out of the 16 burn-only plots (44 percent) had BA >34 m^2 ha^{-1}. Because we were working primarily in mixed-conifer stands, 34 m^2 ha^{-1} is likely a conservative threshold for our study sites, and higher stocking values may be acceptable. The upper management zone (UMZ) defined by Cochran and others (1994) is the stocking level at which a substratum of small diameter trees begins to develop, making forests increasingly susceptible to insect-related mortality. After accounting for the lower maximum-stocking associated with the PAs in this study we calculated a UMZ of 583, which is similar to other UMZ values for interior ponderosa pine and Douglas-fir forest types (Day 2005; Cochran and Barrett 1999; Long and Shaw 2005).

However, Harrod and others (1999) reported a lower UMZ for stands adjacent to the Mission Creek watershed (SDI=263). These values differ because Harrod's calculations (1) were based on ponderosa pine dominated stands that had considerably lower full-stocking values compared to the Douglas-fir PAs used in the current study (Lillybridge and others 1995) and (2) used slightly different UMZ calculations that were adjusted for site productivity (Cochran and others 1994).

Role of Fire in Altering Forest Structure

Since the use of fire suppression activities 50 to 100 years ago, interior ponderosa pine and Douglas-fir forests have experienced a drastic decline in fire frequency (Cooper 1960; Covington and Moore 1994; Everett and others 2000; Fry and Stephens 2006), which has led to the development of a dense substratum of small-diameter trees and an accumulation of coarse woody debris. Prescribed fire is often reintroduced into these ecosystems as a way to restore past forest structure; however, little empirical evidence supports the use of prescribed fires alone in forest restoration (Sackett and others 1996; Thomas and Agee 1986; Youngblood and others 2006). Possible solutions for manipulating overstory structure with fire under these circumstances include using a single high-intensity prescribed fire (Fulé and others 2004) or to use repeated burnings where treatment effects are amortized over time (Miller and Urban 2000). Peterson and others (1994) found that repeated burnings at 4- to 6-year intervals reduced surface and ladder fuels and increased growth in larger residual ponderosa pine trees.

The prescribed burns used in the current study removed only the smallest diameter trees and had an overall negligible effect on forest structural components. Observations made during the burns suggest that the fire intensity was variable within and among study sites. For our study area, Agee and Lolley (2007) reported on the treatment effects on surface fuels and noted that the effect of fire was negligible over 50 to 75 percent of the study area. In one burn-only unit in particular, fire scorched <5 percent of the crowns of trees and less than a third of all trees had any signs of burning. These results suggest that a single, early season burn is ineffective at reducing tree density, but may be effective at reducing some forest floor fuels (Agee and Lolley 2007). Spring burns often cause lower overstory mortality as compared to fall burns, due to the high moisture content in surface and foliar fuels following green-up. Youngblood and others (2006) studied the effect of autumn prescribed fires on overstory structure in ponderosa pine/Douglas-fir forests of eastern Oregon; however, they found that the late-season burns had a similar null effect on overstory structural components as observed in our study.

Trees killed directly by the burn were often left standing following treatment, thereby adding to snag recruitment. Snags are an important aspect of forest structure, particularly for primary and secondary cavity nesters and insect populations (Raphael and White 1984; Harmon and others 1986; Bull and others 1997). While the prescribed burns did increase snag density in this study, most were <20 cm d.b.h.. Cavity nesting birds select trees with larger than average diameters for nesting (Raphael and White 1984) and several species require snags >25 cm d.b.h. for suitable nesting habitat (Ganey and Vojta 2004; Pilliod and others 2006; Thomas and others 1979). Therefore, the general increase in snags should be viewed cautiously in terms of wildlife habitat.

The use of prescribed fire has obvious other advantages as a management tool including reducing ground fuels, increasing nutrient availability and net primary productivity, and reintroducing a natural process back into a historically fire-prone system (Weatherspoon 1996). The spring burns conducted in the experiment were cooler and spottier than were desired and may have led to results that downplay the efficacy of fire to meet forest restoration goals. Evaluations of drier spring burns or fall burns are needed to fully understand the utility of prescribed burning to meet restoration goals (McCandliss 2002).

Reducing Fire Potential with Mechanical Thinning

Thinning alone was capable of reducing canopy fuels, canopy bulk density, and tree stocking by ≥50 percent. Similar results were found in fire and fire surrogate experiments in eastern California and Oregon (Stevens and Moghaddas 2005; Youngblood and others 2006). However, these results ignore the deposition of additional fine- to medium-sized surface fuels created by the thinning treatments that increase flame lengths and torching potential (Agee and Skinner 2005; Peterson and others 2005). Youngblood and others (2006) studied treatment effects on forest structure in ponderosa pine forests of eastern Oregon and found that coarse woody debris density increased when thinning was used alone as compared to when burning was used alone and in combination with thinning. These results are typical for thinning operations (Cram and others 2006; McIver and Ottmar 2007), and the increased fire hazard from the accumulation of these fuels is often a deterrent for the use of thinning alone. However, when the torching index (a measure of the windspeed required to propagate fires into the canopy) was modeled in Crown Mass® using fuel loads comparable to those present following thinning in our study areas indices averaged ~100 km hr^{-1}. This suggests that thinning alone was capable of increasing fire resiliency by reducing tree stocking and crown fuels enough to counteract the resultant accumulation of slash.

Treatment rotations for individual stands often exceed 15 to 20 years; therefore, treatments should reduce stocking levels sufficiently to cover the lag between subsequent treatments. In this study, the limited effects of burning on controlling tree stocking and canopy fuels may diminish quickly and stands in our study will most likely revert to pretreatment stand structures. The drastic effect of thinning on stocking suggests that this treatment is necessary if only a single-entry treatment is feasible and large time gaps between treatments are expected.

The use of mechanical thinning also leaves open the opportunity to combine fuels reduction treatments with other silvicultural treatments elsewhere on the landscape. For instance, group selections and other uneven-aged management practices are becoming increasingly popular in ponderosa pine forests (Youngblood 2005). Incorporating alternative silvicultural prescriptions with regular fuels reduction operations will increase heterogeneity on the landscape and benefit wildlife (Graham and others 2004), aesthetics, increase landscape heterogeneity, and also help recoup some of the costs associated with fuels reduction treatments. Uneven-aged management has proved successful at reducing wildfire severity in similar forest types (Omi and Martinson 2002; Pollet and Omi 2002).

Conclusions

Dry forests of the Western United States have undergone drastic structural changes over the past century that have contributed to an apparent threat of intense crown fire and insect outbreak potential over much of the region. Foresters need to be provided with sound, science-based treatment alternatives to effectively and responsibly manage these public lands. Results from our study suggest that thinning alone is capable of enhancing forest resiliency to fire and insect mortality by reducing overstory density and canopy fuel levels. Burning was not an effective method of controlling overstory fuel loads; however, by reducing surface and other ladder fuels (see Agee and Lolley 2007), burning may be used in conjunction with thinning to restore ecosystem structural and functional components.

Acknowledgments

This is Contribution Number 147 of the National Fire and Fire Surrogate Project (FFS), funded by the U.S. Joint Fire Science Program. We appreciate the field assistance of numerous workers: Scott Conlan, Beth Armbrust, Sara O'Neal, Mara McGrath, Dottie Knecht, Todd Jensen, Tim Hatch, Chad Yenney, Megan Whitmore, Kathleen Moran, Darci Carlson, Alisha Toombs, Pete Ohlson, James Dickinson, and many others. Jim Agee, Bob Gray, and Andy Youngblood provided helpful reviews which greatly improved the manuscript. We thank the Wenatchee River Ranger District, Okanogan-Wenatchee National Forests, for implementing both the prescribed burning and thinning treatments.

References

Agee, J.K. 1990. The historical role of fire in Pacific Northwest forests. In: Natural and prescribed fire in Pacific Northwest forests. J.D. Walstad, S.R. Radosevich, and D.V. Sandberg, eds. Corvallies, OR: Oregon State University Press: 25.37.

Agee, J.K. 1993. Fire Ecology of Pacific Northwest Forests. Washington, DC: Island Press.

Agee, J.K. 1994. Fire and weather disturbances in terrestrial ecosystems of the eastern Cascades. Gen. Tech. Rep. PNW-GTR-320. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Agee, J.K. 1998. The landscape ecology of western forest fire regimes. Northwest Science, 24-34 (special issue).

Agee, J.K. 2003. Historical range of variability in eastern Cascade forests, Washington, USA. Landscape Ecology 18: 725-740.

Agee, J.K.; Lolley, M.R. 2007. Thinning and prescribed fire effects on fuels and potential fire behavior in an eastern Cascades forest, Washington, USA. Fire Ecology 2(2): 142-158.

Agee, J.K.; Skinner, C.N. 2005. Basic principles of forest fuel reduction treatments. Forest Ecology and Management 211: 83-96.

Anderson, H.E. 1982. Aids to determining fuel models for estimating fire behavior. Gen. Tech. Rep. INT-122. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 22 p.

Avery, C.C.; Larson, F.R.; Schubert, G.H. 1976. Fifty-year records of virgin stand development in southwestern ponderosa pine, Gen. Tech. Rep. RM-22. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 71 p.

Brown, R.T.; Agee, J.K.; Franklin, J.E. 2004. Forest restoration and fire: principles in the context of place. Conservation Biology 18: 903-912.

Bull E.L.; Parks, C.G.; Torgersen, T.R.. 1997. Trees and logs important to wildlife in the interior Columbia River Basin. Gen. Tech. Rep. PNW-GTR-391. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 55 p.

Cochran, P.H.; Barrett, J.W. 1999. Growth of ponderosa pine thinned to different stocking levels in central Oregon: 30-year results. Res. Pap. PNW-RP-508. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 27 p.

Cochran, P.H.; Geist, J.M.; Clemens, D.L.; Clausnitzer, R.R.; Powell, D.C. 1994. Suggested stocking levels for forest stands in northeastern Oregon and southeastern Washington. Research Note PNW-RN-513. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 21 p.

Cooper, C.F. 1960. Changes in vegetation, structure, and growth of southwestern pine forest since white settlement. Ecological Monographs 30: 129–164.

Cortner, H.; Moote, M.A. 1999. The politics of ecosystem management. Washington, DC: Island Press. 179 p.

Covington, W.W.; Fule, P.Z.; Moore, M.M.; Hart, S.C.; Kolb, T.E.; Mast, J.N.; Sackett, S.S.; Wagner, M.R. 1997. Restoring ecosystem health in ponderosa pine frests. Journal of Sustainable Forestry 2: 153-181.

Covington, W.W.; Moore, M.M. 1994. Southwestern ponderosa forest structure, changes since white settlement. Ecological Monographs 30(2): 129-164.

Cram, D.; Baker, T.; Boren, J. 2006. Wildland fire effects in silviculturally treated vs. untreated stands of New Mexico and Arizona. Res. Pap. RMRS-RP-55. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 28 p.

Dahms, C.W.; Geils, B.W., tech. eds. 1997. An assessment of forest ecosystem health in the Southwest. Gen. Tech. Rep. RM-GTR-295. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Day, K. 2005. Stocking standards for uneven-aged interior Douglas-fir. University of British Columbia Faculty of Forestry Report. [Online] 29 pp. Available: http://www.forestry.ubc.ca/resfor/afrf/Reports_Index.htm [March 26 2007].

Everett, R.L.; Schellhaas, R.; Keenum, D.; Spurbeck, D.; Ohlson, P. 2000. Fire history in the ponderosa pine/Douglas-fir forests on the east slope of the Washington Cascades. Forest Ecology and Management 129: 207-225.

Fry, D.L.; Stevens, S.L. 2006. Influence of humans and climate on the fire history of a ponderosa pine-mixed conifer forest in the southeastern Klamath Mountains, California. Forest Ecology and Management 223: 428-438.

Fulé, P.Z.; Cocke, A.E.; Heinlein, T.A.; Covington, W.W. 2004. Effects of an intense prescribed forest fire: Is it ecological restoration? Restoration Ecology 12: 220–230.

Gaines, W.L.; Haggard, M.; Lehmkuhl, J.F.; Lyons, A.L.; R.J. Harrod. 2007. Short-term response of land birds to ponderosa pine restoration. Restoration Ecology XX.

Ganey, J.L.; Vojta, S.C. 2004. Characteristics of snags containing excavated cavities in northern Arizona mixed-conifer and ponderosa pine forests. Forest Ecology and Management 199: 323-332.

Ganz, D.J.; Dahlsten, D.L.; Shea, P.J. 2003 The post-burning response of bark beetles to prescribed burning treatments. Fire, Fuel Treatments, and Ecological Restoration: conference proceedings. (P. N. Omi and L. A. Joyce, eds.). Proc. RMRS-P-29. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 143–158.

Graham, R.T.; McCaffrey, S.; Jain, T.B. 2004. Science basis for changing forest structure to modify wildfire behavior and severity. Gen. Tech. Rep. RMRS-GTR-120. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 43 p.

Habeck, J.R. 1990. Old-growth ponderosa pine-western larch forest in western Montana: ecology and management. The Northwest Environmental Journal 6: 271–292.

Hall, F.C. 1977. Ecology of Natural Underburning in the Blue-Mountains of Oregon. PNW R6-ECOL-79-001. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Harmon, M.A.; Franklin, J.F.; Swanson, F.J.; Sollins, P.; Gregory, S.V.; Lattin, J.D.; Anderson, N.H.; Cline, S.P.; Aumen, N.G.; Sedell, J.R.; Lienkamper, G.W.; Cromack Jr., K.; Cummins, K.W. 1986. Ecology of coarse woody debris in temperate ecosystems. Adv. Ecol. Res. 15: 133–302.

Harrod, R.J.; McRae, B.H.; Hartl, W.E. 1999. Historical stand reconstruction in ponderosa pine forests to guide silvicultural prescriptions. Forest Ecology and Management 114: 433-446.

Hawksworth, F.G. 1977. The 6-class dwarf mistletoe rating system. Gen. Tech. Rep. RM-48. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Hessburg, P.F.; Agee, J.K.; Franklin, J.F. 2005. Dry forests and wildland fires of the inland Northwest USA: contrasting the landscape ecology of the pre-settlement and modern eras. Forest Ecology and Management 211(1-2): 117-139.

Hurlbert, S.H. 1984. Pseudoreplication and the design of ecological field experiments. Ecological Monographs 54: 187-211.

Keen, F.P. 1943. Ponderosa pine tree classes redefined. Journal of Forestry 41: 249–253.

Lillybridge, T.R.; Kovalchik, B.L.; Williams, C.K.; Smith, B.G. 1995. Field guide for forested plant associations of the Wenatchee National Forest. Gen. Tech. Rep. PNW-GTR-359. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 335 p. In cooperation with: Pacific Northwest Region, Wenatchee National Forest.

Long J.N.; Shaw, J.D. 2005. A density management diagram for even-aged ponderosa pine stands. Western Journal of Applied Forestry 20: 205-215.

McCandliss, D.S. 2002. Prescribed burning in the Kings River Ecosystems Project Area: lessons learned. In: Proceedings of a symposium on the Kings River Sustainable Forest Ecosystems Project: progress and current status. Gen. Tech. Rep. PSW-GTR-183. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station: 37-46.

McHugh, C.W.; Kolb, T.E.; Wilson, J.L. 2003. Bark beetle attacks on ponderosa pine following fire in northern Arizona. Environmental Entomology 32(3): 510-522.

McIver, J.D.; Ottmar, R. 2007. Fuel mass and stand structure after post-fire logging of a severely burned ponderosa pine forest in northeastern Oregon. Forest Ecology and Management 238(1-3): 268-279.

Miller, C.; Urban, D.L. 2000. Connectivity of forest fuels and surface fire regimes. Landscape Ecology 15(2): 145-154.

Morrow, R.J. 1985. Age structure and spatial pattern of old-growth ponderosa pine in Pringle Falls Experimental Forest, central Oregon, M.S. thesis. Corvallis, OR: Oregon State University. 80 p.

Newton, P.F. 1997. Stand density management diagrams: Review of their development and utility in stand-level management planning. Forest Ecology and Management 98: 251-265.

Omi, P.N.; Martinson, E.J. 2002. Effect of fuels treatment on wildfire severity. Final Report. Submitted to the Joint Fire Science Program Governing Board. Available online: http://www.cnr.colostate.edu/frws/research/westfire/FinalReport.pdf [March 7, 2007].

Patton-Mallory, M. 1997. Southwest wildland/urban interface fire risk reduction workshop; August 4-5, 1997, Flagstaff, AZ. Unpublished summary report on file. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 15 p.

Peterson, D.L.; Johnson, M. C.; Agee, J. K.; Jain, T.B.; McKenzie, D.; Reinhardt, E. D. 2005. Forest structure and fire hazard in dry forests of the western United States. Gen. Tech. Rep. PNW-GTR-628, Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Peterson, D.L.; Sackett, S.S.; Robinson, L.J.; Haase, S.M. 1994. The effects of repeated prescribed burning on Pinus ponderosa growth. International Journal of Wildland Fire 4(4): 239-247.

Pilliod, David S.; Bull, Evelyn L.; Hayes, Jane L.; Wales, Barbara C. 2006. Wildlife and invertebrate response to fuel reduction treatments in dry coniferous forests of the Western United States: a synthesis. Gen. Tech. Rep. RMRS-GTR-173. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 34 p.

Pollet, J.; Omi, P.N. 2002. Effect of thinning and prescribed burning on crown fire severity in ponderosa pine forests. International Journal Wildland fire 11: 1-20.

Raphael, M.G.; White, M. 1984. Use of snags by cavity-nesting birds in the Sierra Nevada. Wildlife Monographs 86: 1–66.

Sackett, S.S.; Haase, S.M.; Harrington, M.G. 1996. Lessons learned from fire use for restoring southwestern ponderosa pine ecosystems. Gen. Tech. Rep. RM-GTR-278. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 53-60.

Sartwell, C.; Stevens, R.E. 1975. Mountain pine beetle in ponderosa pine: prospects for silvicultural control in second-growth stands. Journal of Forestry 73: 136-140.

Scott, J.H. 1998. Fuel reduction in residential and scenic forests: a comparison of three treatments in a western Montana ponderosa pine stand. Res. Pap. RMRS-RP-5. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 19 p.

Scott, J.H.; Reinhardt, E.D. 2001. Assessing crown fire potential by linking models of surface and crown fire behavior. Res. Pap., RMRS-29. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 59 p.

Shaw, J.D. 2000. Application of stand density index to irregularly structured stands. Western Journal of Applied Forestry 15: 40–42.

Shaw, J.D. 2006. Reineke's stand density index: where are we and where do we go from here? In: Proceedings of the Society of American Foresters National Convention Proceedings, October 19-23, 2005. Ft. Worth, TX.

Smith, H. Y.; Anro, S.F., eds. 1999. Eighty-eight years of change in a managed ponderosa pine forest. Gen. Tech. Rep. RMRS-GTR-23. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 55 p.

Stephens, S.L. 1998. Evaluation of the effects of silvicultural and fuels treatments on potential fire behaviour in Sierra Nevada mixed-conifer forests. Forest Ecology and Management 105: 21-35.

Stevens, S.L.; Moghaddas, J.J. 2005. Experimental fuel treatment impacts on forest structure, potential fire, and predicted tree mortality in a California mixed-conifer forest. Forest Ecology and Management 215: 21-36.

Thomas, J.W.; Anderson, R.G.; Maser, C.; Bull, E.L. 1979. Snags. In: Thomas, J.W. (tech. ed.), Wildlife Habitats in Managed Forests: The Blue Mountains of Oregon and Washington. USDA Agricultural Handbook 553. Washington, DC: U.S. Department of Agriculture: 60–77.

Thomas, T.L.; Agee, J.K. 1986. Prescribed fire effects on mixed-conifer forest structure at Crater Lake, OR. Canadian Journal of Forest Research 16: 1082-1087.

van Wagtendonk, J.W. 1996. Use of a deterministic fire model to test fuel treatments In: Sierra forests in Sierra Nevada ecosystem project, final report to Congress. Vol. II Assessments and scientific basis for management options. Davis, CA: University of California, Centers For Water And Wildland Resources.

Weatherspoon, C.P. 1996. Fire-silviculture relationships. In: Sierra forests in Sierra Nevada ecosystem project, final report to Congress. Vol. II Assessments and scientific basis for management options. Davis, CA: University of California, Centers For Water And Wildland Resources: 1167-1176.

Weatherspoon, C.P. 2000. A proposed long-term national study of the consequences of fire and fire surrogate treatments. In: Neuenshwander, L.F., Ryan, K.C., Goldberg, G.E. (eds.), Proceedings of the Joint Fire Science Conference and Workshop, Boise, ID June 15-17. Moscow, ID: University of Idaho:. 117-126.

Weatherspoon, C.P.; Skinner, C.N. 1996. Landscape-level strategies for forest fuel management. In: Sierra Nevada Ecosystems Project: Final report to Congress, Vol. II: Assessments, scientific basis for management options. Davis, CA: University of California, Centers For Water And Wildland Resources.

Woodall, C.W.; Fiedler, C.E.; Milner, K.S. 2003. Stand density index in uneven-aged ponderosa pine stands. Canadian Journal of Forest Management 33: 96-100.

Woodall, C.W.; Miles, P.D.; Vissage, J.S. 2005. Determining maximum stand density index in mixed species stands for strategic-scale stocking assessments. Forest Ecology and Management 216: 367-377.

Youngblood, A. 2005. Silvicultural Systems for Managing Ponderosa Pine. In: Ritchie, Martin W.; Maguire, Douglas A.; Youngblood, Andrew, tech. coord. 2005. Proceedings of the Symposium on Ponderosa Pine: Issues, Trends, and Management. 2004 October 18-21; Klamath Falls, OR. Gen. Tech. Rep. PSW-GTR-198. Albany CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. 281 p.

Youngblood, A.; Metlen, K.L.; Coe, K. 2006. Changes in stand structure and composition after restoration treatments in low elevation dry forests of northeastern Oregon. Forest Ecology and Management 234: 143-163.

FireSmart®-ForestWise: Managing Wildlife and Wildfire Risk in the Wildland/Urban Interface—a Canadian Case Study

Alan Westhaver[1], Richard D. Revel[2], and Brad C. Hawkes[3]

***Abstract**—Reducing the risk of losses from wildfires that threaten homes and communities is a growing priority in Canada. To reduce risk, "FireSmart®" standards have been adopted nationwide for managing forest fuel. However, these standards largely disregard interests of wildlife and conservation of wildlife habitat – thus raising concerns among residents and other stakeholders. To be acceptable, fuel treatments in wildland/urban interface areas of Jasper National Park, Alberta, required that potential environmental impacts and the requirements of wildlife also be carefully considered. A research project conducted in conjunction with the Foothills Model Forest used literature and experimental manipulations to develop ecologically based approaches for treating fuel in ways that optimize conditions for wildlife, within constraints of current standards. The research was conducted during a 30-month prototype project on more than 250 ha of forest surrounding the community of Jasper, Alberta. The study concluded fuel treatments for the purpose of reducing wildfire risk can be compatible with wildlife habitat conservation and ecosystem restoration goals. This paper describes the interface challenges faced by park managers, explains the adaptive management approach used to develop practicable solutions, and describes resulting species-specific mitigations, guidelines, and best practices that satisfy community wildfire protection standards and ecosystem management objectives, concurrently.*

Introduction

Canada is experiencing an increase in interface fires. The vulnerability of people, property, and forests has reached alarming levels during recent fire seasons and helped trigger the Canadian Wildland Fire Strategy (Canadian Intergovernmental Secretariat 2005). Bothwell (2006) documented more than 900 cases of structure loss to interface fire since 1980, and in the past 10 years more than 250 communities and 700,000 Canadians have been threatened directly by wildfires (Natural Resources Canada 2005). In British Columbia, recent fire seasons showed a large upward trend related to the interface when compared to the 10-year average (Fuglem 2004). In 2003, more than 100 of 2,517 wildfires in British Columbia struck interface areas, and 15 were major incidents that caused evacuation of 50,000 people and destroyed 334 homes or businesses.

Several factors combine to underpin the need for more effective community wildfire protection, particularly in Western Canada: (1) increasingly dense country residential development (Duke and others 2003), (2) growing risk of human-caused ignitions, (3) warmer climate resulting in increased frequency, size, and severity of wildfires (Flannigan and others 1998; Flannigan and others 2003), and (4) rising socio-economic costs of fire control (Filmon 2004).

In: Butler, Bret W.; Cook, Wayne, comps. 2007. The fire environment—innovations, management, and policy; conference proceedings. 26-30 March 2007; Destin, FL. Proceedings RMRS-P-46CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 662 p. CD-ROM.

[1] Vegetation/Fire Specialist, Parks Canada, Jasper National Park, Alberta, Canada. alan.westhaver@pc.gc.ca

[2] Faculty of Environmental Design, University of Calgary, Alberta, Canada.

[3] Natural Resources Canada, Canadian Forest Service, Victoria, British Columbia, Canada.

Western Canadian wildland fire managers and researchers have observed disturbing changes in the structure and density of forests formerly subject to frequent disturbance by fire, an upsurge in wildfire intensity at these locations, and a corresponding increase in the difficulty of wildfire control (Quintilio 2005). For example, dense forest annually encroaches on ~30 km^2 of open forest and grassland in the Rocky Mountain Trench of British Columbia (Kootenay National Park 2002). Remote sensing and ground plots revealed significant stand and vegetation changes in Jasper National Park (Rhemtulla 1999; Mitchell 2005). Following the catastrophic 2003 fire season in British Columbia, a Provincial Review (Filmon 2004) concluded past fire suppression has contributed directly to fuel buildup in forests and that this buildup will result in more significant and severe wildfires, including more interface fires, unless action is taken. In Canada, many of the fire-adapted forests most severely impacted are at drier, low elevation areas most attractive to recreational and residential development (Duke 2001). Fuel buildup may be a lesser problem in the boreal forest where stand-replacing fires prevail.

These trends mirror the experience in the United States, where decades of fire exclusion policies have resulted in high accumulations of combustible fuels relative to conditions prior to 1900 (Mutch 1994; Graham and others 2004; United States Department of Agriculture 2005). Covington and Moore (1994) described how once frequent low-intensity surface fires served to clean the forest floor of fine fuels and remove regenerating conifers. From a fire perspective, reduced fire activity results in increased fuel loads, increased fuel continuity, and enhanced probability of crown fire (Daigle 1996; Scott and Reinhardt 2001; Graham and others 2004).

Improvements to fire management such as training, response, and enhancing structural resistance to fire are important, but fuel reduction remains as a leading method to decrease the incidence and severity of interface fires (Partners in Protection 2003). The principles of wildfire behaviour form the basis for fuel modification standards. Byram's equation for fireline intensity (Byram 1959) and more recent analysis by Countryman (1974) and Graham and others (2004) reveal that fuel is the only variable humans can manipulate to reduce the energy released by fire, whereas there is no control over weather or topography. Studies of wildfire behavior and severity in treated and untreated fuels by Martinson and Omi (2003) lend further support for fuel reduction approaches. Specifically, the ignition, development, and spread of wildfire are affected by characteristics of the fuel complex (Canadian Forest Service 1968). These include the total fuel load, fuel size and arrangement, the moisture and chemical content of fuels, and the "canopy base height" and bulk density of fuels (Scott and Reinhardt 2001; Cruz and others 2002). Interface residents and fire prevention agencies manipulate these fuel properties to reduce risk. When they do so, they are also affecting key aspects of wildlife habitat.

Fuel Management Standards in Canada

Current Canadian standards for interface fuel management were developed by the nonprofit organization "Partners in Protection™" and first published in the manual *FireSmart®: Protecting Your Community from Wildfire*, in 1999.

The FireSmart manual sets out preventive standards for management of forest fuels by individual homeowners, or agencies working at larger scales to protect communities. The purpose of these standards is to limit wildfire intensity, ease fire suppression efforts, and prevent structural ignitions (Partners in Protection 2003). Canadian FireSmart standards are based on the National Fire Protection Association code, *NFPA 1144 Standard for Protection of Life and Property from Wildfire* (NFPA 2002). The standards employ the four basic strategies of fuel removal, reduction, isolation, or conversion to alter fuel bed properties to reduce the potential for fire initiation and propagation of crown fire.

These standards require that more fuel be removed as the distance to a home or structure decreases. Based on this, the concept of three concentric "interface Priority Zones" was adopted by Partners in Protection (2003). These zones and the treatments that are found in them served as one basis for this study (fig. 1).

Overall, Canadian fire protection agencies are meeting with limited success in convincing individuals or communities at the interface to voluntarily modify or manipulate forest structure on and around private property. The Auditor General for British Columbia (British Columbia 2001) noted that only 3 percent of communities in the province had undertaken significant levels of risk mitigation, and that little was being done in 55 percent of communities where wildfire risk levels were rated moderate to high. Only 11 percent of communities had undertaken fuel reduction programs of any significance. Independent reviews following large interface fires in Alberta (DeSorcy 2001) and British Columbia (Filmon 2004) both concluded the lack of prefire preparation is a factor, and there is a great need to accelerate

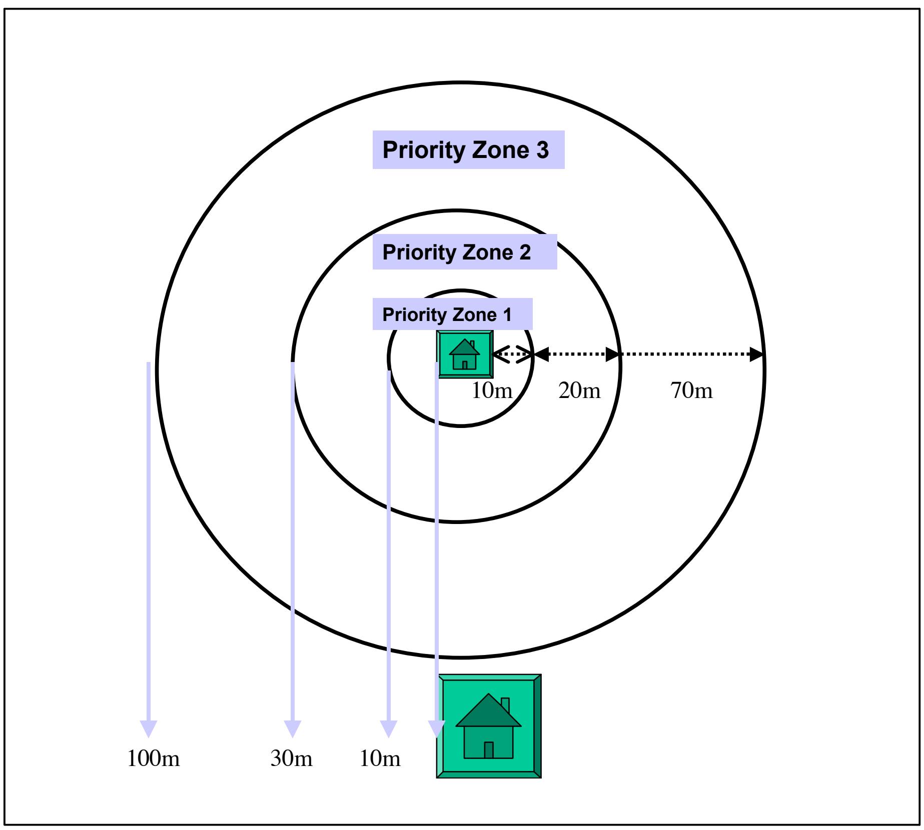


Figure 1—FireSmart fuel management Priority Zones within the wildland/urban interface (Partners in Protection 2003).

fuel management programs, which can ameliorate this danger. Since these surveys, both provinces have instituted improved hazard assessment and fuel management programs; however, the reluctance of residents and communities to treat fuel more aggressively frustrates many wildland and municipal fire managers.

Several reasons for this lack of action have been documented (Boura 1996; Winter and others 2004; McCaffrey 2004b; Mc Gee and others 2005; Brenkert and others 2005): resident perceptions that wildfire risk is lower than it actually is; lack of knowledge about risk reduction measures; willingness by residents to accept the risk of wildfire losses; constraints on the ability, funds, or time to implement solutions; skepticism about the effectiveness of risk reduction measures; lack of trust in public agencies responsible for fuel management; and conflicts between risk reduction measures and other resource values held by residents such as wildlife, conservation, or aesthetics.

Evidence is building that recurrent conflicts between existing standards for risk/fuel reduction and other resource values such as wildlife conservation may deter interface residents or communities from taking preventive actions. In Australia, fire hazard reduction practices reduced environmental qualities and caused bitter social divisions within local communities (Boura 1996). In Arizona local citizens opposed forest thinning “because they moved here for the forest,” making it clear that not everyone was comfortable with the concept of cutting trees or openly protested such actions as being destructive (Winter and others 2004). Graham (2003) listed privacy, wildlife viewing, recreation, aesthetics, and ideas of naturalness as key landscape values that influenced the acceptability of fuel management activities. For many Jasper residents and property owners, it seemed difficult to reconcile FireSmart fuel treatments with the personal importance they placed on aesthetic values, wildlife viewing opportunities, and the “natural” environment they live in. Citizens were also concerned about secondary environmental impacts, such as soil erosion or stream pollution, which may result from mechanized fuel treatment (Westhaver 2003). Consequently, it is easy for conflict to arise between fire managers who advocate manipulation of vegetation, and conservationists who view these actions as destructive (Brown 2002).

Such controversies suggest deficiencies in current approaches to community and residential wildfire protection. Further evidence for deficiencies is found in careful review of current FireSmart standards, which reveals a preoccupation with physical characteristics of the fuel complex and disregard for other resource values such as wildlife, wildlife habitat, biodiversity, cultural, and aesthetic qualities. Likewise, few procedures for limiting the secondary environmental impacts associated with major fuel manipulation projects are included. Interestingly, FireSmart authors recognized these shortcomings but could find little information to address these issues (Partners in Protection 2003).

Conversely, fuel initiatives have the best chance of being implemented if managers provide effective responses to the questions, objections, and concerns of residents (Winter and others 2002; McCaffrey 2004a). A better understanding of how fuel reduction treatments affect forest resources is required to minimize and resolve conflicts and to more effectively manage wildlife habitat (Kotliar and others 2002). The hesitancy of interface residents to implement FireSmart measures, due to conflicts with other resource values or needs such as wildlife, conservation, and aesthetics, was a primary motivation for this research.

Study Problem and Purpose

Based on the foregoing description, it is clear that conflicts between fuel modification to reduce wildfire risk and conservation of other resource values must be reconciled if objectives for protecting wildland/urban interface communities from wildfire are to be achieved. An urgent need for increased community wildfire protection, deep concerns of local citizens for wildlife and environmental protection, and Parks Canada's mandate for ecological integrity provided an opportunity to integrate innovation and research into a prototype program of fuel treatment in the wildland/urban interface at Jasper, Alberta. This situation also makes the town of Jasper an ideal site for gauging public support for modified fuel treatments.

The primary purpose of this research was to develop, implement, and recommend practicable, ecologically based approaches for managing vegetation at the wildland/urban interface in ways that optimize conditions for wildlife, within constraints of current fuel treatment standards. A secondary purpose, not discussed in this paper, was to establish a methodology for monitoring the long-term effects of fuel management on wildlife habitat and use (Westhaver 2006).

Study Area

The 250+ ha study area is within a heavily forested area of Jasper National Park, Alberta, at the confluence of three large glacial valleys. These fuel treatment areas are arrayed around the town of Jasper (fig. 2) and the recreation cottage subdivision at Lake Edith. Research was conducted under the joint auspices of Parks Canada, the Foothills Model Forest, and University of Calgary.

The area lies in the valley-bottom "Montane" ecoregion (Holland and Coen 1982) at an elevation of about 1100 m. This area is among the most productive and biologically diverse ecosystems in Jasper National Park (Holroyd and Van Tighem 1983). A wide range of forest types comprise much of the park's critical ungulate winter range, and other specialized wildlife habitats.

Coniferous forests of the study area are mostly composed of mature lodgepole pine (*Pinus contorta* Dougl. *ex* Loud.), with less area of Douglas-fir (*Pseudotsuga menziessi* (Mirb) Franco) forest and mixed conifer forest. White spruce (*Picea glauca* (Moench) Voss) and Douglas-fir are typically late-succession species with white spruce dominating conifer regeneration in mesic and hygric sites, and lodgepole pine and Douglas-fir regeneration in xeric sites. Plant species and communities in this ecoregion are adapted to frequent, low-intensity surface fire or mixed-intensity fire (Tande 1979; Achuff 1996; Andison 2000). Low intensity (stand maintaining) surface fires predominated in grasslands and open canopy Douglas-fir and lodgepole pine stands. High intensity (stand replacing) crown fires prevailed in moister, continuous pine stands on the valley sides and some valley bottom areas (Tande 1979). Due to the absence of fire for much of the past century, formerly open, savannah-like Douglas-fir forest and lodgepole pine forest in the study area have changed significantly. They are now characterized by a scattering of dominant widely spaced, large diameter Douglas-fir veterans (200 to 300 years old) that are ingrown with a dense multilayered canopy of shorter, smaller-diameter lodgepole pine and Douglas-fir.

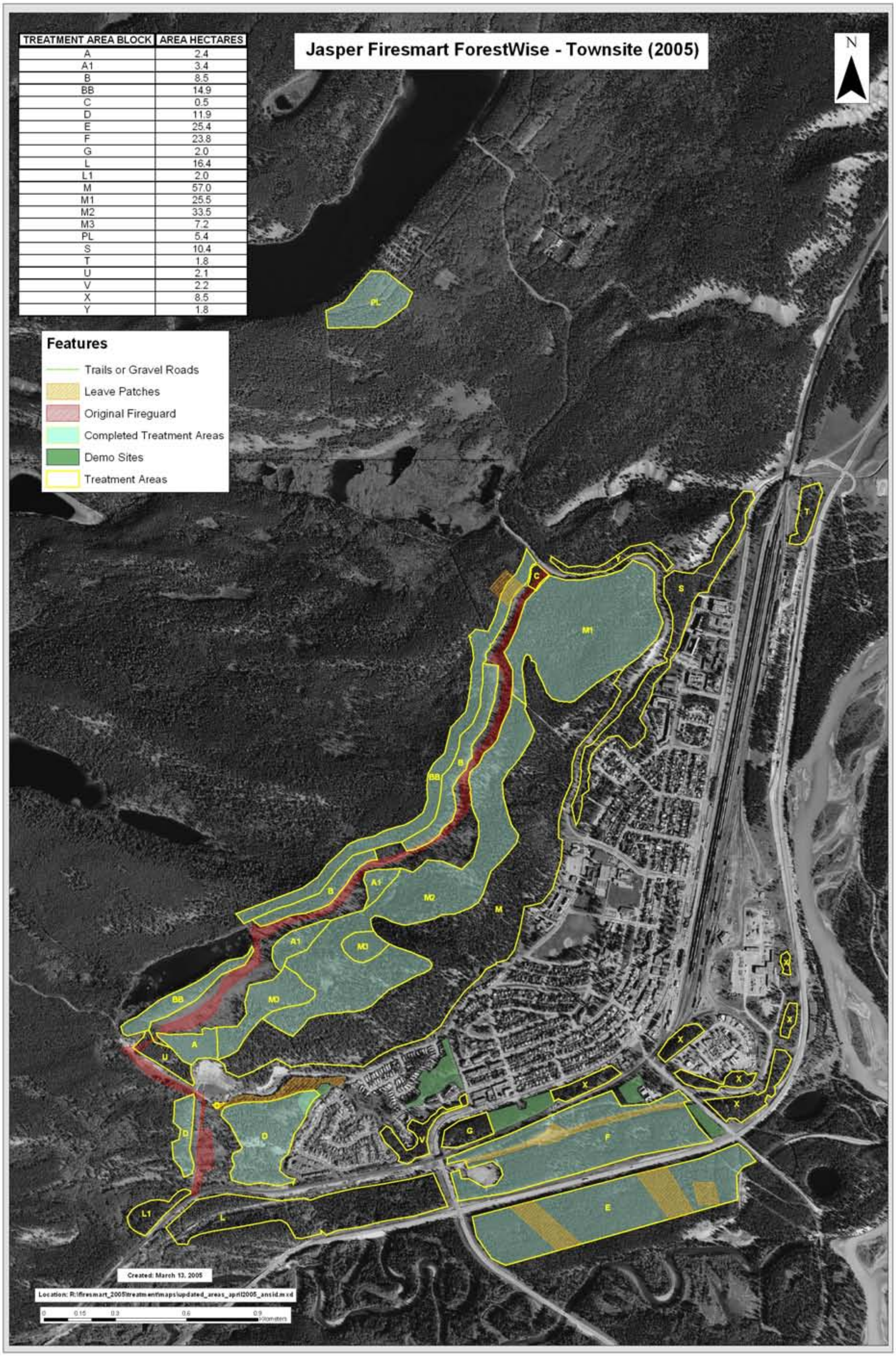


Figure 2—Wildland/urban interface operating areas surrounding the town of Jasper.

Prior to Euro-American arrival, aboriginal peoples influenced these Montane ecosystems and the vegetation found here for more than 10,000 years (Heitzmann 2001; White 2001). Although aboriginal peoples appear to have ignited the majority of Montane fires, lightning ignitions also played a role in establishing ecosystem patterns, processes, and the plant composition now being managed (Wierzchowski and others 2002). Since settlement by nonnatives, anthropological use of fire has dramatically declined in this area (White 2001).

Impacts of the recent "fire-free" period on vegetation are significant. Over the past 65 years the amount of Montane forest older than 100 years has nearly quadrupled from 21 to 78 percent (Andison 2000). Between 1915 and 1995, the proportion of the Montane occupied by grasslands and open forest habitats decreased by more than 50 percent, with similar decreases in the number of these patches/100 ha (Rhemtulla 1999; Mitchell 2005). Hammond (2003) stated that much of the current structure of Montane forest is an artifact of recent fire management practices, rather than reflective of natural processes and the historical range of variation. Subsequently, Parks Canada concluded that, due to fire control, the current fire regime and forest conditions are outside the historical ranges of variation, that fire must be actively restored, and that risks to developed areas must be ameliorated (Parks Canada 2000).

For Parks Canada, it is also important to avoid wildlife/human conflicts (Ralf and Bradford 1998); maintain grizzly bear habitat effectiveness (Parks Canada 2000); provide connectivity and corridors so that wildlife, particularly carnivores, are able to move freely through the landscape (Mercer and Purves 2000); and provide adequate protection for species listed under the Canadian Species at Risk Act.

The interface is also the portion of Jasper National Park that receives the majority of human development and use. Jasper, a community of about 5,000 residents and 500 businesses, is the service centre for park visitors and administration, and a division point for Canadian National Rail. Up to 20,000 visitors can be accommodated nightly and more than 2 million visitors use the park each year (Parks Canada 2000). Wildfire risk (La Morte and Associates 1996) in the town area is substantial and has been recognized for many years (Carnell and Anderson 1974; Haney and Anderson 1978; Fenton 1986; FireLine Consulting 1997; Mortimer 1998, 1999; Blackwell and Mortimer 2004). Risk arises from a combination of high probability of fire ignition from frequent lightning, industrial, transportation, and other human-caused sources and extreme consequences that would result, given the expectation of a fast-moving high intensity wildfire.

Starting in 1999, solutions to reduce wildfire risk were methodically implemented. Initial efforts focused on infrastructure improvements, structural modifications, and better emergency preparedness (Jasper Interface Steering Team 2002). By 2001, efforts shifted to fuel reduction, by landowners and Parks Canada. At the same time, residents and park managers became increasingly aware that fuel manipulations could adversely affect wildlife and wildlife habitat, and deficiencies in FireSmart standards grew more apparent. Without more appropriate fuel measures to address resource and social concerns, it seemed unlikely that sufficient public or management support for fuel reduction programs would be obtained. It also seemed obvious that improvements to standard fuel treatments could, and should, be made. This study addresses these deficiencies.

Methods

This study employed a combination of literature review, experimentation learning through adaptive management (Walters and Holling 1990), and deductive analysis to develop innovative fuel treatments that better accommodate wildlife while managing interface vegetation to reduce wildfire risk. Improved fuel treatments were applied by labor crews and specialized industry contractors, then evaluated and refined by Parks Canada in a 250-ha prototype fuel management project at Jasper, Alberta. The work took place over three winters between 2003 and 2005. This approach was adopted as the best means of achieving the goals of this study and overall risk reduction objectives at Jasper, given the constraints of time, and the near absence of reproducible scientific studies specific to fuel treatments in the wildland/urban interface. Figure 3 summarizes the overall sequence of analytical steps employed to achieve the study purpose.

The key principles of wildland fire behavior (Van Wagner 1977; Forestry Canada Fire Danger Group 1992; Scott and Reinhardt 2001; Cruz and others 2002; Graham and others 2004) and home ignition (Cohen 2000a,b;

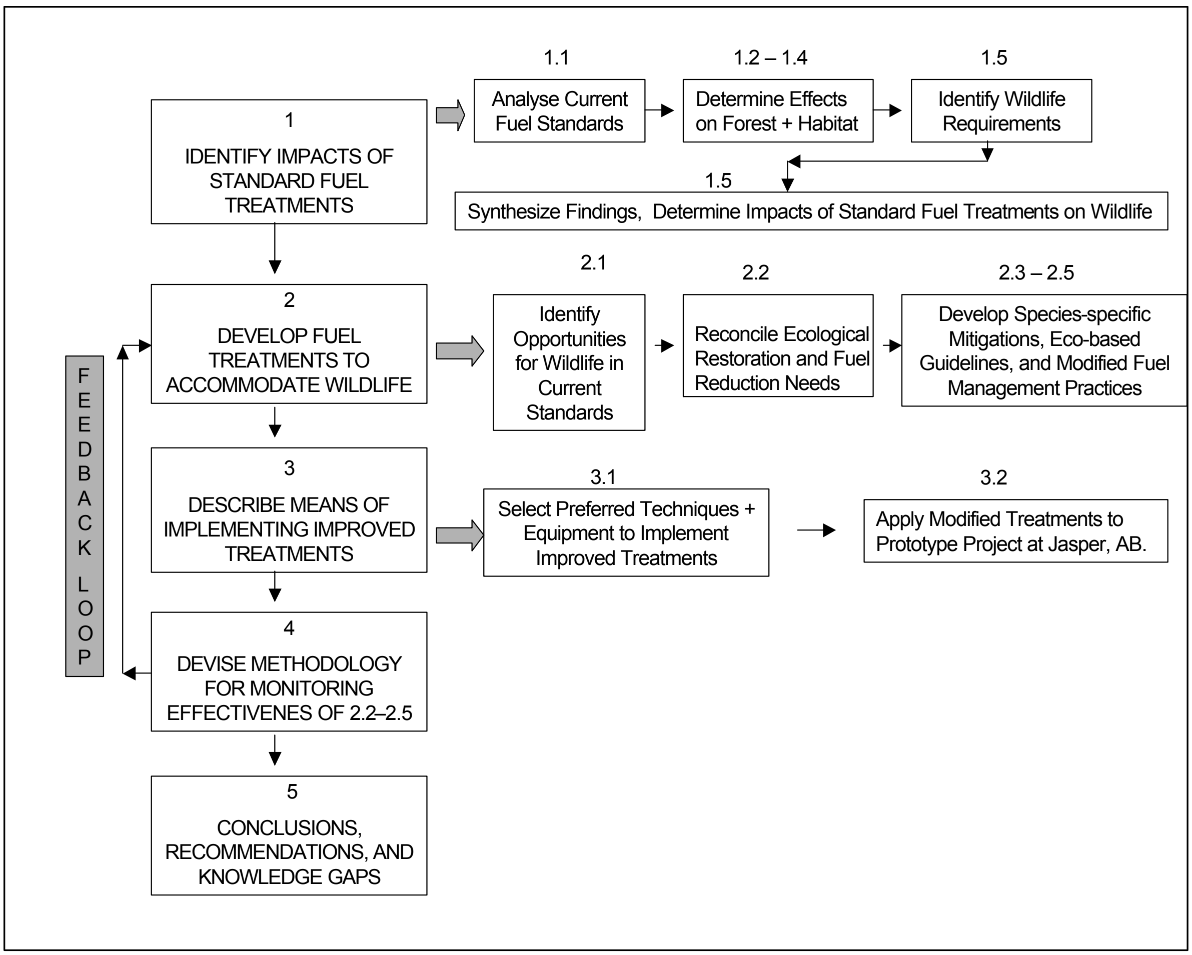


Figure 3—Schematic of research methods.

Cohen and Stratton 2003) were reviewed at the onset of the study. This was done to avoid violating the intent or efficacy of existing fuel treatment standards when proposing more environmentally sensitive methods. FireSmart standards were dissected and reorganized in relation to six horizontal fuel bed layers as described by Sandberg and others (2001) to facilitate a logical review of the ecological effects of fuel treatments and practical presentation of improved methods (table 1). For biological reasons, Sandberg's ground fuel stratum (2001) was sub-divided into fine and coarse woody fuels, and the tree canopy sub-divided into overstory and understory, thus creating eight layers in this study.

Extensive literature reviews were conducted to identify potential impacts of fuel treatments on abiotic forest components such as insolation, temperature, wind flow, effective precipitation, relative humidity, soil moisture, and soil nutrient status. Literature was also surveyed about the habitat roles of each fuel bed stratum to help predict the direct and/or indirect effects of fuel treatments on each of these. Existing literature was reviewed to determine how fuel management treatments alter important habitat features. We chose habitat trees, forest edge, coarse woody debris, and wildlife corridors as important habitat attributes, and grasslands, aspen forest, and wetland/riparian areas as being significant habitat types. Next, we identified the potential impacts of fuel treatments on 41 species of wildlife common to the interface. Selected species included four cavity excavators, eight songbirds, six raptors, 12 small mammals, one bat, six carnivores, three ungulates, and one amphibian.

Table 1—Fuel bed layers (from Sandberg and others 2001) used to assess wildlife habitat impacts and develop mitigation techniques.

Fuel bed strata	Characteristics
1. Ground fuel stratum	Duff or organic soil horizons, roots, and buried wood. Generally, ground fuels are consumed by long duration smoldering fire, after passage of the flame front characteristic of surface and crown fires.
2. Moss-lichen-litter stratum	"Fine" fuels consisting of bryoids and loose undecayed needles and leaves. These fuels burn during flaming and glowing combustion phases of surface fires.
3. Woody fuel stratum	Fine (<0.76 cm), medium (0.76 to 7.5 cm), and coarse (>7.5 cm) woody material on, or in contact with, the ground; may be sound or rotting, and arranged individually (stumps), loosely, or in piles.
4. Low vegetation stratum	Grasses and herbs. Cured fine fuels burn quickly contributing to surface fire intensity, but not to fire residence time.
5. Shrub stratum	Dwarf shrubs, tall shrubs, and coniferous regeneration. Burn vigorously in surface fires to increase fire intensity depending on fuel moisture content. These fuels serve as connecting "fuel ladders" and transmit surface fire into the canopy.
6. Tree canopy stratum	Crown or "aerial" fuels consisting of live and dead trees (needles and branches <0.76 cm) and arboreal lichens. Continuous, high density, canopies lead to crown fire and ember spotting.

Current fuel reduction standards were examined, by fuel bed layer and interface Priority Zone, to discern prospects for incorporating measures that could improve wildlife and habitat quality, or at least reduce adverse impacts, without reducing effectiveness of fuel treatments. Literature pertaining to forest health, natural disturbance, and ecological restoration was then surveyed to establish possible linkages with vegetation manipulation for fire protection purposes.

Once potential mitigations for protection of wildlife and habitat were identified, these were incorporated into prototype fuel treatments and presented in the form of "prescriptions." Unique prescriptions were developed for each forest type in the study area. To aid in assessing the practicability of the prototype fuel treatments they were first applied at several 0.5 to 1.5 ha "demonstration sites." Initially, Parks personnel worked with resident volunteers during neighborhood "work-bees" to implement fuel treatments. Later, between April 2003 and October 2005 these treatments were refined and applied on much larger areas around the town of Jasper, by specialized timber firms under contract to Parks Canada.

Results

Detailed information about FireSmart fuel standards, literature reviews, and step-wise analyses of impacts of fuel treatments on abiotic forest components and biological attributes of fuel beds, and the impacts of fuel treatments on 41 species of birds, mammals, and amphibians common to wildland/urban interface areas are found in Westhaver (2006), which also provides the results of an analysis to identify opportunities for accommodating wildlife and habitat attributes in each forest/fuel bed stratum (within the constraints of current fuel treatment standards). See Westhaver also for details of other results of the prototype project not discussed in this paper, including a methodology for long-term monitoring of wildlife and habitat responses to fuel treatments, and assessment of mechanized techniques for implementing large-scale fuel treatments.

We investigated the potential for achieving ecological restoration concurrent with measures for community wildfire protection. That approach is advocated by several authors (Arno and Wakimoto 1987; Covington and Moore 1994; Fule and others 2001; Brown 2002; Omi and Joyce 2003) but was, to our knowledge, untested in Canada. We found strong similarities between the solutions required to resolve ecological problems in fire-dependent forests such as forest in-growth, forest encroachment, and replacement of deciduous species by conifers, and fire protection issues caused by hazardous fuel accumulations. We judged that, by selectively thinning the forest canopy to restore stand structure and composition to within their historic ranges of variability, the net effect is also to reduce wildfire risk. We also concluded that by using information about historical forest density and structure as a guide to thinning intensity, wildfire risk can be reduced (in some areas) to levels below what could be expected by applying FireSmart standards alone. These overlapping objectives did not extend to even-aged lodgepole pine forests initiated by stand-replacing fires. In these stands, prescribed thinning standards result in habitat conditions that depart from historic norms, but may still benefit wildlife. For example, marten may find more meadow vole prey within thinned stands, but the density of red squirrels in the interface zone is likely to be less than found during pretreatment levels.

Numerous opportunities for maintaining or enhancing wildlife conditions within constraints of current fuel treatments were identified after examining FireSmart standards. Due to stricter needs for fuel removal close to structures, opportunities increased with increasing distance from structures. Five strategies were identified for managing the forest canopy to benefit wildlife: (1) variations of single-tree thinning, (2) cluster thinning, (3) selective preservation of habitat trees, (4) stand type conversion, and (5) selection for prevention of posttreatment windthrow. The opportunity analysis was carried out through other fuel bed/forest layers and yielded many more wildlife prospects in treated fuels (Westhaver 2003).

Species-Specific Mitigations for Wildlife and Habitat Conservation

A key result of this study was to synthesize information about the life/habitat needs of wildlife common to the interface and identify mitigations to minimize the impact or obtain wildlife benefits within the context of current fuel treatments. A sampling of that content from Westhaver (2006) is provided in table 2. This synthesis resulted in a variety of species-specific conservation measures to minimize adverse impacts to wildlife or, alternatively, optimize wildlife benefits from fuel management treatments. Overall, we suggest that protection of habitat trees, coarse woody debris, and structural diversity within stands are the most significant mitigation factors. Species-specific mitigations were refined during three operating seasons of the Jasper prototype fuel management project to ensure their practicability. The full set of wildlife habitat requirements and mitigations are summarized in seven tables, grouped by species with similar habits and life requirements, and are presented in Westhaver (2006).

Ecosystem Based Fuel Management Guidelines – by Priority Zone and Fuel Bed Strata

For each interface Priority Zone and within each of the eight fuel bed strata, we developed and field-tested ecosystem based fuel treatment guidelines for benefits to wildlife or reducing potential adverse impacts of fuel management activities. Once again, these guidelines respect the overriding principle that FireSmart standards for reducing fire intensity be followed.

In Priority Zone 1, these guidelines provided for preserving or planting deciduous trees to provide important seasonal habitat, measures to allow selective retention of existing snags and creating additional snags by topping mature conifers, suggestions for preserving "feature" trees while reducing ignition potential, managing native shrubs to optimize forage, shade, and cover for wildlife, cultivating fire-resistant ground covers, and preserving isolated logs.

Even more extensive opportunities for accommodating wildlife are possible in Priority Zones 2 and 3. Guidelines were provided that recommend retention of all deciduous trees and offer a series of principles to preserve long-term wildlife benefits when deciding which conifers to retain or remove from mixedwood or pure conifer stands. Guidelines to identify and preferentially retain long-lived tree species and individuals with windfirm traits are presented. Trees with twin, multiple, and broken tops or fire scars should be retained since these deformities, and associated decay, make these trees highly suitable for wildlife nesting, roosting, and feeding sites. Exceeding the single-tree spacing standards is recommended to create forest gaps or open

Table 2—Example habitat requirements and mitigations to minimize impacts of fuel management or obtain benefits for interface wildlife.

Species	**Habitat Requirements**	**Mitigations to Minimize Impact or Obtain Benefits**
Pileated Woodpecker	Widespread but relatively uncommon year round resident of most Canadian forests; has a large territory; needs minimum 33 cm Diameter at Breast Height (DBH) snags or live trees with decay for excavating nests and roosts; ants and insects in trees and logs are main year round food; uses live hollow or decaying trees for drumming; attracted to sheltered clumps of dead trees and downed logs.	Retain a mix of forest ages and types in the region; retain 12-15 snags and 12-15 living trees with decay (legacy trees) per ha of all diameters, species and sizes with bias towards large diameter (>33 cm DBH) trees; broken-top trees most important; use cluster thinning technique to retain cover adjacent habitat trees; retain trees infested with ants/insects; retain up to 50 logs/ha on ground (long and large is best) and extra snags for forage and future downed logs; keep tall stumps of all sizes; survey areas for active use by woodpeckers first.
Black-capped Chickadee	Common year-round resident Canada-wide; feed by gleaning insects and insect eggs from bark, twigs, boles, and foliage of trees and shrubs from ground to crowns; seeds, berries augment diet; can excavate nests in rotted wood; use existing cavities/hollow trees; stubs are important nest sites; select nest trees <or= 10 cm. DBH, often in open areas; roost in cavities/dense conifers out of wind.	Retain or create a variety of dead or dying trees of different diameters and species for nesting and foraging; preserve broken-topped trees, even short stubs; thinning will encourage seed sources from native flowering plants and berry production; augment these with planted landscapes around home and/or bird feeders; preserve shelter around habitat trees and small clusters of conifers for roosting out of the wind and rain.
Red-backed Vole	Common in boreal and mountain forest across Canada; closely linked with moist, mossy, mature conifer forest; downed woody material very important for cover; feeds heavily on fungi (mushrooms) associated with decaying wood; also eats seeds, insects, berries; use squirrel middens; key prey items.	Leave abundant coarse woody debris, large logs, small brush piles, and decaying matter to foster fungus foods and provide shelter and moisture; use cluster thinning and protect shrubby understory to preserve pockets of dense forest and shaded sites; limit thinning in moist forest areas where possible; protect squirrel middens.
Weasel	Coarse woody debris provides access to under-snow environments and cover for potential prey species; most common in regenerating forest and grassy areas suited to prey species, residual trees.	Leave abundant coarse woody debris, large logs, and small brush piles where possible to foster abundant prey and provide cover. Leave protruding debris to provide access routes and under snow travel routes; use cluster thinning and protect shrubby understory to preserve pockets of dense forest and shaded sites; protect squirrel middens.
White-tailed Deer	Found across Canada in grassland, parkland and boreal mixedwood; spring/summer diet mostly flowering plants, grasses; browse on deciduous trees and shrubs in winter; mostly inhabit forest edges to feed in open and seek cover in forest/shrubs; small conifer thickets are winter refuge.	Interface areas can provide forest edge favorable to white-tailed deer; encourage and preserve deciduous shrubs and aspen during thinning; open canopy will increase summer forage availability; preserve thickets of coniferous saplings in deciduous/mixedwood forest for cover (remove mature conifers that overtop regeneration to reduce fire spread).

forest habitats that provide habitat diversity while further decreasing fuel continuity, which significantly reduces fire spread rates while increasing ease of fire control. All habitat trees with nests and cavities should be preserved. Wildlife use can be increased by pairing habitat trees with living trees, or by preserving clusters of habitat trees. A minimum of 12 to 15 snags per hectare should be retained for optimal wildlife conditions. In the forest understory, rather than removing all coniferous regeneration, overtopping mature trees can be removed in some cases to provide increased wildlife cover and security while also allowing for long-term tree replacement and seral succession. At least 25 to 350 linear metres of logs should be left on the ground, with preferential protection for older, larger, and more decayed individuals.

"Best Practices": Guidelines for Modified Fuel Management

This study also developed a series of general guidelines for modified fuel practices more sensitive to ecological considerations in the wildland/urban interface. These are not specific to wildlife species or interface priority zone.

Burning of woody debris in many smaller piles is recommended in preference to disposal methods such as chipping and spreading. This encourages nutrient cycling and hastens establishment of native plant cover. Restricting mechanized fuel operations to winter when organic layers are frozen and covered with insulation snow will minimize soil disturbance and disruption of low habitat structure. Curtailing the season and hours of mechanical operations allows wildlife migrations and diurnal movements. We found that key habitats such as forest edge could be enhanced by enlarging and making existing forest openings more irregular in shape, and that knowledge of wildlife habits and local animal movements can be used to preserve existing wildlife corridors or ensure adequate hiding/security cover for animals as they move between foraging sites. We recommend minimal vegetation disturbance around groundwater discharge areas, temporary pools, and moist depressions but compensating for this with adjacent areas of more stringent fuel reduction.

We also produced guidelines for adapting thinning from below methods to Douglas-fire and open lodgepole pine forest types and regimes of frequent fire. These guide tree retention decisions in terms of age, diameter, species, and spacing and utilize large veteran trees as "anchor" points to start the process. Conversely, decision rules were developed to adapt thinning from above methods for use in denser, even-aged lodgepole pine stands to encourage stand/habitat diversity and succession of shade tolerant species. Guidelines for minimizing posttreatment windthrow include selective retention of trees with both lateral and tap root systems, greater height and width of live crown, and low slenderness index along with liberal use of cluster thinning. Detailed guidelines for all types of wildlife trees are provided (Westhaver 2006).

Altogether, the foregoing species-specific mitigations, Priority Zone and fuel bed layer guidelines, and general best practices form a set of ecologically based criteria for modifying current fuel management practices in ways that benefit wildlife, but do not compromise risk-reduction objectives of FireSmart standards.

Discussion

Developing the above guidelines and mitigations by adaptive management approaches, during an operational fuel management project, proved to be an effective method for testing and refining practicable solutions. This approach allowed for continuous exchange between researchers and the manual crews, specialized forestry harvesting contactors, and equipment operators responsible for implementing them. That feedback resulted in many practical improvements. Also, adopting a collaborative approach involving operators and crews improved communications regarding wildlife conservation objectives, and led to a shared interest in achieving positive results. As an example, enthusiastic equipment operators offered up many abilities and mitigative actions that heavy equipment is capable of performing, but fuel managers were unaware.

Our assessment of potential ecological effects of standard fuel treatments revealed that manipulating fuel load, arrangement, and size distribution also resulted in substantial alterations to important wildlife habitat qualities. Specifically, we noted that fuel modification directly or indirectly affected most aspects of forest structure, forest composition, and forest function, and that these effects can lead to a wide range of adverse impacts upon wildlife and wildlife habitat. As a corollary, we also concluded that knowledge of these effects was useful to guide fuel manipulation programs in a more informed way, thus allowing adverse impacts to be avoided and potential wildlife benefits to be realized. We judged that the correlation between fuel bed strata and ecological or habitat layers was strong, and this analogy was useful for organizing, understanding, and presenting the effects of fuel manipulation, as well as developing more holistic fuel treatments.

Existing literature provided sound information about life requirements for wildlife. However, we found that most literature concerning wildlife response to forest disturbance was related to major events such as clearcut logging or wildfire, but there are few studies, and few experimental data, to verify the response of wildlife to fuel treatments that leave significant canopy cover, a less severe form of disturbance. Our forecasts of potential impacts of fuel treatments were hampered by this knowledge gap. Future wildlife studies in fuel treatments would be beneficial; in aid of this, pretreatment sampling of small mammal and ungulate activity was conducted in permanent 90 x 90 m grids (Westhaver 2006).

The ability to provide benefits for habitat and wildlife varies between vegetation and fuel types. For example, it is desirable to preserve an ongoing supply of snags of all structural forms (Bull and others 1997), in a variety of topographic positions, and with a range of adjacent cover (Brittingham and De Long 1998). However, we found that the ability to do so was significantly limited in even-aged lodgepole pine stands, whereas opportunities to meet these objectives were plentiful in mixed conifer and Douglas-fir forest types. Forest edge can be increased or decreased during fuel treatments by varying the pattern and degree of canopy thinning, creating or augmenting forest openings, and aligning treatments with topographic or soil type boundaries. However, the utility of artificially created openings and edges is poorly known.

Study Limitations and Knowledge Gaps

This and other attempts to develop ecologically based fuel treatments will continue to be hampered until more field studies to scientifically assess the effects of fuel treatments and the responses of habitat and wildlife are conducted. In aid of this, a fixed plot sampling methodology for monitoring long-term changes in vegetation conditions and wildlife use was developed and put into place prior to fuel manipulations at Jasper (Westhaver 2006). Followup studies are strongly recommended in this prototype area, and other locations, to help fill current knowledge gaps. Aside from limitations that result in applying literature from other forest disturbances that are similar, but not identical to fuel treatments, are limitations that may result from conclusions drawn from studies conducted in similar but different ecosystems.

Given that this study was partly motivated by perceived conflicts between fuel treatments and other values held by interface residents, it is advisable that sociological research be initiated to determine if the improved treatments described by this study are, in fact, more acceptable to these people. We also suggest that, due to the great importance of coarse woody debris for wildlife, studies be directed at better determining threshold levels of debris that can be retained for wildlife purposes without compromising fire protection objectives.

Through this research, we are hopeful that wildland and municipal fire managers will augment the dominant viewpoint of "vegetation as fuel" with a more holistic perspective of vegetation as the basis for wildlife populations and other social or ecological values held by interface residents. In this way concerns of interface residents can be addressed, and a significant barrier to fire prevention actions removed.

Acknowledgments

The authors thank Parks Canada and the Foothills Model Forest for encouraging this research, a component of a large-scale operational undertaking called the *FireSmart – ForestWise Communities Project* in Jasper, Alberta. Our sincere gratitude goes to many local stakeholders who provided encouragement, provoked ideas, and shared in the passion of this project. We are indebted to Brian Wallace, Kevin Van Tighem, and Ron Hooper of Jasper National Park, and to Don Podlubny of the Foothills Model Forest. Our particular thanks go to the gifted field supervisors and members of field crews from the Metis Nation of Alberta, to the exceptional people from the forest industry, and especially to FireSmart Technicians Clayton Syfchuck, Mike Suitor, and Lorraine Wilkinson. Drs. Cormack Gates, Darren Bender, Bill Ross, Michael Mc Mordie, and Pauline Fisk of the University of Calgary provided invaluable support and feedback during this research. Above all, the lead author wishes to express his great appreciation to Lisa, Heather, Robin, and Theresa Westhaver for their loving support and patience throughout this adventure.

References

Achuff, P.L. 1996. Fire in the Rocky Mountain National Parks. Unpublished Parks Canada Paper presented at the National Prescribed Fire Workshop, La Maurice National Park. 19 p.

Andison, D.W. 2000. Landscape level fire activity on foothills and mountain landscapes of Alberta. Bandaloop Landscape-Ecosystem Services. Foothills Model Forest. Ecology Research Series, Report No. 2.

Arno, S.F.; Wakimoto, R.H. 1987. Fire ecology of vegetation common to wildland homesites. In: Fischer, W.C. and S.F. Arno, compilers. 1987. Protecting People and Homes From Wildfire in the Interior West. Proceedings. Gen. Tech. Rep. 251. Ogden, UT: U.S. Department of Agriculture, Forest Service. Intermountain Research Station. 213 p.

Blackwell, B.A.; Mortimer, D. 2004. Jasper National Park municipal wildfire protection strategy. Final Report. Prepared by B.A. Blackwell and Associates and FireLine Consulting and Instruction Ltd. for Jasper National Park. Internal report.

Bothwell, P. 2006. Unpublished data. Fire Research Officer, Canadian Forest Service, Northern Forestry Centre, Edmonton, Alberta.

Boura, J. 1996. Fire and biodiversity: the effects and effectiveness of fire management. Biodiversity Series, Paper No. 8. 9p. http://www.environment.gov. au/life/general_info/biodiver_8/paper22.html, accessed May, 2005.

Brenkert, H.; Champ, P.; Flores, N. 2005. Mitigation of wildfire risk by homeowners. Res. Note RMRS-RN-25. Fort Collins, CO. U.S. Department of Agriculture, Forest Service. Rocky Mountain Research Station. 9 p.

British Columbia. Office of the Auditor General. 2001. Managing interface fire risks. Report; 2001/2002:1. 111 p.

Brittingham, M.C.; De Long, C.A. 1998. Management practices for enhancing wildlife habitat. Pennsylvania State University. College of Agricultural Sciences, Cooperative Extension. 10 p.

Brown, R. 2002. Thinning, fire, and forest restoration: a science-based approach for National Forests in the Interior Northwest. Washington, DC: Defenders of Wildlife. 40 p.

Bull, E.L.; Parks, C.G.; Torgersen, T.R. 1997 Trees and logs important to wildlife in the interior Columbia River Basin. Gen. Tech. Rep. PNW-GTR-391. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 55 p.

Byram, G.M. 1959. Combustion of forest fuels. Chapter 1: 61 – 89. In: Davis, K.P. (ed.). Forest fire control and use, 2nd edition. New York: McGraw-Hill.

Canadian Intergovernmental Conference Secretariat. 2005. Backgrounder: Canadian Wildland Fire Strategy Declaration, Canadian Council of Forest Ministers. 3 p. Ref: 830-858/005. http://www.scics.gc.ca/cinfo05/830858005_e.html Accessed January, 2006.

Canadian Forest Service. 1968. Canadian forest fire danger rating system, fire behavior prediction system (FBP) component.

Carnell, D.; Anderson, G. 1974. Proposal for the development of a fire protection zone around Jasper town site. Jasper Warden Service. Unpublished.

Cohen, J.D. 2000a. Examination of the home destruction in Los Alamos associated with the Cerro Grande fire. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Cohen, J.D. 2000b. Preventing disaster: home ignitability in the wildland/urban interface. Journal of Forestry 98(3): 15-21.

Cohen, J.D.; Stratton, R. 2003. Home destruction within the Hayman fire perimeter. In: Graham, R.T. (tech ed). 2003. Hayman Fire case study. Gen. Tech. Rep. RMRS-GTR-114. Ogden, UT:. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 396 p.

Countryman, C.M. 1974. Can Southern California conflagrations be stopped? Gen. Tech. Report. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station.

Covington, W.W.; Moore, M.M. 1994. Post-settlement changes in natural fire regimes and forest structure: ecological restoration of old-growth ponderosa pine forest. In: Sampson, R. Neil: Adams, D.L., (eds.) Assessing forest ecosystem health in the inland West. New York: The Haworth Press Inc.: 153–181.

Cruz, M.G.; Alexander, M.E.; Wakimoto, R.H. 2002. Predicting crown fire behavior to support forest fire management decision-making. In: Forest fire research and wildland fire safety. Rotterdam, Netherlands: Millpress.

Daigle, P. 1996. Fire in the dry interior forests of British Columbia. Ministry of Forests Research Program. Extension Note #8. Victoria, BC, Canada: British Columbia Ministry of Forests. 6 p.

DeSorcy, G.J. 2001. Chisholm fire review committee: Final report. Commissioned by Alberta Sustainable Resource Development. 50 p.

Duke, D.L. 2001. Wildlife use corridors in the Central Canadian Rockies: multivariate use of habitat characteristics and trends in corridor use. M.Sc. Thesis. Edmonton, Alberta, Canada: University of Alberta. Department of Biological Sciences.

Duke, D.L.; Quinn, M.; Butts, B.; Lee-Ndugga, T.; Wilkie, K. 2003. Spatial analysis of rural residential expansion in Southwestern Alberta. Calgary, Alberta, Canada: University of Calgary, Miistakis Institute for the Rockies. 49 p.

Fenton, G. 1986. Pyramid bench fire protection plan. Jasper Warden Service. Unpublished. Park. Internal Report. 300 p.

Filmon, G. 2004. Firestorm 2003, provincial review. Report to the Provincial Government of British Columbia. Gary Filmon, Chair. 100 p.

FireLine Consulting and Instruction. 1997. Inter-park hazard evaluation project: Prairie and Mountain Parks. Report to Parks Canada – Western Fire Management Centre.

Flannigan, M.; Stocks, B.; Wotton, M. 2003. Climate change and boreal fire activity: fact sheet 9. Sault Ste. Marie, Ontario, Canada: Natural Resources Canada, Canadian Forest Service, Great Lakes Forestry Centre. http://www.nofc.forestry.ca/climate/en/factsheets/factsheet9_e.html

Flannigan, M.; Wotton, M.; Carcaillet, C.; Richard, P.; Campbell, I.; Bergeron, Y. 1998. Fire weather: past, present and future. In: Proceedings of the 3rd International Conference of Forest Fire Research and the 14th Conference Fire and Forest Meteorology. Vol. 1: 113-128.

Forestry Canada Fire Danger Group. 1992. Development and structure of the Canadian forest fire behavior prediction system. Information Report ST-X-3. 63 p.

Fuglem, P. 2004. Personal communication. Victoria, British Columbia, Canada: Director, British Columbia Ministry of Forests, Protection Program.

Fule, P.Z.; McHugh, C.; Heinlein, T.A.; Covington, W.W. 2001. Potential fire behavior is reduced following forest restoration treatments. In: Ponderosa pine ecosystems restoration and conservation: steps toward stewardship. Compiled by R.K. Vance, C.B. Edminster, W.W. Covington and J.A. Blake. Proceedings RMRS-P-22. Fort Collins, CO: U.S. Department of Agriculture, Forest Service. Rocky Mountain Research Station.

Graham. R.T. (tech ed). 2003. Hayman Fire case study. Gen. Tech. Rep.. RMRS-GTR-114. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Stations. 396 p.

Graham, R.T.; McCaffrey, S.; Jain, T.B. (tech ed). 2004. Science basis for changing forest structure to modify wildfire behavior and severity. Gen. Tech. Rep. RMRS-GTR-120. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 43 p.

Hammond, H. 2003. Technical review of FireSmart – ForestWise Methods Jasper National Park. Unpublished Parks Canada report by Silva Ecosystem Consultants Ltd. Slocan Park, British Columbia. 33 p. and follow-up letter report to Parks Canada, Jasper. January, 2006.

Haney, B.; Anderson, G. 1978. Proposal for reduction of forest fire fuel hazards bordering Jasper townsite. Jasper Warden Service. Unpublished report.

Heitzmann, R.J. 2001. In: Collection of Papers from the 33rd Meeting of the Canadian Archeological Assoc. Edited by Jean-Luc Pilon. Ontario Archeological Society.

Holland, W.D.; Coen, G.M. (gen ed). 1982. Ecological (Biophysical) Land Classification of Banff and Jasper National Parks. Volume II: Soil and Vegetation Resources. Publication No. SS-82-44. Alberta Institute of Pedology.

Holroyd, G.L.; Van Tighem, K.J. 1983. Ecological (Biophysical) Land Classification of Banff and Jasper National Parks. Volume III, Parts A and B: The wildlife inventory. Edmonton, Alberta, Canada: Canadian Wildlife Service. 667 p.

Jasper Interface Steering Team. 2002. Unpublished meeting minutes of the resident's wildland/urban interface advisory group. Monthly meetings. Jasper, Alberta.

Kootenay National Park. 2002. Environmental assessment for the Redstreak ecological restoration in Kootenay National Park. Resource Conservation file report. 36 p.

Kotliar, N.B.; Hejl, S.J; Hutto, R.L.; Saab, V.A.; Melcher, C.P.; McFadzen, M.E. 2002. Effects of fire and post-fire salvage logging on avian communities in conifer-dominated forests of the Western United States. Studies in Avian Biology 25:49 – 64.

La Morte and Associates. 1996. Risk assessment of fir management alternatives: Mountain Parks, Parks Canada. Final report. Victoria, British Columbia. 65 p.

Martinson, E.J.; Omi, P.N. 2003. Performance of fuel treatments subjected to wildfires. In: Omi, P. N. and L.A. Joyce, tech ed. 2003. Fire, fuel treatments, and ecological restoration: conference proceedings. Proceedings RMRS-P-29. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 475 p.

McCaffrey, S. 2004a. Fighting fire with education: What is the best way to reach out to homeowners? Journal of Forestry. July/August 2004: 12-19.

McCaffrey, S. 2004b. What factors are most important in shaping the views of residential-wildland intermix homeowners about wild hazard and fuels management? In: 2nd symposium on fire economics, planning and policy: a global view. Cordoba, Spain, April 19 – 22, 2004.

McGee, T.; McFarlane, B.; Varghese, J. 2005. An exploration of wildfire risk reduction within communities directly affected by the Lost Creek fire in 2003. Foothills Model Forest Final Report. 19 p.

Mercer, G.; Purves, H. 2000. An initial assessment of wildlife movement corridors in the Three Valley Confluence of Jasper National Park. Warden Service Report. Unpublished. November, 2000. 32 p.

Mitchell, M.P. 2005. Montane landscape heterogeneity and vegetation change in Jasper National Park (1949-1997). M.Sc. thesis. Prince George, British Columbia, Canada: University of Northern British Columbia. 132 p.

Mortimer, D. 1998. Town of Jasper interface protection project, Jasper National Park. Fireline Consulting and Instruction. Report prepared for Parks Canada. 65 p.

Mortimer, D. 1999. Lake Edith cottage development facility protection project, Jasper National Park. FireLine Consulting and Instruction. Report prepared for Parks Canada. 65 p.

Mutch, R.W. 1994. Fighting fire with prescribed fire: a return to ecosystem health. Journal of Forestry. 92(11): 31-33.

National Fire Protection Association. 2002. NFPA 1144 – Standard for protection of life and property from wildfire, 2002 edition. NFPA. Batterymarch Park, MA. 19 p.

Natural Resources Canada. 2005. Canadian Forest Service – Viewpoint: a new wildland fire strategy for Canada. 3 p. http://www.nrcan.gc.ca/cfs-scf/national/what-quoi/viewpoint/index_e.php?ArticleId=221. Accessed January, 2005.

Parks Canada. 2000. Jasper National Park of Canada management plan. Catalogue Number R64-105/28-2000E. Ottawa, Canada: Minister of Public Works and Public Services Canada. Department of Canadian Heritage. 78 p.

Partners in Protection. 2003. FireSmart: Protecting your community from wildfire. Second Edition. Edmonton, Alberta, Canada: Capital Color Press Ltd.

Quintilio, D. 2005. Presentation to the Jasper Interface Steering Team, March 14, 2005, Jasper, Alberta.

Ralf, R.; Bradford, W. 1998. Bear/human conflict management plan, Jasper National Park. Internal Report, Warden Service. 65 p.

Rhemtulla, J.M. 1999 Eighty years of change: the Montane vegetation of Jasper National Park. M.Sc. Thesis. Alberta, Canada: University of Alberta.

Sandberg, D.V.; Ottmar, R.D.; Cushon, G.H. 2001. Characterizing fuels in the 21st century. International Journal of Wildland Fire 10: 381-387.

Scott, J.H.; Reinhardt, E.D. 2001. Assessing crown fire potential by linking models of surface and crown fire behavior. Res. Paper RMRS-RP-29. Fort Collins, CO. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 59 p.

Tande, G.F. 1979. Forest fire history around Jasper townsite, Jasper National Park, Alberta. M.Sc. Thesis. Alberta, Canada: University of Alberta. 169 p.

U.S. Department of Agriculture, Forest Service. 2005. A strategic assessment of forest biomass and fuel reduction treatments in Western States. Gen. Tech. Rep. RMRS-GTR-149. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 17 p.

Van Wagner, C.E. 1977. Conditions for the start and spread of crown fire. Canadian Journal of Forest Research. 7: 23-24.

Walters, C.; Holling, C.S. 1990. Large-scale management experiments and learning by doing. Ecology 71: 2060-2068.

Westhaver, A.L. 2003. Environmental Screening Report. *FireSmart – ForestWise* community protection and forest restoration project; Foothills Model Forest, Jasper National Park. Park Registry File J03–004. Jasper National Park. April, 2003. 81 p.

Westhaver, A.L. 2006. FireSmart – ForestWise: Managing wildlife and wildfire risk in the wildland/urban interface. M.Sc. thesis. Alberta, Canada: University of Calgary, Faculty of Graduate Studies, Resources and Environment Program. 224 p.

White, C.A. 2001. Aspen, elk, and fire in the Canadian Rocky Mountains. Ph. D Thesis. Faculty of Graduate Studies. Department of Forestry. University of British Columbia.

Wierzchowski, J.; Heathcott, M.; Flannigan, M.D. 2002. Lightning and lightning fire, Central Cordillera, Canada. International Journal of Wildland Fire. 11, 41-51.

Winter, G.; Vogt, C.; Friedy, J.S. 2002. Fuel treatments at the wildland/urban interface: common concerns in diverse regions. Journal of Forestry. January/February 2002: 15-21.

Winter, G.; Vogt, C.A.; McCaffrey, S. 2004. Examining social trust in fuels management strategies. Journal of Forestry. September 2004: 8-15.

This page is blank on purpose

Smoke Management

This page is blank on purpose

Use of Historic Images as a Tool for Estimating Haze Levels—Natural Visibility and the Role of Fire

Gordon Andersson[1]

Abstract*—The Regional Haze rule addresses visibility impairment in 156 Federal Class I areas. The goal of the rule is to remove all anthropogenic air pollution from the National Parks and Wilderness areas. Determining natural visibility conditions is an interesting and complicated problem. There is a large archive of pre- and early-settlement narratives, landscape paintings, and photographs that could be used as part of a weight-of-evidence demonstration in regional haze State implementation plans (SIPs), especially for Western States. With an understanding of inherent limits, these materials could be used for qualitative evaluation of the early American atmosphere. Despite large uncertainties and with knowledge of film properties, application of quantitative analysis of contrast in photographs is possible and could provide estimates of visual range. These issues are introduced here as a theoretical treatment with some reference material for further investigation and practical application.*

Background

The Regional Haze Rule (RHR), published July 01, 1999 (64 FR 35714), addresses prescribed fire as one sector of visibility impairment (with stationary, mobile, and area sources). The national goal expressed in the Clean Air Act is "the prevention of any future, and the remedying of any existing, impairment of visibility in mandatory Class I Federal areas which impairment results from manmade air pollution." States need to establish "reasonable progress goals" for each Class I area with the objective of achieving natural visibility conditions by 2064. The 20 percent worst visibility days must be continuously improved, and the 20 percent best days must not deteriorate. The VIEWS Web site (Visibility Information Exchange Web System at http://vista.cira.colostate.edu/views/) serves as the national repository of visibility data and analysis, and incorporates the IMPROVE database (Interagency Monitoring of Protected Visual Environments, the national monitoring network of air samplers and database to implement the regional haze program: http://vista.cira.colostate.edu/improve/). VIEWS provides estimates of natural component concentrations at the Class I areas based on measured values at the IMPROVE monitors. Natural visibility is also sorted into 20 percent best and worst days.

In the preamble to the RHR, the Environmental Protection Agency (EPA) writes that States should not attempt to recreate historical (pre-Euro-American settlement) conditions, but rather determine current natural conditions. In related guidance documents, EPA allows considerable flexibility in the use of the IMPROVE and other air monitoring data as well as weight-of-evidence arguments addressing aspects of modeling and source attribution.

In: Butler, Bret W.; Cook, Wayne, comps. 2007. The fire environment—innovations, management, and policy; conference proceedings. 26-30 March 2007; Destin, FL. Proceedings RMRS-P-46CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 662 p. CD-ROM.

[1] Planner Air Policy, Minnesota Pollution Control Agency, St Paul, MN. gordon.andersson@state.mn.us

Although it addresses concentrations of fine particle (PM2.5) in the air, the RHR is not a NAAQS (National Ambient Air Quality Standards, which are established by EPA for six "criteria" pollutants). NAAQS primary standards are human health-based, and secondary standards are welfare-based. Welfare includes ecological effects and visibility, among other effects, and so the RHR is similar to a secondary standard. The RHR is basically an esthetic rule about what you see. It is appropriate to include photographs and art work as records and representations in reviews of visibility. Photographs are used in signage about diminished views at many National Parks, and they are part of the documented daily record at a number of Class I areas. This paper proposes that some of these esthetic media can also be used for analysis of historic visibility conditions.

The Historical Record

A large body of 19th century historical evidence bears on this issue—written narratives, landscape paintings, and landscape photographs—that, especially in the West, records conditions before the widespread use of internal combustion engines, large industries, and other human-made pollution sources (with the exception of fire). Despite the position expressed by EPA, such images would include depictions of natural visibility at that time, which would resemble in most part the contribution of natural sources today. It is somewhat unexpected that so many of these records describe or portray some amount of haze on the landscape.

The Western Class I areas would benefit most from a review of historic images (fig. 1). In general, they include more extreme topography and vertical surfaces with longer views and measurable "targets" than Eastern areas. (It is these same features that resulted in their designation as Parks or Wilderness areas.) Also, natural contributions were then (and are now) a larger component of haze in the West than in the East and, therefore, more likely to appear in the records than haze due to human-made sources.

Both Western landscape photographers and painters were instrumental in establishing National Parks in the West based on these same productions. William H Jackson's photographs and Thomas Moran's paintings convinced Congress to protect Yellowstone as a National Park in 1872 and Jackson's and Albert Bierstadt's pictures of Yosemite played a large part in its designation in 1890. This presentation will mostly address the use of depictions in landscape painting and photographs with a few examples.

Written Records

Written narratives can provide descriptions of relative haziness or clarity, but they would best be used as accompaniment to photographs, paintings, or sketches made of that same scene on the same day, or, with less specific application, the same season. Notebooks by the painter or photographer that describe the view would either support or qualify the conditions presented in the rendered image. Albert Bierstadt, for example, on each of his trips to the West made numerous notes that described the scenes painted in his oil sketches. In these he recorded from direct observation the colors, light, clouds, and atmospheric conditions.

Travelers' descriptions of landmarks in diaries and letters could provide independent dated information or might supplement recorded images. The overland migrants to the West Coast traveled chiefly through summer and

Figure 1—"Picture Rock at Crooked Lake" by Francis Lee Jaques, 1947 (courtesy of Minnesota Historical Society © 2003). A location in the Boundary Waters Canoe Area Wilderness, Superior National Forest, Minnesota, a Class I area. The vistas in the Class I areas in the Great Lakes region are seen across large lakes or the length of long lakes. These cliffs in the BWCAW provide vertical surface—a rare topography. Note the obscured view to the left of the cliffs.

used the same routes. Such limits of time and place provide for comparisons that include similar season, feature orientation, and position of sun. In addition to such records, compilations of regional histories based on primary materials concentrate descriptions to a place. Stegner (1982), for example, includes extensive quotations of Clarence Dutton, a geologist and companion in John Wesley Powell's exploration, and a description from 1882 of the haze in the Grand Canyon, a present day Class I area. The review of written records would be fairly labor-intensive requiring extensive filtering of texts to find pertinent descriptions.

Landscape Paintings

More than narrative descriptions, the use of pictorial media have limitations that must be understood and applied to estimating haze levels. This is more so because they provide immediate appearances that seem to be real.

The landscape painters of this period—Frederick Church, Jasper Cropsey, Asher Durand, George Inness, Thomas Moran, Sanford Gifford, and others—painted from nature, often creating oil sketches out of doors and completing canvases in the studio (fig. 2). The painters of the old West (such as Bierstadt and Moran) were from the Mid-Atlantic States. Their paintings were a medium of communicating the grandeur and vistas of the Western

Figure 2—"A Scene on Tohickon Creek: Autumn" by Thomas Moran, 1868 (courtesy of Minneapolis Institute of Art © 2003). An early image from the East (Pennsylvania) by an artist most famous for later panoramas of the West. Due to the season, the background haze may represent smoke from vegetative burning with little biogenic contribution. (Note for this and some other figures: Images of paintings are made from scans of 35 mm slides obtained from museums. In general they are significantly degraded in sharpness and color and are for illustration only. Museum Web sites, Web searches for specific paintings, exhibit catalogues and books, available in museums and libraries, and the original paintings and photos in museum collections provide the best reference material.)

topography. For example, Bierstadt's large-scale paintings were exhibited for paid admission on tours of Eastern cities. Moran's huge paintings "Grand Canyon of the Colorado" (1872) and "The Chasm of the Colorado" (1874) were both purchased by Congress and hung in the Capitol in Washington, DC. There would be a natural tendency for these depictions to portray distant peaks and open spaces through clear air, whether the air was clear or not. In terms of the RHR, these paintings would more likely depict a day from among the "20 percent best days" to "20 percent middle days" than the most hazy days with greatly diminished views. Whether Eastern or Western scenics, some pieces portray crystalline air and many miles of view; some, dramatic storms and clouds over distant peaks; and many, a golden light of late afternoon with a lot of light scattering from fine aerosols. Many of these last still have a long visual range to show distant formations through the haze.

Problem of Sampling Error

The use of paintings to look at visibility must be done with a knowledge of the artist and his body of work. This may include styles and phases and the placement of a particular painting in the artist's development. Of course, to draw conclusions from a single painting (or photo) of a single feature is not reasonable. Any small number of records presents a large problem of "sampling error." For comparison, the IMPROVE air monitors sample the air every third day. The RHR apportions the air data into quintiles with each 20 percent representing at maximum 24 days a year.

There are a few ways that sample size might be increased if one were to use the historic record. A series of paintings of one landscape feature by one artist over time would provide one preferred "database." It would show the range of the artist's representation and scene changes through the year at different seasons and times of day in different light with different sun angles.

Researchers at the University of Birmingham, England, propose this very process to analyze air pollution conditions in London from evidence in a series of paintings by Claude Monet of the Houses of Parliament in 1899 to 1901 (Baker and Thornes 2006). Monet was a master of Impressionism whose canvases include many series of the same subject in different light conditions. In all he completed 19 paintings of the Parliament buildings, and nine of them show the sun. These London paintings were made in the period of his mature style. Despite this, the authors determined that he correctly rendered the effects of sunlight on the building and they matched the solar inclination to the dates of his paintings. Having determined "elements of accurate observation" and "real quantitative information" in this series, they believe that historical conditions of air quality can be derived from the same paintings. Monet chose to paint the sun effects on the façade as they were presented to him. Every painter from nature chooses which physical elements of the subject to include and with what specificity, and which elements to omit, alter, or add.

Late Impressionist paintings are less representational than the landscape paintings of both the American East and the West. The 19th century landscapers practiced realism or naturalism in large part. On the American scene, Albert Bierstadt's series of paintings of the Yosemite Valley (1865, 1868, 1872) might be compared to a Monet series (fig. 3). However, both Bierstadt's large-scale paintings of the Yosemite Valley and Thomas Moran's painting of the canyon of the Yellowstone River are composites, created from oil sketches, that include landscape features within the same view that are not present in the three dimensional world (Wilton and Barringer 2002). Right away, this should diminish the credibility of either of these paintings as physical records, including the relative clarity of the atmosphere. If one can move a mountain, one can even more easily clarify or obscure the view at a given time with less interpretation. The mountain subjects that Bierstadt painted in large format, after joining the Frederick Lander railway survey expedition to present-day Colorado in 1858, were similarly largely invented. Moran became more stylized in later years adding many atmospheric effects to his landscapes (fig. 4). To use fanciful (less realistic) representations of landscape at face value is problematic, as they depict momentary events in the artist's imagination, whether or not they happened, or might have happened, in nature

A second approach would be to compare different artists' renderings of the same scene, such as Sanford Gifford's painting (1860) of Mt Katahdin in Maine (fig. 5) and Frederic Church's (1853) picture of the same feature. If different artists portrayed the same atmosphere conditions affecting the view of a landmark, at the same season and time of day, one could argue that the similarity may be due to those actual conditions and not to the artist's preferences. To be fair in using such a method, where different depictions show different levels of haze, one must acknowledge that the samples are too disparate to make estimates of average conditions and, at most, conclude that the differences lie somewhere within a range of actual conditions.

Figure 3— "Looking Down Yosemite Valley, California" by Albert Bierstadt, 1865 (courtesy of Birmingham Museum of Art © 2003).

Figure 4—"Grand Canyon of the Colorado" by Thomas Moran, 1892 (courtesy of Philadelphia Museum of Art © 2003).

Figure 5—"The Wilderness" by Sanford Gifford, 1860 (courtesy of Toledo Museum of Art © 2003). The view is of Mt Katahdin in Maine, now in Baxter State Park, and climbed by Henry David Thoreau.

Yet a third approach to address the issue of "sampling error" is one that adds corroborative information to photographs and paintings. The photographer William Henry Jackson and the painter Thomas Moran both accompanied the Ferdinand Hayden geological survey expedition to Yellowstone in 1871. There, Moran made numerous watercolor and gouache drawings of landscape features with an "intense concern for accuracy" (Wilton and Barringer 2002). As with many artists, a separate "reality" was later created on the final oil canvases completed in the studio, which may be quite independent of the studies, sketches, and notes that were made in the field. Jackson made numerous silver albumen photographic plates in Yellowstone (fig. 6). In 1873, Moran also traveled with the Powell expedition to the Grand Canyon of the Colorado River. And in 1892, he again visited the Grand Canyon with Jackson. In the case of these two Western Class I areas, there exist contemporary written descriptions, photographic prints, and pencil and paint sketches as well as completed oil paintings that hang in several museums. This information recording the same landscape and features could be compared for agreement, consistency, and anomaly in visibility.

Many collections and "coffee table" books include landscape reproductions with descriptive text, biographical information, and the name of the museum that owns the original artwork. Wilton and Barringer (2002) provide an extensive treatment of representations of this period in American painting.

Figure 6—"The Three Tetons" by William Henry Jackson, 1873 (courtesy of Minneapolis Institute of Art © 2003). Taken from Yellowstone National Park; one of 11 Jackson photos in the MIA collection and one of the less hazy in appearance.

Landscape Photographs

Photographs, either inside or outside Class I areas, are much less subject to "interpretation" by the artist. Photography and painting are differentiated by manipulation of subject matter and by the time to create the image. Though each present a moment in time, the one is made in an instant and the other may be completed after weeks or months of work. Landscape paintings of the 1800s too lack the intrinsic credibility of photographs and, without supplemental information, one can neither conclude that a scene is average or typical, nor that it never happened.

The preponderance of the 156 Federal "mandatory" Class I areas addressed by the RHR are in the West (112, outside of Alaska and Hawaii), and this is where, at the time, there was less anthropogenic influence on the atmosphere. William Henry Jackson and others (Carleton Watkins, Timothy O'Sullivan, Samuel Bourne, Alfred Hart) made series of photos inside present-day Yellowstone and Yosemite National Parks and other Western regions (fig. 7).

Qualitative and quantitative assessment—The paintings and photos of 19th century artists have intrinsic historic interest, but with qualitative assessment they can be useful in helping to define natural visibility conditions. Using

Figure 7—American Indians on horseback at Glacier National Park; photographer unknown, 1912 (courtesy of Minnesota Historical Society © 2003).

such historical records is a different method of reconstructing "natural" conditions and it might be used to supplement or compare the quantitative methods of natural source concentrations derived from measured filter data. If measurement is possible, the visual historical record becomes more applicable to haze research and estimation of natural conditions.

The simplest measure that might be done from images is visual range. This does require that distances from the point of view in the photograph (or painting) to features in the landscape be known to the individual who examines the image. Such distances can be approximated in the real world by a visit to the featured site or with the use of topographical maps. Visual range is demonstrated with light extinction (bext) and deciviews on the IMPROVE homepage, and it is also the visibility metric used by the "haze cams" on State and RPO Web sites across the country (fig. 8, 9). With an estimated visual range, one can calculate an estimated general light extinction and estimated deciviews.

To correctly measure visual range, one observes a large black object against a light background or the bright horizon. Simply stated, the observer visual range is the distance at which the object disappears. A painting (or a photograph) can indicate a visual range if features in the background become invisible, but this can only be an approximation of actual visual range, and it would probably be less than that measured with a black object. Actual visual

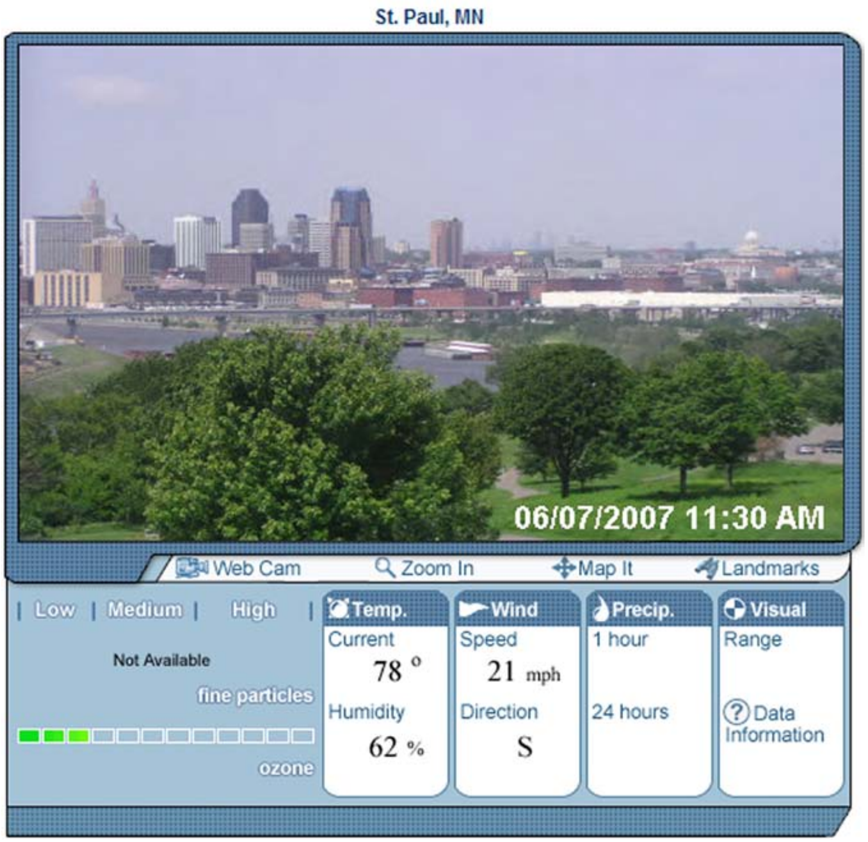


Figure 8—St Paul, MN, "haze cam" image showing "current conditions. The live image is updated every 15 minutes. Visual range, measured by nephelometer, has been reported with the met data beneath the picture on many haze cam sites.

Figure 9—"St Paul from Dayton's Bluff, July 6, 1888" by Alexis Fournier (courtesy of Minnesota Historical Society © 2003). This watercolor shows a view of early St Paul, MN, from a location and orientation similar to the haze camera (fig. 8).

range will usually be greater than the distance to the target object. With any painting, one must bear in mind that the apparent visual range is in the painting and not in nature, although it might have been accurately recorded from the landscape at a point in time.

Large uncertainties exist in contrast measurements from transparencies (Molenar undated). Even "live" visual range is affected by the sun angle, the target object characteristics, and sky conditions. Measuring contrast from photographs depends on these factors as well as the qualities of the film. Lack of supplementary information of archival photographic prints that includes the properties of the film, its density and response to light, and the deterioration of the prints make calculated measurements of extinction more difficult (Molenar, pers. comm.). Quantification of visual range in photographic prints by experienced technicians with contrast instruments (densitometer that measures reflectance) can derive estimates but not fixed values.

The IMPROVE photographic record—35 mm cameras have been collocated with the aerosol monitors at IMPROVE sites in at least 46 National Parks, Refuges, and Wilderness areas. These daily images (three slides per day) have been archived as a record of visibility conditions. The VIEWS Web site includes a large number of images from these Class I areas in "spectrum" series with graduated differences in ug/m3 of aerosols, light extinction (bext), and deciview (dv) values for each image: (http://vista.cira.colostate.edu/views/Web/IMPROVE/Data_IMPRPhot.htm)

Light extinction coefficients were estimated for each of these photographs with contrast measurements made with a transmittance densitometer. Copeland (undated) found large uncertainties using a 68 percent confidence interval when comparing measured visual range to actual visual range even where a dark target was in the frame.

William Henry Jackson—Although a number of photographers made images of the old West, Jackson was unusually prolific, including in a 1875 catalogue more than 2,000 albumen silver prints taken between 1869 and 1875 as part of the Hayden U.S. Geological Survey (Sandweiss 2002).

In addition to the catalogs published by Jackson, more recent works provide side-by-side comparisons of photographs by Jackson with contemporary photographs taken of the same scene from about the same point (Fiedler and Jackson 1999, 2005). This allows for the direct comparison of the air quality on those 2 days separated by more than 100 years. By using the same latitude/longitude and orientation, these photos provide equal distances to vertical features in the distance. It would be most useful if these images were taken on the same dates to account for seasonal differences and it does not reduce the sampling error issue discussed above. As they are largely made in summer, the chances would be about one in 100 that the images were made on the same date. However, because daily variation is often greater than seasonal difference, valid comparisons of visibility do not depend on same-day images. One could examine a large number of paired images and estimate the range and the mean of clarity/haziness for the "before" and "after" pictures. These references and others (such as Hales 1988) would seem to be useful to Colorado, with its 12 Class I areas, to supplement its air monitoring data.

The Role of Fire

Haze is apparent in many paintings and photographs from the 19th century. A good argument can be made that much of this is due to fire on the landscape. Many of the Eastern paintings (by Church, Cropsey, Durand, Moran, Gifford) might represent smoke from the felling and burning of the Eastern hardwood forest as a component of visible air pollution. Large portions of the land area were clearcut and burned for cropland by the Euro-American settlers. Primary forest was converted to log piles that burned for days, and the wood was readjusted for further combustion. Due to land-use practices, the annual net flux of carbon (C) to the atmosphere was positive from before 1850, peaked at 328.74 Tg/yr in 1881, and did not go negative until 1923 (Houghton and Hackler 2002) (fig. 10).

In the East, emissions from coal-burning factories and some coal-burning trains, and residential cooking and heating would also be a component of visible air pollution especially after 1850. In 1850, some 5,402 1000 metric tons (mt) of carbon were produced by coal burning in the United States; 15,775 1000 mt were generated in 1865; and 101,603 1000 mt in 1890 (Marland and others 2006). The amount of carbon added to the atmosphere by land-use changes in 1881, however, was six times that added by coal burning in that year.

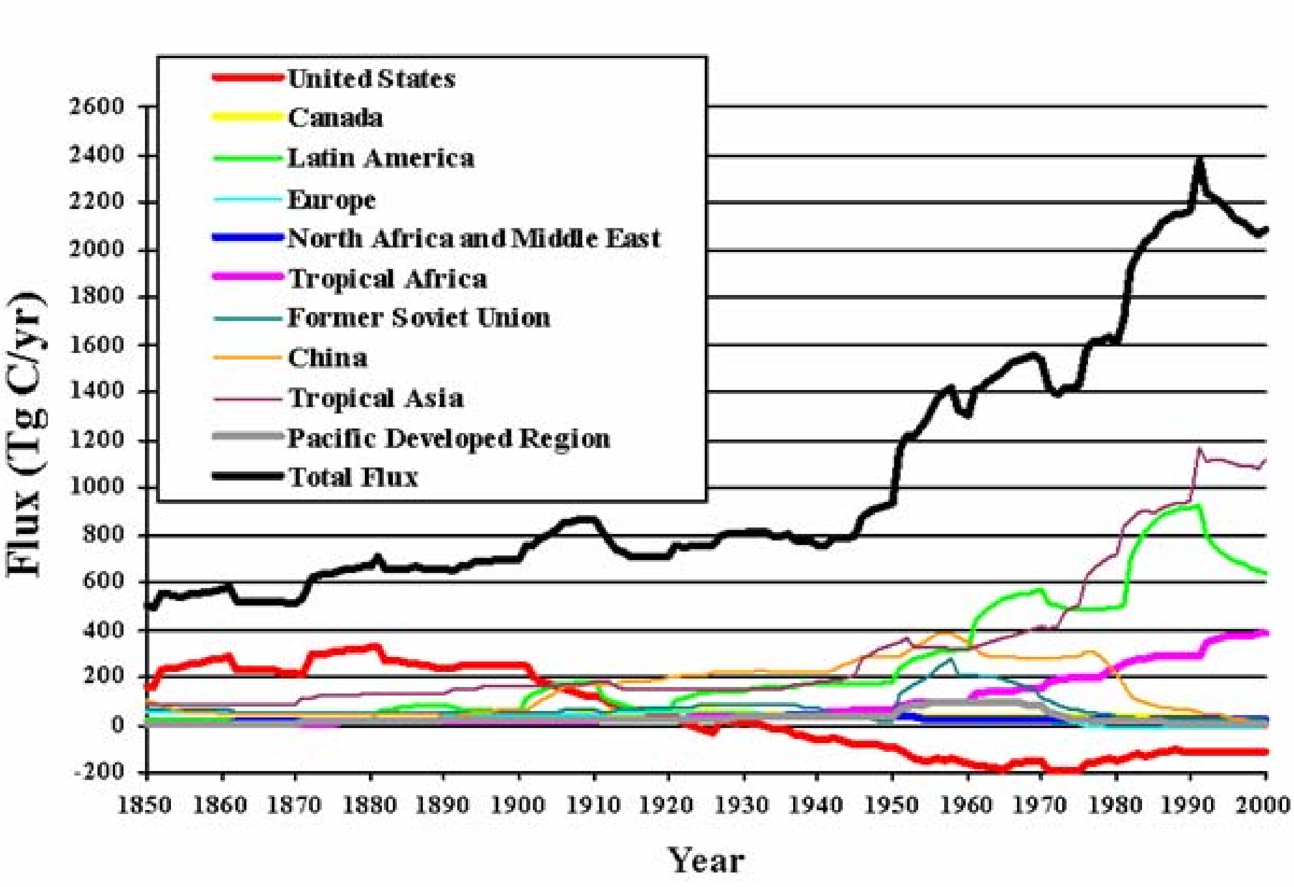


Figure 10—Annual net flux of carbon to the atmosphere from land-use changes worldwide, 1850 through 2000 (Houghton and Hackler 2002). Note that carbon release peaked in the United States in 1881 from clearing and burning the Eastern forest.

With little industry or transportation sources in the West, much of the visibility impairment would be due to biogenic sources, including wildfire, and intentional burning. American Indians used fire extensively for multiple purposes (see Pyne and others 2000).

According to Leenhouts (1998), wildland fires burned 34 to 86 x 10^6 ha (megahectares) annually in the preindustrial era, consuming 530 to 1228 teragram (Tg) of biomass. By comparison, he calculates that contemporary wildland, prescribed, and agricultural fires combined burn 4.5 to 7.4 Mha per year and consume 24 to 136 Tg of biomass per year (data are from his "Results" section). He added that about 10 times more landscape was burned, eight times more biomass was consumed, and seven times more emissions were produced in the preindustrial conterminous United States than at present due to biomass burning.

The pollutants that affect visibility and that are derived from vegetative burning are PM10, PM2.5, nitrogen oxides (NOx), ozone, organic carbon, and elemental carbon. Ozone, which can form "smog" or haze, is not directly produced by fires but from other combustion products (NOx and volatile organic compounds or VOCs). Nitrates too are not primary products of burning but are formed by the chemical transformation of NOx. About 90 percent of smoke particles are PM10 and 70 percent are PM2.5 (EPA 1998).

EPA Treatment of Fire in Rules

The Clean Air Act Amendments (1977 and 1990 parts 169A & B) and the Regional Haze Rule (1999) require that human-made pollution that affects visibility be prevented and reduced. In a regulatory sense, whether the smoke component of haze is natural or anthropogenic is a fundamental issue. The convention among fire agencies is that lightning-ignited fires are natural. This is a source-based definition of emissions determined by the mode of the fire ignition. Reasonably, arson fires are clearly anthropogenic. Accidental fires (such as cigarette, railroad, and escaped camp fires) too are considered human-caused. Extending this logic to prescribed burns classifies them too as anthropogenic. Fire emissions are usually treated as area sources in air quality emission inventories, and the emission components from vegetative burning are similar, regardless of the mode of ignition (fig. 11).

Despite this, sec. 1.15 of EPA "Guidance for Estimating Natural Visibility Conditions Under the Regional Haze Rule" (Sept 2003) states, "In some cases, regional organizations [RPOs] have found it useful to classify fire emissions into two categories, natural and man-made, for the purposes of estimating natural visibility conditions. While EPA is not expressing an opinion on the importance of classifying fires, it supports those organizations who wish to do so for the purposes of estimating visibility conditions. However, the EPA does not require the distinction between natural and man-made fires." Apparently, this means that EPA could consider all fires as natural (and part of natural haze) or all fires as man-made (and subject to the RHR). This lack of clarity is perpetuated by the final Exceptional Events (EE) Rule (72 FR 13559) published March 22, 2007. Congress passed the SAFE-TEA-LU bill (2005) that revised sec. 319 of the CAA to address exceptional events and defined them in part as "not reasonably controllable or preventable." In the EE rule, EPA says that prescribed fires may qualify as exceptional events if they meet the statutory definition and a State smoke management program (SMP) is in place. This confusion might be addressed in part when EPA releases new guidance to replace the "Interim Air Quality Policy on Wildland and Prescribed Fires" (April 23, 1998), due in July 2008.

Figure 11—Burning the piled brush and debris after lumbering has been completed, Minnesota National Forest Reserve; photo by W.E. LaFontain, November 18, 1904 (courtesy of Minnesota Historical Society © 2003). Slash burning after clearcutting the red and white pine forests of Minnesota for construction of Midwestern cities. Lumbering began in the 1830s and peaked at more than 1 billion board-feet in 1900. The last sawmill closed in 1930.

Summary

A number of artistic, technical, and regulatory issues attend an effort to use the large archive of descriptions and representations of the early American landscape as a tool to estimate natural visibility conditions and regional haze in early settlement (East) and presettlement (West) America. The haze seen in many paintings and photographs could contain a large component of fire emissions that would combine both natural and human-ignited sources. Estimating the proportions of each by region presents a problem. Further, EPA has not formally separated fire emissions by source in RHR implementation, in apparent conflict with the Clean Air Act Amendments.

Despite these problems, work could be done on each of these topics by individual States to derive or to support the values that it includes in the regional haze SIP. In particular, a number of the Class I areas in the West are supported by a large history of narratives, drawings, paintings, and photographs that describe or portray the atmosphere at different times in those areas or regions. Each of these media has limitations that must be considered. The fire science literature on natural and Native American fire could be correlated to the historical writings and images. Despite large uncertainties, application of quantitative analysis of contrast in photographs can provide estimates of haze concentrations and light extinction. In many locations, qualitative analysis of the image archive and additional research could be used to supplement the calculations of natural visibility based on current concentrations of air pollution.

References

Baker, Jacob; Thornes, John E. 2006. Solar position within Monet's Houses of Parliament. Proc. R. Soc. A. 462(2076): 3775-3788.

Copeland, Scott. [undated] Summary of limitations and value of slide-based visual range measurements. [Online] Available: http://vista.cira.colostate.edu/improve/Publications/GrayLit/gray_literature.htm

Environmental Protection Agency. 1998. Interim Air Quality Policy on Wildland and Prescribed Fires.

Fiedler, John; Jackson, W.H. 1999. Colorado 1870 - 2000. Englewood, CO: Westcliffe Publishers. 224 p.

Fiedler, John; Jackson, W.H. 2005. Colorado 1870 - 2000 II. Englewood, CO: Westcliffe Publishers. 108 photos; 156 p.

Hales, Peter B. 1988. William Henry Jackson and the Transformation of the American Landscape. Philadelphia, PA: Temple University Press. 198 photos; 368 p.

Houghton, R.A.; Hackler, J.L. 2002. Carbon Flux to the Atmosphere from Land-Use Changes. In: Trends: A Compendium of Data on Global Change. Oak Ridge, TN: U.S. Department of Energy, Oak Ridge National Laboratory, Carbon Dioxide Information Analysis Center.

Leenhouts, Bill. 1998. Assessment of biomass burning in the conterminous United States. Conservation Ecology [Online]. 2(1): 1. URL:http://www.consecol.org/vol2/iss1/art1.

Marland, G.; Boden, T.A.; Andres, R.J. 2006. Global, Regional, and National CO_2 Emissions. In: Trends: A Compendium of Data on Global Change. Oak Ridge, TN: U.S. Department of Energy, Oak Ridge National Laboratory, Carbon Dioxide Information Analysis Center.

Molenar, John V. [undated] Uncertainty analysis of calculated extinction from apparent contrast measurements from images of natural targets. [Online] Available: http://vista.cira.colostate.edu/improve/Publications/GrayLit/gray_literature.htm

Pyne, Stephen J.; Williams, Gerald W.; Barrett, Stephen W.; Brown, Hutch. 2000. Fire Management Today. 60(3):4-48.

Sandweiss, Martha A. 2002. Print the Legend: Photography and the American West. New Haven, CT: Yale University Press. 402 p.

Stegner, Wallace. 1982. Beyond the Hundredth Meridian: John Wesley Powell and the Second Opening of the West. Lincoln, NB: University of Nebraska Press. 438 p.

Wilton, Andrew; Barringer, Tim. 2002. American Sublime: Landscape Painting in the United States 1820-1880. Princeton, NJ: Princeton University Press. 282 p.

This page is blank on purpose

Smoke Monitoring Network on 2006 Northern California Fires

Brenda Belongie[1] and Suraj Ahuja[2]

Abstract—*Long-duration fire activity during the 2006 northern California fire season presented an excellent opportunity to create a temporary air-quality/smoke-monitoring network in the complex terrain across northwestern California. The network was established through cooperative interagency coordination of Federal officials, the California Air Resources Board (CARB), and local Air Pollution Control Districts (APCDs). This network addressed concerns over air quality and potential firefighter- and citizen-health issues. Equipment deployed included real time $PM_{2.5}$ monitors (EBAMs and DataRAM's) at seven stations. The reported network data were posted daily on the Internet (in the public domain). The archived field-gathered data set will also provide a database for future research and verification of modeled Blue Sky output for particulate concentrations (run by the University of Nevada, Reno). Lessons learned from establishing and supporting such a temporary network will help make future projects more successful. Overall, the network data were well received, especially by local residents.*

Introduction

In July and early August 2006, a long-term, multifire episode developed in northwestern California over adjacent areas of the Shasta-Trinity, Six Rivers, and Klamath National Forests. Based on previous experience with dense smoke events that occurred in 1977, 1987, 1999, and 2002 under similar fire regimes, fire and air quality officials soon concluded that significant amounts of smoke were likely to blanket the area for a minimum of several weeks.

A closer look at the physical shape of the terrain in the area (fig. 1) shows that deep river valleys with steep hillsides are typical in this region. This creates efficient "smoke traps," especially overnight when inversions become established, and local downslope, downdrainage winds carry smoke through the terrain and valleys. Dense smoke can limit the amount of daytime sunshine that reaches the ground, which in turn can inhibit the atmospheric mixing possible due to surface heating by the sun. Without much daytime mixing, smoke can linger in these canyons and valleys, creating long periods of poor air quality conditions. Lower sun angles and longer days in late summer also exacerbate these conditions.

Smoke Monitoring Network

A quantitative sampling network had never been used to monitor heavy smoke events during previous long-term fire episodes in the area (Fontana 2007). In 2006, however, a temporary smoke monitoring network was

In: Butler, Bret W.; Cook, Wayne, comps. 2007. The fire environment—innovations, management, and policy; conference proceedings. 26-30 March 2007; Destin, FL. Proceedings RMRS-P-46CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 662 p. CD-ROM.

[1] Predictive Services Meteorologist, U.S. Department of Agriculture, Forest Service, Redding Fire Weather Center, Northern California Service Center, Redding, CA. bbelongie@fs.fed.us

[2] North Zone Air Quality Specialist, U.S. Department of Agriculture, Forest Service, Region 5, Mendocino National Forest, CA.

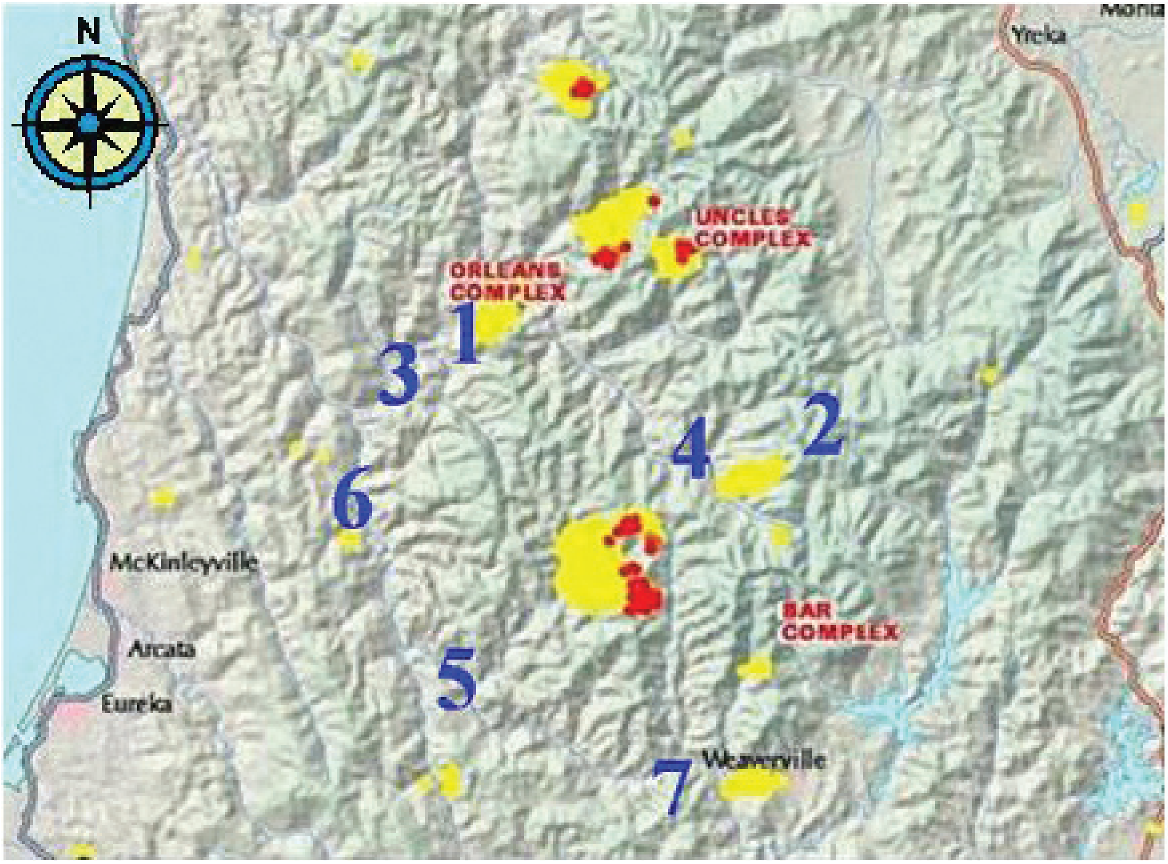


Figure 1—This map of the project area in northwestern California shows the sampling sites: (1) Somes Bar, (2) Callahan, (3) Orleans, (4) Petersburg, (5) Burnt Ranch, (6) Willow Creek, (7) Junction City.

deployed for the first time through cooperative interagency actions between local air quality district, Federal, and State officials. Initial discussions and development of an action plan were done via conference calls. The principal cooperating agencies included the North Coast Unified and Shasta County Air Quality Management Districts, Siskiyou County Air Pollution Control District, USDA Forest Service, USDI Bureau of Land Management, California Air Resources Board (CARB), and the California Department of Forestry and Fire Protection (CDF).

The network monitored $PM_{2.5}$ values from August through October using both EBAMs and DataRAMs provided by several agencies (USDA Forest Service, BLM, CARB). Most of the monitors were borrowed from operations outside the local area. The seven sampling sites (fig. 1) were chosen after considering population center locations, likely areas of the largest or longest lasting fires, and local meteorology. None of the sampling locations were existing full-time air quality monitoring sites. A contract agreement was set up with Air Resource Specialists, Inc., of Boulder, CO, to have them do onsite calibrations of the sampling units to ensure as accurate and comparatively equal data as possible.

Local Air Quality Management District (AQMD), Air Pollution Control District (APCD), and fire officials were concerned about both the exposure duration and $PM_{2.5}$ concentrations experienced by local residents and firefighters. Although there are published Environmental Protection Agency

(EPA) standards relating $PM_{2.5}$ concentrations to human health (reflected in table 1), there are no established Federal or documented CDF standards or policies uniformly applying those values to firefighter activities.

A daily summary text product with expected weather affecting dispersion and the previous 3 days' peak $PM_{2.5}$ concentrations at each site was produced collaboratively by Redding Fire Weather Center and CARB meteorologists (tables 1 and 2). It was posted on the Redding Fire Weather Center Web site by 1400 hours (2 p.m.) daily.

The 2 months of detailed information the network yielded has been archived and will be used for future research and verification of modeled Blue Sky output for particulate concentrations (run by the University of Nevada, Reno, for the northern California area).

Challenges Encountered

Network maintenance and logistical support were somewhat problematic at times during this project, in part because there were no other examples of such networks used on large fires that we could emulate. Some of the instruments required a person to report the observed values, and it was difficult at times to find someone who could reliably perform the necessary duties daily. Unfortunately there were occasional data gaps when some paper sensor tapes ran out or sampling was rendered invalid because of holes in the tape. Overall, however, most of these issues were resolved fairly soon, and the data input became quite consistent.

Table 1—Air Quality Guide for Fine Particulate Matter (PM2.5) Pollution. This table was included at the end of the daily summary product (source: CARB). The assumption was that supplying local citizens with air quality information would help them decide which actions to take to address their individual health situation.

24-hr average concentration (ug/m3)	Air quality index	Air quality category	Cautionary statement
0 - 15	Up to 50	Good	None
>15 - 40	51-100	Moderate	Unusually sensitive people should consider reducing prolonged or heavy exertion.
>40 - 65	101-150	Unhealthy for sensitive groups	People with heart or lung disease, older adults, and children should reduce prolonged or heavy exertion.
>65 - 150	151-200	Unhealthy	People with heart or lung disease, older adults, and children should avoid prolonged or heavy exertion. Everyone else should reduce prolonged or heavy exertion.
>150 - 250	201-300	Very unhealthy	People with heart or lung disease, older adults, and children should avoid all physical activity outdoors. Everyone else should avoid prolonged or heavy exertion.
>250 - 500	301-500	Hazardous	Everyone should avoid all physical activity outdoors. People with heart or lung disease, older adults, and children should remain indoors and keep activity levels low.

Table 2—Sample content of the daily product posted on the Web site.

SMOKE SUMMARY FOR NORTHERN CALIFORNIA WILDFIRE AREAS

Tuesday October 31, 2006
1400 PST
Issued by the Redding Predictive Service Unit in cooperation with the California Air Resources Board

For Air Quality Advisories in your area, please call your local air district at the following numbers…

DISCUSSION: A weak high pressure ridge that has been over northern CA for the past several days will drift east on Wednesday as a Pacific storm approaches the north coast. There should be little change in smoke concentrations today from Monday's readings. On Wednesday stability will decrease as southwesterly winds increase, leading to better mixing and lower smoke concentrations. Higher humidity and occasional rain from Wednesday night through Saturday should reduce smoke production and smoke concentrations.

LATEST PM 2.5 MEASUREMENTS
(micrograms per cubic meter)
All data are preliminary

SOMES BAR

Date	1-hr Peak/Time	24hr Average	Air Quality
10/30/06	61/0900	7	Good
10/29/06	76/0900	13	Good
10/28/06	55/0900	17	Moderate

ORLEANS

Date	1-hr Peak/Time	24hr Average	Air Quality
10/30/06	37/2200	13	Good
10/29/06	29/0300	15	Moderate
10/28/06	33/0700	16	Moderate

****
Overall air quality numbers are mainly in the Good category. A weak disturbance making its way into the north state will keep air quality numbers in the same range tomorrow through the end of the week.

Depending on where you are, you may or may not be impacted, and the situation could change very quickly. If you see or smell smoke, consider restricting your outside activities. Until the weather conditions change and the smoke conditions improve, individuals should consider taking the following actions:

- Healthy people should delay strenuous exercise, particularly when they can see or smell smoke
- Children and the elderly should consider avoiding outdoor activities, particularly prolonged outdoor exertion
- People with heart or upper respiratory illnesses should remain indoors
- Asthmatics should follow their asthma management plan
- Contact your doctor if you have symptoms such as chest pain, chest tightness, shortness of breath, or severe fatigue
- Keep airways moist by drinking lots of water

See the table below for advice that is specific to each air quality category….[see table 1]

Conclusions

The time, effort, and costs involved with creating and maintaining a temporary smoke monitoring network make such projects most feasible only during long-term large fire incidents. Providing summarized information via the Internet is efficient and, in this case at least, was reportedly well received by the public. Establishing some monitoring network parameters and plans ahead of time would help define its operation. For instance, outlining the environmental conditions that warrant when/where to establish a network, and prearranging equipment loans and cooperators to help with network maintenance, could all be preestablished protocols. These actions would help expedite network deployment and minimize data gaps during its operation.

References

Fontana, Chris. 2007. Personal conversation.

Missoula Technology and Development Center. Spring 2001. Health Hazards of Smoke. Missoula, MT: U.S. Department of Agriculture, Forest Service, Missoula Technology and Development Center. 10 p.

Reinhardt, Timothy E.; Ottmar, Roger D.; Hanneman, Andrew J.S. 2000. Smoke Exposure Among Firefighters at Prescribed Burns in the Pacific Northwest. PNW-RP-526. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 45 p.

Sharkey, Brian. 1997. Health Hazards of Smoke, Recommendations of the Consensus Conference, April 1997, Part 1 of 6. Missoula, MT: U.S. Department of Agriculture, Forest Service, Technology and Development Program. 10 p.

This page is blank on purpose

Visualization and Modeling of Smoke Transport Over Landscape Scales

Glenn P. Forney[1] **and William Mell**[1]

***Abstract**—Computational tools have been developed at the National Institute of Standards and Technology (NIST) for modeling fire spread and smoke transport. These tools have been adapted to address fire scenarios that occur in the wildland urban interface (WUI) over kilometer-scale distances. These models include the smoke plume transport model ALOFT (A Large Open Fire plume Trajectory model) and WFDS (Wildland-urban interface Fire Dynamics Simulator) for fire spread and smoke transport in the wildland-urban interface. The visualization tool is called Smokeview. In this paper, an overview of the physical basis of the fire spread and smoke transport models will be discussed briefly along with the visualization of characteristic results using Smokeview. A technique will be described for visualizing smoke realistically, and indications will be given how Smokeview can be applied to other fire models.*

Introduction

The National Institute of Standards and Technology (NIST) has developed a suite of validated computational tools for the simulation and visualization of fire spread and smoke transport. These tools have been adapted for addressing fire scenarios that occur over distances of the order of kilometers, in particular, fire scenarios that address the wildland urban interface (WUI) problem. These models include the smoke plume transport model ALOFT (A Large Open Fire plume Trajectory model; Walton and others 2003) and the model WFDS (Wildland-urban interface Fire Dynamics Simulator) for fire spread and smoke transport in the wildland-urban interface (Evans and others 2004; Mell and others 2007). The visualization tool is called Smokeview (Forney and others 2003; Forney and McGrattan 2004). These tools were developed with an emphasis on ease of use on affordable computer platforms. In this paper, the physical basis of the fire spread and smoke transport models will be discussed briefly along with presentation of characteristic results using Smokeview. Smokeview visualizes data in several ways: by animating two-dimensional slices of gas phase quantities such as temperature or smoke concentration, by animating flow vectors and animating surface conditions such as incident heat flux or burning rates at the forest floor and also by animating iso-surfaces showing all places in the simulation scenario where a gas phase quantity takes on a specified value.

Smokeview is capable of rendering smoke and fire realistically using smoke concentrations computed by WFDS. By taking account of smoke properties, visibility can be assessed. We will discuss the potential use of Smokeview for the visualization of predictions from other smoke transport models.

In: Butler, Bret W.; Cook, Wayne, comps. 2007. The fire environment—innovations, management, and policy; conference proceedings. 26-30 March 2007; Destin, FL. Proceedings RMRS-P-46CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 662 p. CD-ROM.

[1] Research Scientists, Building and Fire Research Laboratory, National Institute of Standards and Technology, Gaithersburg, MD. Lead author at glenn.forney@nist.gov

Modeling Fire Spread in the Outdoors

Computer modeling and visualization are important tools for understanding many complex processes. Fire behavior is no exception. Fire models range in complexity from simple algebraic correlations for predicting quantities such as flame heights or flow velocities to moderately complex differential equation based zone fire models for predicting quantities spatially averaged over large regions. Both classes of models work well when used appropriately but break down for complicated flows or geometries. For such cases, computational fluid dynamics (CFD) techniques are required.

Computing Fire and Smoke Spread with CFD

The Fire Dynamics Simulator (FDS) has been developed at NIST to simulate the effects of fire and smoke spread (McGrattan 2004; McGrattan and Forney 2004). FDS predicts smoke and/or hot air flow movement caused by fire, wind, and other factors by solving numerically the fundamental equations governing fluid flow, commonly known as the Navier-Stokes equations. The fire model WFDS builds on FDS by adding algorithms needed for solving the wildland interface problem. In particular, algorithms for modeling flame spread on or among the types of materials encountered in the WUI such as grassland, trees, shrubs, and so on. An experimental program is also proceeding to determine important material properties required by the WUI models (Manzello and others 2006).

WFDS is a physics-based fire-atmosphere coupled model that uses a form of CFD known as large eddy simulation (LES) to predict the thermal conditions resulting from a fire. These types of models require significantly more computational resources than the most commonly used fire spread models such as BEHAVE (Andrews and Bevins 1999) and FARSITE (Finney and Andrews 1999), which are semiempirical or empirical. However, there are a number of fire behavior problems, of increasing relevance, that are outside the scope of empirical and semiempirical models. Examples are wildland-urban interface fires, assessing how well fuel treatments work to reduce the intensity of wildland fires, and investigating the mechanisms and conditions underlying blowup fires and fire spread through heterogeneous fuels. WFDS uses approximations to the governing equations of fluid dynamics, combustion, and the thermal degradation of solid fuel. The LES approximation for solving the governing equations is a way of describing the effect of turbulence on the flow field. Turbulence is a phenomenon that causes gases to mix over a wide range of length scales making it hard to replicate with even the fastest computers. The combustion model assumes that fuel and oxygen burn readily when mixed. The fire itself is a heat source term in the governing equations, creating buoyant motion that drives the smoke and hot gases throughout the domain of the simulation. The smoke yield is specified for a given fuel type based on measurements.

The downside of a CFD calculation such as WFDS is that depending on the computational resources, it can easily take days to run. As a result, parallelization techniques become important for splitting the work load among multiple computers, thereby speeding up the calculation and allowing results to be generated in a reasonable time.

Simulation Overview

WFDS, like any CFD model, requires that the scenario of interest be divided into small control volumes called computational cells. The model then computes the density, velocity, temperature, pressure, and species concentration of the mass distribution (gas + particulates) in each cell based on the conservation laws of mass, momentum, and energy. WFDS simulates the spread of the fire by calculating the thermal degradation of the vegetative fuels. This is driven by the radiative and convective heat fluxes from the fire and depends on material properties of the vegetation. The spatial resolution of the simulation depends on the number of cells used to discretize the volume of interest, much like the quality of a digital photograph depends mainly on the number of pixels. The number of cells is ultimately limited by the computing power available and the time available for the calculation. Current PCs limit the number of cells to a few million. Many more cells may be used if calculations are run in parallel by splitting up the problem into parts and solving each part on a different PC. Model users must balance how much detail they want to incorporate with run times required to perform the computation. In general, finer grids result in longer calculations, which produce better results. Ultimately, one reaches a point of diminishing returns where the answer becomes insensitive to the increasing resolution of the grid.

The temporal resolution or time step size is determined from the grid resolution and the flow speed. The time step is chosen by WFDS, so that flow does not cross more than one grid cell during a single time step.

Both FDS and Smokeview would not have been possible without the recent advent of high-speed computers for performing computations, fast video cards for visualizing results and the Internet for exchanging information and ideas. These programs also would not have been possible without the research needed to develop the underlying fire models and the techniques needed to implement these models accurately and efficiently.

While simple line plots are adequate for visualizing the results of simple fire models, more sophisticated techniques are needed for interpreting the massive amounts of data generated by CFD models. This is where visualization tools such as Smokeview, the companion to WFDS, become essential.

Visualizing Smoke

Smokeview displays smoke allowing quantitative assessment using standard visualization techniques such as animated tracer particles that follow the flow, animated shaded 2D and 3D contours that display flow quantities, and animated flow vectors that display flow quantities and direction. Smokeview also visualizes smoke realistically by converting soot density to smoke opacity, displaying smoke as it would actually appear. These visualization techniques highlight different aspects of the underlying flow phenomena.

Visualization is essential at all stages of the process. It is used before a run to verify the correctness of scenario geometry (locations and size of simulation features, for example), during a run to monitor the simulation (ensure boundary flows are behaving as intended), and after the run has been completed to analyze the results.

Smokeview consists of about 70,000 lines of code. Most of it is written in C using standard libraries such as OpenGL (Shreiner and others 2005) and GLUT (Kilgard 1996) for graphics; GD (Web site: http://www.boutell.com/gd/), libpng (http://www.libpng.org/pub/png/), and libjpeg (http://www.ijg.org) for generating image files; and libzip (http://www.gzip.org/zlib/) for compression. A portion of Smokeview is written in Fortran 90 to input data generated by WFDS. The use of portable libraries allows Smokeview to run on many platforms including Windows, and various versions of Unix such as IRIX (for the SGI), Linux, and OSX (for the Macintosh). *(Any mention of commercial products is for information only; it does not imply recommendation or endorsement by NIST.)*

Though Smokeview is usually used to visualize the results of WFDS or FDS simulations it is also used by other models. For example, Smokeview is used to visualize simulation results of the zone fire model CFAST (Jones and others 2004). An earlier version of Smokeview was adapted for visualization of the constituents of concrete during its formation in Concreteview (Bentz and Forney 2000) and molecular dynamics simulations in Molecview (Stoliarov and others 2003). The file formats that Smokeview uses for visualizing data are documented in both the Smokeview (Forney and McGrattan 2004) and FDS (McGratan and Forney 2004) users guide, enabling other fire models to make use of Smokeview as a visualization postprocessor.

Scientific Visualizations

Figures 1, 2, and 3 show simulations of a crown fire spreading left to right from a virgin, untreated, forest stand into a treated stand. The fuel properties in the untreated stand are based on those measured in the black spruce and Jack pine overstory stands in the Northwest Territory of Canada during the International Crown Fire Modeling Experiments (Alexander and others 2004).

Particles—WFDS uses particles as modeling elements to account for heat transfer and momentum drag that occurs during tree burning. This is illustrated in figure 1a. Particles may also be used to visualize the fire and smoke flow. Figure 1b shows a realistic view of the trees.

Slice planes—Smokeview allows animated color shaded contours of calculated gas quantities to be drawn at any horizontal or vertical plane in the simulation. To minimize file output, the user specifies the particular slice planes to be visualized. If disk space is not an issue, then the user may specify the entire 3D volume. Smokeview then allows the user to scroll through the 3D volume of data one slice at a time displaying any horizontal or vertical plane. Figure 2 illustrates temperature contours in a vertical plane through the center of a grassland fire. Temperatures below 100 ^{o}C are truncated. Figure 2a shows solid shaded contours while figure 2b shows a vector plot. The data are colored the same way in both cases. Vector animations as illustrated in figure 2b are better than regular slice animations at highlighting flow changes, especially in regions where temperatures are uniform.

Isosurfaces—Smokeview uses isosurfaces to identify where a specified level of a gas phase quantity occurs rather than *how much*. For example, WFDS uses a mixture fraction model to simulate combustion. In this model, there is a critical or stoichimetric mixture fraction value, such that regions greater than the critical value are fuel rich and regions less than the critical value are fuel lean. Burning then occurs, according to the model, on the level surface where the mixture fraction equals this stoichimetric value. Therefore, it is of interest to visualize these locations. This is done using animated isosurfaces.

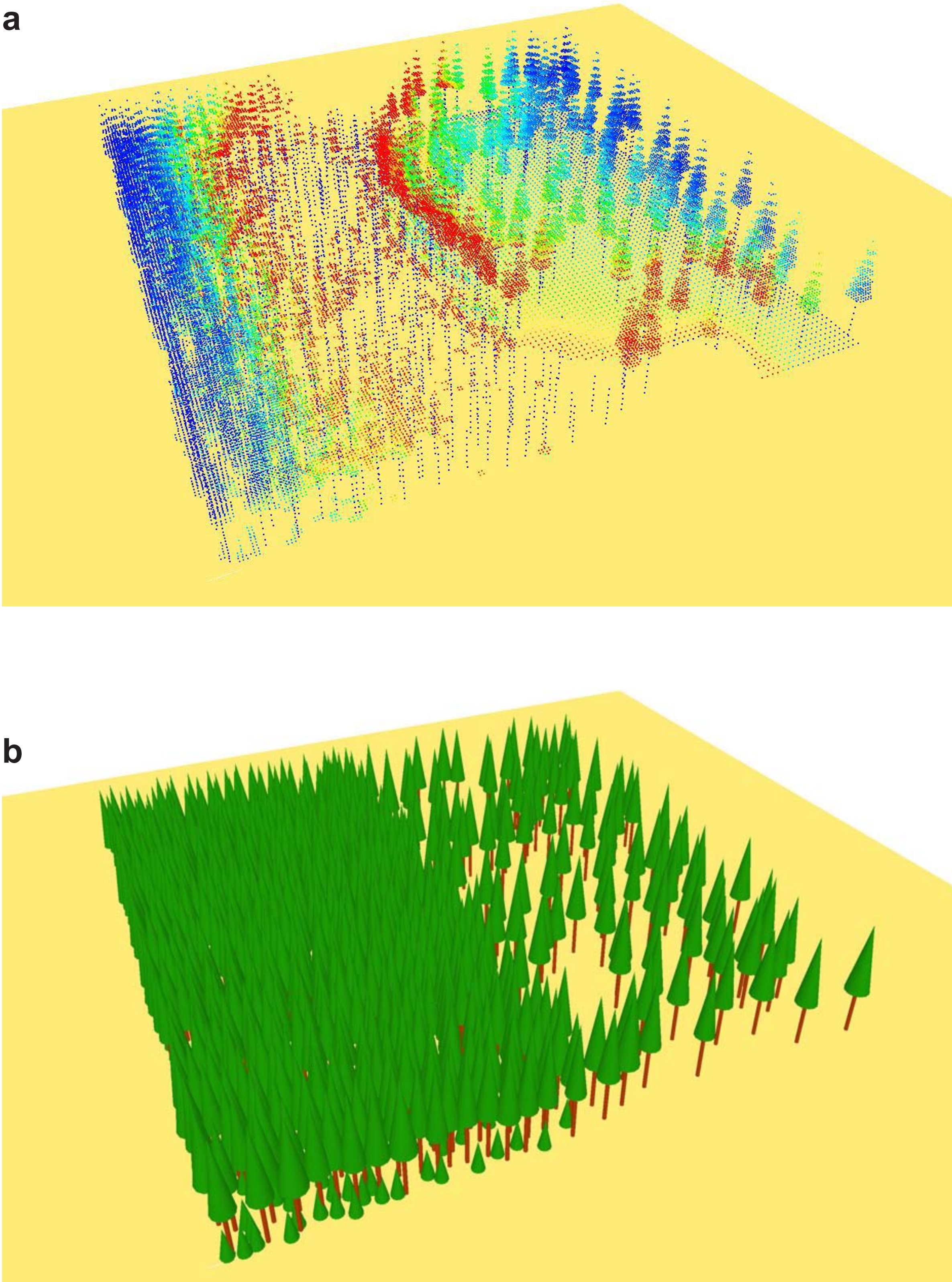


Figure 1—Particle and realistic view of a crown fire simulation burning with wind from the left at 4.0 m/s (8.9 mph). Colors in the particle view represent temperature. Regions colored red are 200 °C (410 °F) or warmer, regions colored blue are about 25 °C (77 °F). Tree section is 50 m on a side. (1a) Trees drawn and modeled using particles. Particles release heat. Particles also drag or slow down air flowing past. (1b) Trees drawn realistically.

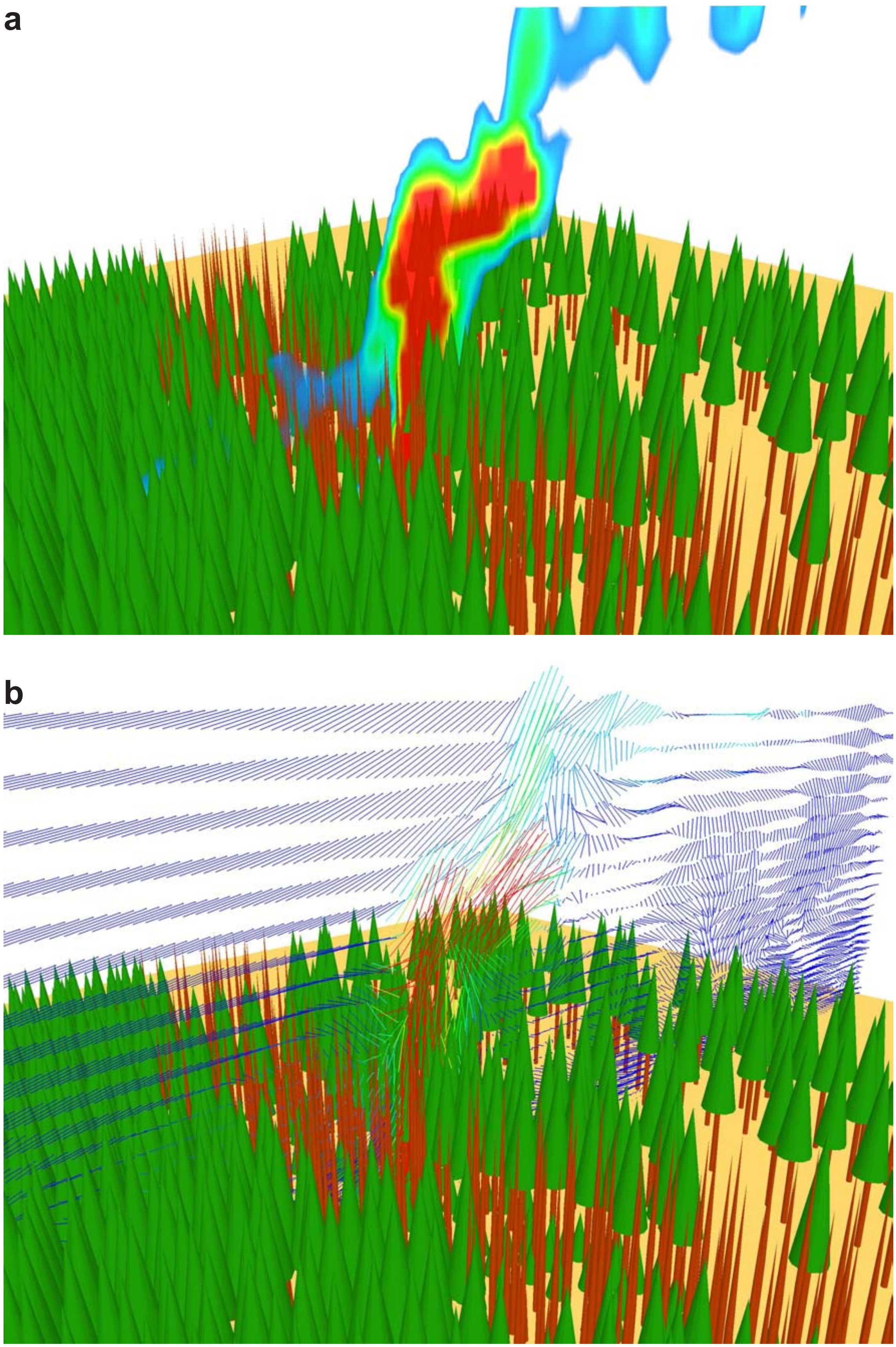


Figure 2—Snapshot of shaded temperature contours and flow vectors through the center of a crown fire simulation with wind velocity boundary condition (from the left) of 4.0 m/s (8.9 mph). Colors represent temperature. Regions (or vectors) colored red are 200 °C (410 °F) or warmer, regions colored blue are about 25 °C (77 °F) . The region in the plot with temperature below 50 °C (122 °F) is hidden. Tree section is 50 m on a side. (2a) Shaded temperature contours. (2b) Colored flow vectors.

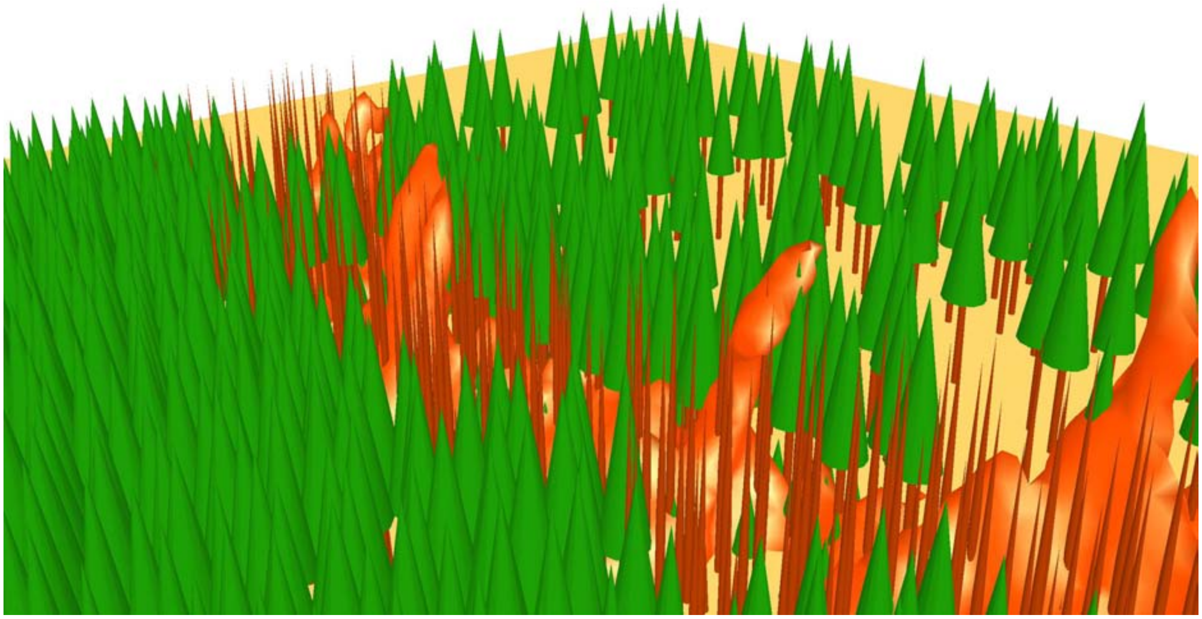


Figure 3—Snapshot of an iso-surface for of stoichimetric mixture fraction, a reasonably accurate surrogate for visualizing flames.

The isosurfaces are generated at each desired time step using a marching cube algorithm (Lorensen and Cline 1987) modified to remove ambiguities. A decimation procedure is used to reduce the number of resulting triangles by collapsing nodes of triangles with large aspect ratios and retriangulating. This makes the isosurface look better and also reduces storage requirements. Figure 3 illustrates the use of iso-surfaces for visualizing the stoichimetric mixture fraction at the same time and view point as seen in figure 2.

Realistic Visualization

Visualizing smoke realistically is challenging for three reasons. The storage requirements for describing smoke throughout the simulation scene at every time step can easily exceed the disk size capacities of present 32 bit operating systems, which would typically be 2 GB. The computation required both by the CPU and the video card to display each frame can easily exceed 0.1 s, the time corresponding to a 10 frame/s display rate. The physics required to describe smoke and its interaction with itself and surrounding light sources is complex and computationally intensive. Approximations and simplifications are required.

Smoke visualization techniques described previously, such as the use of tracer particles or shaded 2D contours are useful for analyzing data quantitatively, but are not suitable for applications where realism is required. Some examples of such applications are using Smokeview as a virtual fire fighter trainer or using Smokeview to examine the obscuration effects of smoke on an outdoor environment.

The approach used by Smokeview for visualizing smoke realistically is similar to that taken in Fedkiw and others (2001) except that interactions with smoke and light are not considered (only the effects of smoke obscuration are visualized). The video hardware is exploited to perform an obscuration calculation by using OpenGL to display a series of partially transparent parallel planes. The planes are chosen from the 3D obscuration data set computed by WFDS to be the ones most perpendicular to the viewer's line of sight. Different plane orientations are chosen in real time as the viewer rotates the scene. The transparencies are computed based on physics using data derived from a WFDS calculation. Vertices in each plane are colored black. The vertices are also assigned an OpenGL α opaqueness parameter. The assigned value depends on the optical smoke thickness, with 0.0 used for completely transparent smoke and 1.0 for completely opaque.

Computing opaqueness—The α values are precomputed by WFDS using Beer's law (Siegel and Howell 2001):

$$\alpha = 1 - \exp(-ks\Delta x) \tag{1}$$

for a particular view direction (down the *x* axis) where Δx is the distance between two nodes, *k* is the soot mass extinction coefficient and *s* is the soot density. Beer's law is an empirical relationship relating light absorption to the material properties of the media the light is traveling through, in this case soot or smoke. Smokeview currently does not consider light scattering effects with smoke.

Adjusting opaqueness—The absorption parameter, α needs to be adjusted when the view direction is not aligned along the axis orthogonal to the viewing planes (as in fig. 4), the distance between adjacent smoke planes changes, or viewing planes are skipped.

Ten million exponential operations per second are required to display smoke with corrected α's at 10 frames per second if the simulation has grid dimensions of 100*100*100. Recent advances in CPU and video hardware makes these types of visualizations possible. These corrections may also be performed in the video card (GPU), resulting in increased display rates since the GPU performs the corrections simultaneously at all or many of the grid nodes rather than one at a time as the CPU would.

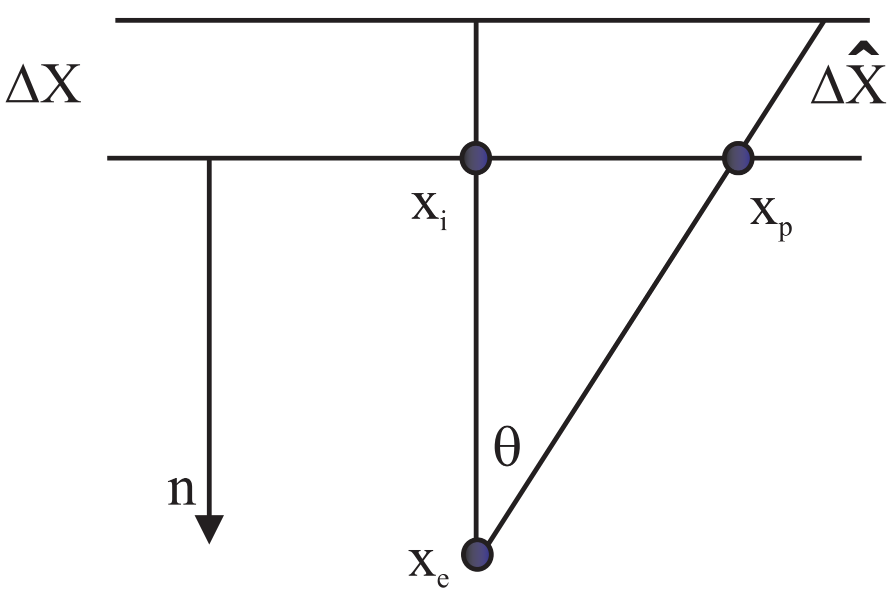


Figure 4—Illustration of the adjustment needed to the opaqueness parameter, α, for non axis aligned views. The α value along the ray containing the $\hat{x}$ segment needs to be larger to account for the longer path length.

The α obscurations are precomputed using the distance *Δx* between adjacent planes along the x-axis. The adjusted $\hat{\alpha}$ expressed in terms of $\Delta\hat{x}$ is given by

$$\hat{\alpha} = 1 - \exp(-ks\Delta\hat{x}) \qquad (2)$$

Equations 1 and 2 may be used to solve for $\hat{\alpha}$ in terms of α to obtain

$$\hat{\alpha} = 1 - (1-\alpha)^{\Delta\hat{x}/\Delta x} \qquad (3)$$

after noting that

$$1 - \hat{\alpha} = \exp(-ks\Delta\hat{x}) = \exp(-ks\Delta x)^{\Delta\hat{x}/\Delta x} = (1-\alpha)^{\Delta\hat{x}/\Delta x}$$

The computation of equation 3 is expensive because the exponential is computed at each grid node for every time step. In addition, numerical cancellation may occur for α close to zero leading to loss of significant digits. Both problems may be solved by expanding equation 3 in a Taylor series and keeping only the first few terms:

$$\hat{\alpha} \approx \alpha r - \frac{a^2}{2} r(r-1) + \frac{a^3}{2} r(r-1)(r-2)$$

where $r = \sec(\theta) = \Delta\hat{x} / \Delta x = \|x_p - x_e\| / n \cdot (x_p - x_e)$, *n* is the unit vector normal to the current plane being drawn, α is the angle between the view direction and the normal vector *n*, x_e is the observers position, and x_p is the vertex being drawn (along the view direction). These terms are illustrated in figure 4.

When planes are skipped equation 3 may be simplified. In particular when every second plane is skipped, $\Delta\hat{x} / \Delta x = 2$, so that equation 3 simplifies to

$$\hat{\alpha} = 1 - (1-\alpha)^2 = 2\alpha - \alpha^2$$

The video hardware uses α values contained in the smoke planes to obscure the background much like a camera uses a neutral density filter to darken a scene. Extending the analogy, Smokeview uses one *neutral density filter* (numerically) for each plane of smoke data. On a node by node basis then, each smoke plane obscures the current image stored in the OpenGL back buffer by the amount (1-α) to form a new back buffer image. A simplistic description of one step of this process is given by

new buffer image = (1-α) * old buffer image

This process is repeated for each smoke plane. Figure 5 illustrates this process for smoke and fire spread over a large grassland fire simulated by WFDS. The fuel properties are based on those measured in grassland plots during experiments conducted in Australia. A further description of the fuels and simulations is in Mell and others (2007).

The visualization is performed by displaying a series of partially transparent planes. For illustration, these planes are made more conspicuous (in fig. 5a) by skipping smoke planes (displaying every third plane) and orienting them along the x axis. Figure 5b shows the visualization as it would normally appear with all slice planes shown and oriented toward the viewer.

a

b

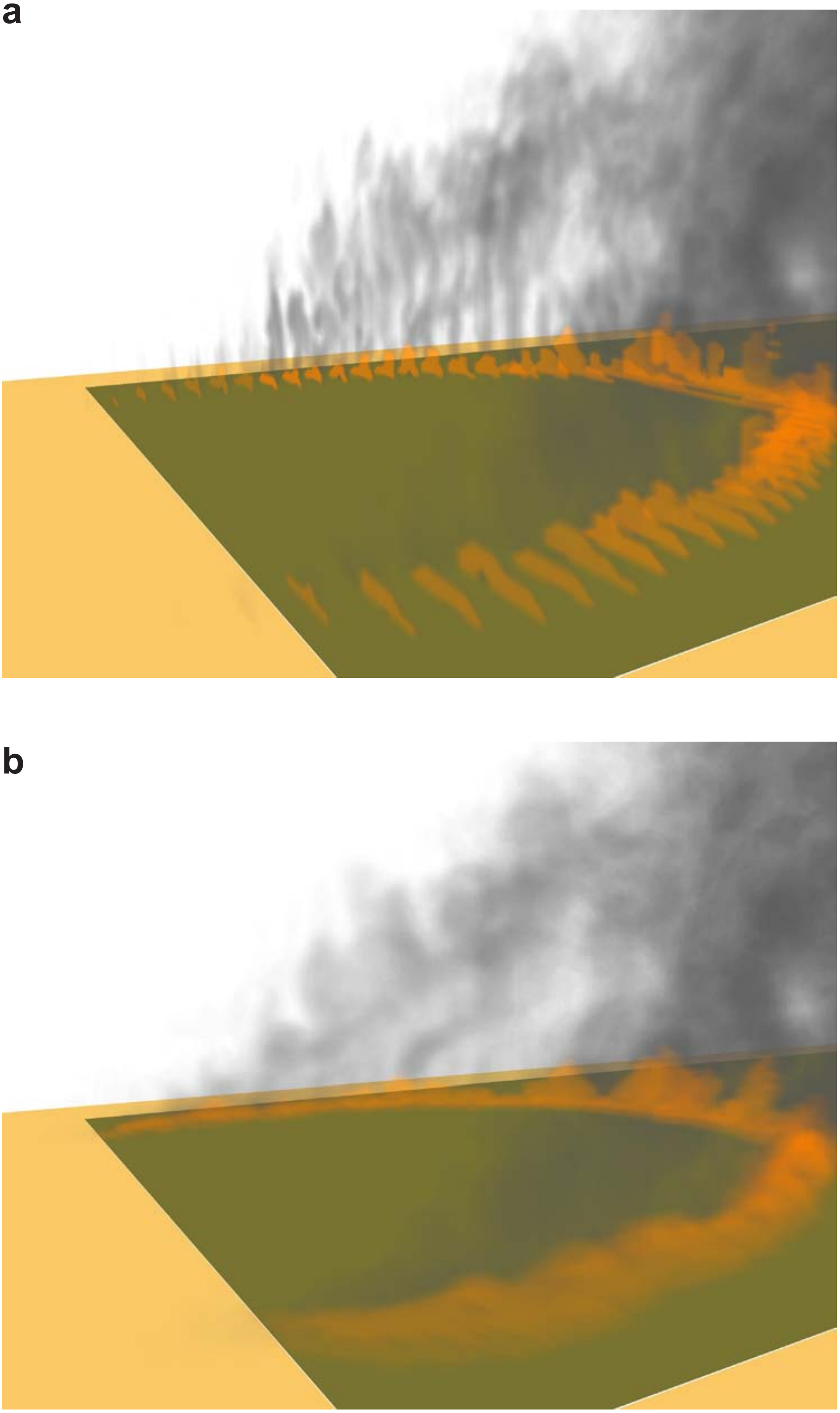


Figure 5—Realistic visualization of a large grass fire simulated using WFDS. Planes in the top image are drawn to be conspicuous by skipping two out of every three planes and by aligning planes along the x axis. All planes in the bottom image are displayed (none are skipped) and they are aligned to be closest to perpendicular of all possible plane orientations. (5a) Slices skipped and oriented along x directions. (5b) All slices shown and oriented toward viewer.

Summary

Smokeview is used to visualize data simulated by WFDS, the NIST wildland fire dynamics simulator. Smokeview uses several techniques to visualize data, some scientific and some realistic. The realistic technique uses the video hardware found on modern computers to convert soot densities computed by WFDS to opacities displayed on the computer screen. The local values of obscuration are computed by WFDS for all grid nodes using soot density, grid spacing, and the soot mass extinction coefficient appropriate for visible light and the fuel being burned. This is a one time computation. Smokeview, on the other hand, integrates these local values along the line of sight each time the view position or direction changes and for each frame of data.

Smokeview is a scientific visualization tool that has been adapted to display data for several types of applications and it may be adapted to display data simulated by fire models used to solve other aspects of the WUI problem.

Additional Information

"Fire on the Web" (http://fire.nist.gov) contains resources related to fires including images and movies of real fires along with measured heat release data, software for modeling fire flow, and links to NIST publications related to fire. Information on the fire modeling software FDS and Smokeview may be found at http://fire.nist.gov/fds. Further information about the wildland urban interface adaptation of FDS (WFDS) may be found at http://www2.bfrl.nist.gov/userpages/wmell/public.html.

Acknowledgment

The authors are grateful to acknowledge Kevin McGrattan for developing FDS, the foundation of WFDS, and making it available for use in this WUI modeling work.

References

Alexander, M.; Stefner, C.N.; Mason, J.A.; Stocks, B.J.; Hartely, J.R.; Maffey, M.A.; Wotton, B.M.; Taylor, S.W.; Lavoie, N.; Dalrympte, G.N. 2004. Characterizing the Jack pine - black spruce fuel complex of the international crown fire modeling experiments (ICFME). NOR-X 393. Canadian Forest Service, Northern Forestry Centre.

Andrews, P.L.; Bevins, P.L. 1999. BEHAVE Fire Modeling System: Redesign and Expansion. Fire Management Notes 59:16-19.

Bentz, D.P.; Forney, G.P. 2000. User's Guide to the NIST Virtual Cement and Concrete Testing Laboratory, Version 1.0. Technical Report NISTIR 6583. Gaithersburg, MD: National Institute of Standards and Technology.

Evans, David D.; Rehm, Ronald G.; Baker, Elisa S. 2004. Physics-Based Modeling for WUI Fire Spread - Simplified Model Algorithm for Ignition Structures by Burning Vegetation. NISTIR 7179, 2004.

Fedkiw, Ronald; Stam, Jos; Jensen, Henrik Wann. 2001. Visual simulation of smoke. In: Eugene Fiume, editor, SIGGRAPH 2001, Computer Graphics Proceedings. ACM Press/ACM SIGGRAPH: 15-22.

Finney, M.A.; Andrews, P.L. 1999. A Program for Fire Growth Simuluation. Fire Management Notes 59:13-15.

Forney, G.P.; Madrzykowski, D.; McGrattan, K.B.; Sheppard, L. 2003. Understanding fire and smoke flow through modeling and visualization. Computer Graphics and Applications 23(4):6-13.

Forney, G.P.; McGrattan, K.B. 2004. User's Guide for Smokeview Version 4 - A Tool for Visualizing Fire Dynamics Simulation Data. NIST Special Publication 1017. Gaithersburg, MD: National Institute of Standards and Technology.

Jones, W.W.; Peacock, R.D.; Forney, G.P.; Reneke, P.A. 2004. CFAST, Consolidated Model of Fire Growth and Smoke Transport (Version 5). Technical Reference Guide. NIST Special Publication 1030. Gaithersburg, MD: National Institute of Standards and Technology.

Kilgard, Mark J. 1996. OpenGL Programming for the X Window System. Reading, MS: Addison-Wesley Developers Press.

Lorensen, William E.; Cline, Harvey E. 1987. Marching cubes: A high resolution 3d surface construction algorithm. Proceedings of the 14th annual conference on Computer graphics and interactive techniques. ACM Press: 163-169.

Manzello, Samuel L.; Cleary, Thomas G.; Shields, John R.; Yang, Jian. 2006. On the ignition of fuel beds by firebrands. Fire and Materials 30:77-87.

McGrattan, K.B. 2004. Fire Dynamics Simulator (Version 4), Technical Reference Guide. NIST Special Publication 1018. Gaithersburg, MD: National Institute of Standards and Technology.

McGrattan, K.B.; Forney, G.P. 2004. Fire Dynamics Simulator (Version 4), User's Guide. NIST Special Publication 1019. Gaitherburg, MD: National Institute of Standards and Technology.

Mell, William; Jenkins, Mary Ann; Gould, Jim; Cheney, Phil. 2007. A physics-based approach to modeling grassland fires. International Journal of Wildland Fire 16(1):1-22.

Shreiner, Dave; Woo, Mason; Neider, Jackie; Davis, Tom. 2005. OpenGL Programming Guide - The Official Guide to Learning OpenGL, Version 2. 5th edition. OpenGL Architecture Review Board. Stoughton, MS: Addison-Wesley.

Siegel, Robert; Howell, John R. 2001. Thermal Radiation Heat Transfer. 4th edition. New York: Taylor & Francis, Inc.

Stoliarov, S.I.; Westmoreland, P.R.; Nydeb, M.R.; Forney, G.P. 2003. A reactive dynamics model of thermal decomposition in polymers: I. Poly (methyl methacrylate). Polymer 44(3):883-894.

Walton, W.D.; McGrattan, K.B.; Mullin, J.V. 2003. A Smoke Plume Trajectory Model for Personal Computers. Technical Report NIST SP 995. Gaithersburg, MD: National Institute of Standards and Technology.

Validation of BlueSky Smoke Prediction System Using Surface and Satellite Observations During Major Wildland Fire Events in Northern California

Lesley Fusina[1], Sharon Zhong[1], Julide Koracin[2], Tim Brown[2], Annie Esperanza[3], Leland Tarney[4], and Haiganoush Preisler[5]

***Abstract**—The BlueSky Smoke Prediction System developed by the U.S. Department of Agriculture, Forest Service, AirFire Team under the National Fire Plan is a modeling framework that integrates tools, knowledge of fuels, moisture, combustion, emissions, plume dynamics, and weather to produce real-time predictions of the cumulative impacts of smoke from wildfires, prescribed fires, and agricultural burn activities. Currently, BlueSky smoke predictions are available daily across the contiguous United States. The output has been used by air regulators, burn bosses, and smoke managers as a guide to help make 'go' and 'no-go' decisions about prescribed fires and plan burn operations. It also helps track day-to-day emissions from wildland and prescribed fires. BlueSky is establishing its reputation as a one-stop shopping for regional smoke concentration and emissions tracking across all land ownership, and is being used by more and more users especially in the West. On the other hand, little is known about the accuracy of its predictions of smoke transport and dispersion under different meteorological conditions. This ongoing study aims at validating BlueSky predictions using in-situ and satellite observations. The study domain is northern California and southern Oregon during the last 2 weeks of August 2006 when several major wildland fires broke out in the region. The predicted smoke concentrations are evaluated by the $PM_{2.5}$ data at several stations, and the plume trajectories are compared with satellite images. Sensitivity tests are performed to identify potential sources in the smoke predictions so that improvements can be made to the BlueSky prediction system.*

In: Butler, Bret W.; Cook, Wayne, comps. 2007. The fire environment—innovations, management, and policy; conference proceedings. 26-30 March 2007; Destin, FL. Proceedings RMRS-P-46CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 662 p. CD-ROM.

[1] Department of Geography Michigan State University, East Langing, MI. Lead author at fusinale@msu.edu.

[2] Desert Research Institute, Nevada System of Higher Education, Reno, NV.

[3] U.S. Department of the Interior, National Park Service, Sequoia and Kings Canyon National Parks, California.

[4] U.S. Department of the Interior, National Park Service, Yosemite National Park, California.

[5] U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, Albany, CA.

Introduction

BlueSky, developed by the U.S. Department of Agriculture, Forest Service, AirFire Team, is a smoke modeling framework that integrates consumption, emissions, meteorology, and dispersion models to predict smoke trajectories and concentrations of particulate matter. BlueSky smoke predictions are available daily across the contiguous United States and the output has been used by air regulators, burn bosses, and smoke managers as a guide to help make 'go' and 'no-go' decisions about prescribed fires, plan burn operations, and help track day-to-day emissions from wildland and prescribed fires. BlueSky is establishing its reputation as a one-stop shopping for regional smoke concentration and emissions tracking across all land ownership, and is being used by more and more users especially in the West, as this area is subject to higher risk of wildland fires than other parts of the country. Few studies have compared BlueSky predictions with actual observation. Validation efforts to date have been limited to isolated fire cases in the Northwest (Adkins and others 2003; Berg and others 2003; Larkin and others 2006).

As part of an effort to provide better information on fire weather and smoke dispersion/transport, the California and Nevada Smoke and Air Committee (CANSAC) has been running the coupled MM5 model and BlueSky smoke prediction system in real-time for California and Nevada. In this paper, we describe some preliminary results from an effort to validate the CANSAC BlueSky smoke predictions as part of a project funded by the Joint Fire Science Plan to develop tools for estimating contributions of wildland and prescribed fires to air quality in the Sierra Nevada.

Study Domain, Cases, Data

The study focuses on the area of northern California and southern Oregon during the last 2 weeks of August 2006 when a stream of major wildfires broke out in this area. These large fires provide a clear smoke signal on satellite imagery and surface PM monitors, creating an ideal environment for comparison efforts. Figure 1 shows the station locations where in-situ particulate matter and meteorological variables were collected. The predictions of BlueSky PM concentrations associated with these fires were produced by CANSAC at the Desert Research Institute. Four nested domains were used with the innermost domain of 4-km grid spacing covering California and Nevada. The meteorological input was provided by the MM5 forecast. Initial and boundary conditions for the MM5 forecasting were obtained from the

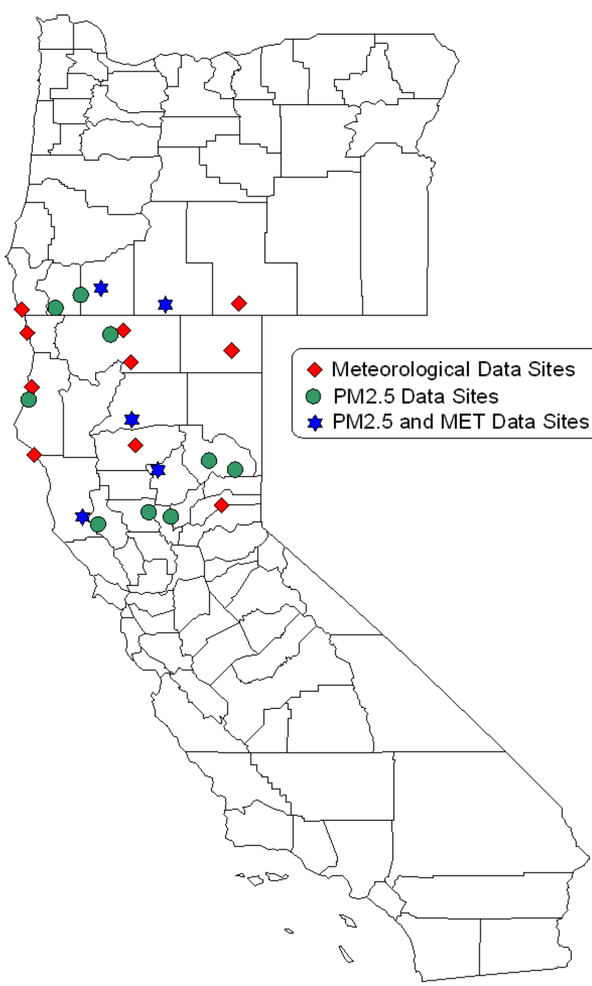


Figure 1–Locations of $PM_{2.5}$ monitoring sites and surface meteorological observation sites in the study domain.

6 hourly 40-km Eta forecasts from the National Center for Environmental Predictions. The details of BlueSky and MM5 configuration can be found at the CANSAC Web site at: http://www.cefa.dri.edu/COFF/.

$PM_{2.5}$ in-situ hourly measurements for approximately a dozen stations were obtained from both the Environmental Protection Agency (EPA) and Oregon's Department of Environmental Quality. Daily satellite images were downloaded from the National Geophysical Data Center's Satellite Fire Detections Web site (map.ngdc.noaa.gov/website/firedetects/viewer.htm). Hourly extracted $PM_{2.5}$ concentrations by station were compared with time series of observed measurements. An average of $PM_{2.5}$ concentrations taken from a fire free period during (July 16-24, 2006) was subtracted from the observed $PM_{2.5}$ value in an effort to view the fire induced effect on $PM_{2.5}$. Qualitative comparisons of smoke trajectories were done between the daily satellite images and the BlueSky output. Time series analysis of the MM5 model was necessary to be sure the meteorological variables being supplied to BlueSky were not causing inaccuracies in predicted smoke plume trajectories. In-situ hourly weather data were collected for 15 stations from the National Climatic Data Center Web site (www.ncdc.noaa.gov/oa/ncdc.html).

Results

Past studies concerning the accuracy of BlueSky have found that plume trajectories seem to agree well with satellite observations, but tend to underpredict $PM_{2.5}$ concentrations (Larkin and others 2006). Our investigation into BlueSky's accuracy concerning fires in northern California has produced similar results. As figure 2 shows, BlueSky has captured very well

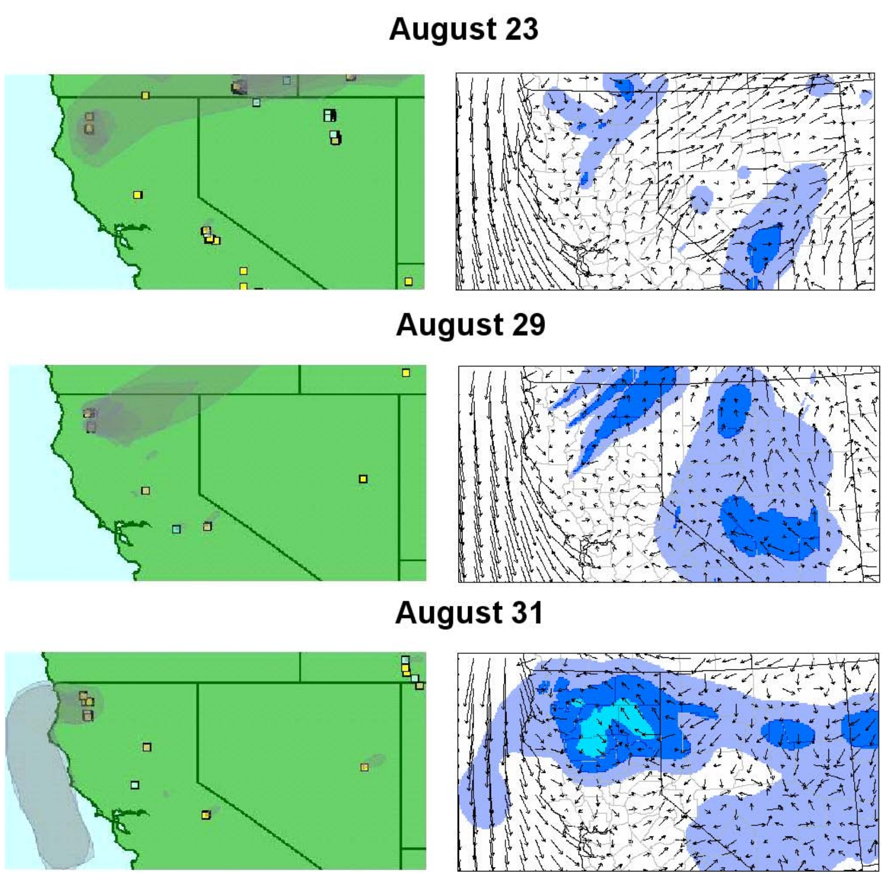


Figure 2–4km model domain used. The left panel shows the National Geophysical Data Center satellite images of smoke plume. The right panel shows the corresponding images from BlueSky output.

the trajectory and shape of the observed smoke plumes from the fires near the California and Oregon border. There are smoke plumes in Nevada in the BlueSky predictions that are absent from satellite images. The cause for this discrepancy is being investigated, and is likely due to inaccurate information on fire emissions.

Time series analysis of $PM_{2.5}$ concentrations at selected stations (fig. 3) shows increases of modeled values when observed values increase. The observed concentrations of $PM_{2.5}$ are a combination of emissions from fires and other emissions sources including primary and secondary sources. The only emission sources in BlueSky, however, are wildland and prescribed fires. To isolate the contributions to PM concentrations from fires, the hourly observed values during this period were subtracted from the mean hourly values from a fire-free period prior to the beginning of these fires. The negative values at a particular hour, therefore, imply that the observed value is less than the 'fire-free' mean value for that hour. Although these time series show relatively good agreement between BlueSky $PM_{2.5}$ concentrations and the observed measurements, BlueSky does not do well in capturing all of the smaller $PM_{2.5}$ fluctuations. Klamath Falls in Oregon is a good example. The model shows two large increases in PM concentration but fails to pick up the many smaller fluctuations. That said, the model in all cases has good quantitative agreement of $PM_{2.5}$ concentrations, which is different from previous studies where BlueSky was found to underpredict $PM_{2.5}$ concentrations (Larkin and others 2006).

The time series in figure 3 also shows small time lags between the model and observed concentrations. Figure 4 shows a sequence of meteorological time series at Klamath Falls. There tends to be a good agreement between the modeled and observed variables, but the model is underpredicting windspeed, which is probably the cause for the delay in the BlueSky predicted peak $PM_{2.5}$ value compared to the observed onset time of the peak. The time series of

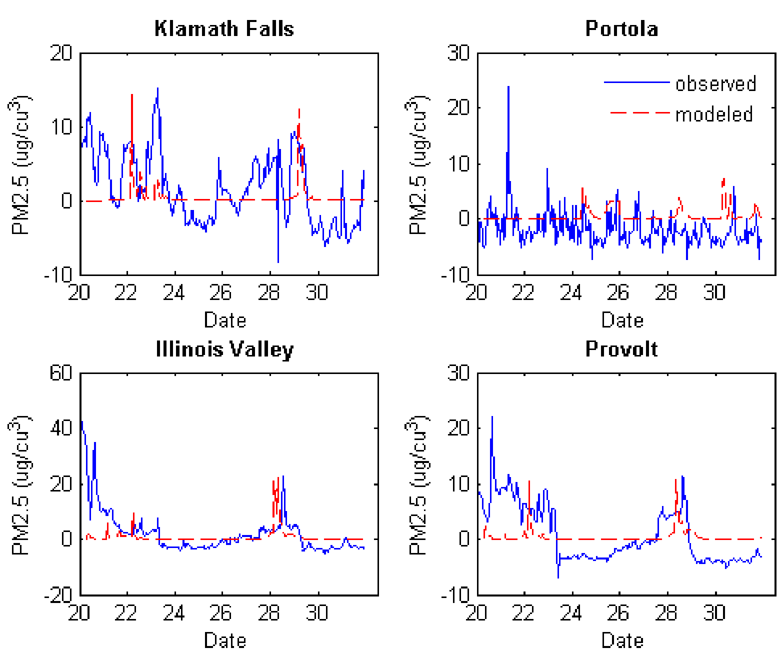


Figure 3–Time series of observed and modeled $PM_{2.5}$ concentrations at study sites. To isolate the contributions to PM from the fires, the hourly observations of $PM_{2.5}$ were subtracted by the hourly mean obtained using data from a fire-free period just before the study period.

the three remaining stations in figure 3: Portola, Illinois Valley, and Provolt, demonstrates the opposite situation, where the impact of $PM_{2.5}$ is sooner than observations show. Most likely, one could follow the same logic as above and assume the reason for this is due to overprediction of windspeeds, as figure 5 shows. However, in this study, the overprediction of MM5 windspeeds was not common in respect to how many times $PM_{2.5}$ impacts were predicted sooner than observed. One possibility is that MM5 overpredicts upper level winds. At the time of this writing, the predicted upper level meteorological conditions including windspeed, wind direction, stability, and boundary layer heights, are being compared with the twice daily rawinsonde soundings at Medford, OR. Other factors could also contribute to the disagreement between the modeled and predicted concentrations and sensitivity simulations will be performed to isolate these factors.

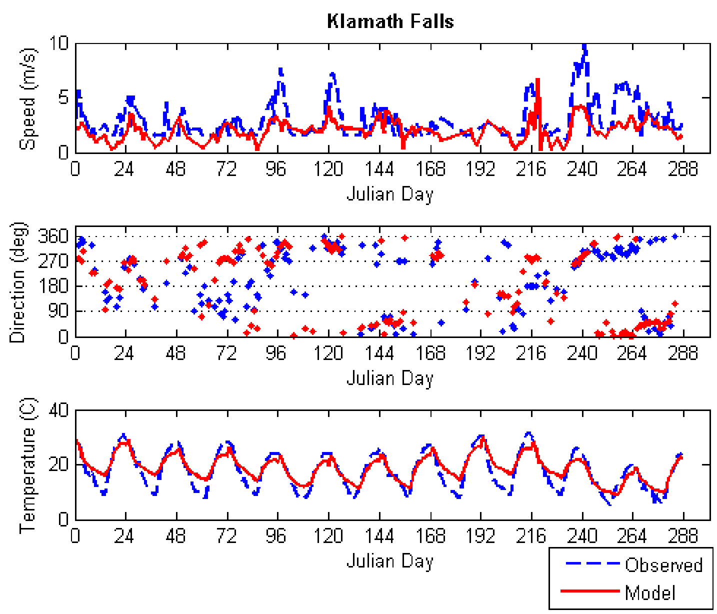


Figure 4–Time series of meteorological variables of Klamath Falls, OR. MM5 shows relatively good agreement with observations but slightly slower windspeeds, which was found to be normal in this study.

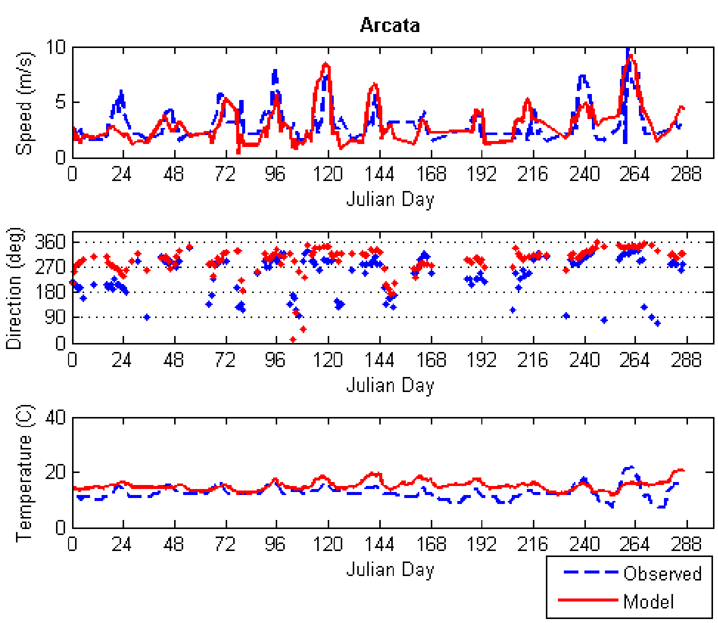


Figure 5–Same as figure 4, but for Arcata, CA.

Summary

In attempts to validate the accuracy of the BlueSky smoke model used by air regulators, burn bosses, and fire managers across the United States, a study over northern California during the last 2 weeks in August is being investigated. Preliminary results show good agreement between BlueSky smoke plume trajectories and satellite images. Although plume shape does not seem to be overly consistent between the two, BlueSky does do a reasonably good job in capturing accurate concentrations for large increases of $PM_{2.5}$ at surface stations. Meteorological analysis has also shown good agreement between observed and predicted values. Errors in MM5 windspeed predictions were evident, but alone those were not consistent enough to account for all inaccuracies within BlueSky.

Ongoing work includes more analysis of the meteorology supplied to BlueSky by the MM5 model. Specifically, upper air data will be reviewed to see if the plume trajectory behavior exhibited by BlueSky is in agreement with the MM5 model. Upper air data can also help to clarify discrepancies at the surface when predicted surface concentrations of $PM_{2.5}$ do not agree with the observed concentrations, but smoke plume trajectories do. More study into the actual smoke plumes predicted by BlueSky and the $PM_{2.5}$ concentrations within the plumes will be done by comparing them with aerosol optical depth data. Sensitivity studies will be done, forcing components of BlueSky to behave a certain way, in hopes to isolate which of those components of BlueSky—meteorological variables, emissions, plume dispersion, and so forth—are causing the major inconsistencies between BlueSky predictions and observations.

Acknowledgments

This study is made possible with the support and funding by the interagency Joint Fire Science Plan. Thanks to Anthony Barnack at the Oregon Department of Environmenal Quality for his help in obtaining $PM_{2.5}$ data.

References

Adkins, J.W.; O'Neill, S.M.; Rorig, M.; Ferguson, S.A.; Berg, C.M.; Hoadley, J.L. 2003. Assessing the Accuracy of the BlueSky Smoke Modeling Framework During Wildfire Events. Paper read at 5th Symposium on Fire and Forest Meteorology and the 2nd International Wildland Fire Ecology and Fire Management Congress, at Orlando, FL.

Berg, C.M.; O'Neill, S.M.; Ferguson, S.A.; Adkins, J.W. 2003. Application of the BlueSky Smoke Modeling Framework to the Rex Creek Wildfire. Paper read at 5th Symposium on Fire and Forest Meteorology and the 2nd International Wildland Fire Ecology and Fire Management Congress, at Orlando, FL.

Larkin, N. K.; O'Neill, S.M.; Soloman, R; Krull, C.; Raffuse, S.; Rorig, M.; Peterson, J; Ferguson, S.A. 2006. The BlueSky Smoke Modeling Framework. Atmospheric Environment, in review.

Development and Demonstration of Smoke Plume, Fire Emissions, and Pre- and Postprescribed Fire Fuel Models on North Carolina Coastal Plain Forest Ecosystems

Robert A. Mickler[1], Miriam Rorig[2], Christopher D. Geron[3], Gary L. Achtemier[4], Andrew D. Bailey[1], Candice Krull[2], and David Brownlie[5]

***Abstract**—Wildland fuels have been accumulating in the United States during at least the past half-century due to wildland fire management practices and policies. The additional fuels contribute to intense fire behavior, increase the costs of wildland fire control, and contribute to the degradation of local and regional air quality. The management of prescribed and wildland fire on Federal, State, and private lands pose critical challenges for the characterization of preburn fire fuels and postburn carbon consumption assessments, predicting smoke trajectories and concentrations, and modeling air quality emissions. Prescribed and wildland fires are both important sources of airborne fine particulate matter ($PM_{2.5}$) and ozone (O_3) precursors such as nonmethane volatile (VOCs) and semivolatile organic compounds (SVOCs), nitrogen oxides (NO_x), carbon monoxide (CO), and methane (CH_4). We quantified pre- and postburn belowground and aboveground biomass to determine fuel consumption for fine and coarse woody material, shrub, herbs, litter, and duff, and assessed fire effects on plant communities. The BlueSky smoke prediction modeling framework, and the BlueSky Rapid Access Information System (BlueSkyRAINS) were implemented to model smoke trajectory and $PM_{2.5}$ concentrations at ground level in the downwind smoke plume. $PM_{10 \text{ and } 2.5}$ and photochemically and radiatively important trace gases during the flaming and smoldering stages of prescribed burns were characterized and fire emission modeled to determine emission factors for chemical species.*

Introduction

Fire has played a major role in determining the distribution of plants across the Coastal Plain of the Southeastern United States. The extent of fire dependent ecosystems has been reduced as a result of fire exclusion and landuse conversion. Wildland fire fuel loading throughout the United States has become a hazard to life, property, ecosystem health, and the habitat of threatened and endangered species as a result of past fire exclusion policies and practices. Land managers are concerned that fuel loads are reaching hazardous levels that can lead to widespread catastrophic wildfires in forest ecosystems and the wildland/urban interface. This wildland fire risk is currently impacting ecosystem management planning throughout the Southeast.

In: Butler, Bret W.; Cook, Wayne, comps. 2007. The fire environment—innovations, management, and policy; conference proceedings. 26-30 March 2007; Destin, FL. Proceedings RMRS-P-46CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 662 p. CD-ROM.

[1] Program Manager and Forest Scientist, respectively, Alion Science and Technology, Inc., Durham, NC. Lead author rmickler@alionscience.com

[2] Meteorologists, U.S. Department of Agriculture, Forest Service, Seattle, WA.

[3] Atmospheric Scientist, U.S. Environmental Protection Agency, Research Triangle Park, NC.

[4] Meteorologist, U.S. Department of Agriculture, Forest Service, Athens, GA.

[5] Regional Ecologist, U.S. Fish and Wildlife Service, Tallahassee, FL.

Measurement and Modeling of Down Woody Debris and Fuels

Fuel classification during the past 75 years has evolved from a fire control planning focus to the beginning of predictive fire behavior modeling in the 1970s. Current fuel classification models have focused on the rate of spread, resistance to control, and the flame length of fires in surface fuels. Fire behavior is predicted by using 13 stylized fuel models (Rothermel 1972; Albini 1976). Decision support systems such as FARSITE and the National Fire Danger Rating system are based on the Rothermel fire spread model and are the basis of predicting fire behavior today. Land managers recognize that these models are limited in their ability to predict extreme fire behavior, persistent fires, and fuel consumption. Some of these limitations are currently being addressed by a fuel characteristic classification (FCC) (Sandberg and others 2001).

The availability of fire-spread models has increased the need for quantitative fuel field data. A line-intersect method developed by Brown and others (1982) has been widely adopted to quantify fuel-loading inputs. The USDA Forest Service Forest Inventory and Analysis (FIA) program recognized the need for extensive information on fuels across the landscape. Fuel field protocols (http://fia.fs.fed.us/library/field-guides-methods-proc/) were piloted by the former Forest Health Monitoring Program between 1998 and 2000, and implemented in 2001 on a $1/16^{th}$ subset of the standard base FIA grid plots. FIA methods generally partition the forest ecosystem into pools for live trees, down deadwood, standing dead trees, understory vegetation, forest floor materials, and soil. Estimating site-specific fuels from this database has been particularly problematic. The data are not consistently available from the FIA inventory data source and there are little data on fuel loading in the scientific literature. Additionally the biomass algorithms are based nationally on available data collected regionally for tree, shrub, and herbaceous species and associated wood density for decay classes.

Past fuel and fire behavior research has resulted in only qualitative measures of fuel loads and rates of spread. A more detailed fuel classification, based on species composition, standing dead and down deadwood, fuel size classification, understory vegetation, and vertical distribution of fuels, would have much more utility than the broad fuel model classification system now in use. Fire in the deep organic soil areas of the Coastal Plain is frequently associated with costly blowup wildfires and soil fires started from prescribed fire fuel reduction and habitat management burns. Wildfires in this area can, under certain combinations of fuel and weather, grow from a low intensity burn to a virtually uncontrollable burn until weather conditions change or the fire has run out of fuel. Control efforts are often hampered by inaccessibility, poor soil trafficability on wet organic soils in the area, and fires that tend to burn deeply into the organic soils. A better understanding of the behavior of fires and the role of fuel loading in fire behavior will contribute to the control of wildfires and the use of prescribed fire as a management tool in the region.

Fire Emissions Monitoring and Emission Factor Modeling

Landscape scale emissions of trace gases and PM are typically determined using the approach of Taylor and Zimmerman (1991) and Hao and Liu (1994):

$$M = A \bullet B \bullet \alpha \bullet \beta$$

where *M* is the amount of biomass consumed annually, A is the total land area burned annually (ha yr^{-1}), B is the average organic matter (fuel load) per unit area in individual biomes (metric tons or MT ha^{-1}), α is fraction of above ground biomass to total, and β is the burning efficiency (fraction consumed) of the above ground biomass. Total emission of a given compound is given by multiplying *M* by an emission factor, which is typically expressed in units of g-C/kg-C fuel consumed.

These emission factors and total emissions of trace gases and PM from individual fires are typically determined using a carbon mass balance approach as described in Ward and Hardy (1988) as:

$$F_t = \left[\frac{C_t}{(C_{CO2} + C_{CO} + C_{CH4} + C_{TPM} + C_{VOC})} \right] CS_F$$

where F_t is the flux of the target compound(s), C_t is the concentration of the target compound(s), $C_{CO2,CO,CH4,TPM,VOC}$ are sample concentrations of CO_2, CO, CH_4, total PM, and total VOC, respectively, and CS_F is the fuel consumption (carbon mass) per unit area. Nitrogenous emissions are calculated similarly. These approaches have been used to calculate emission factors (EFs) and total emission fluxes from the Coastal Plain prescribed fires in North Carolina.

The mass balance approach takes advantage of the turbulent state of mixing in fire plumes, which means that particles and gases will be transported in similar proportions as they move from the source. This allows for the calculation of valid mass balance estimates of PM and gases in plumes that cool to ambient conditions, appropriate for assessing impacts on air quality and atmospheric chemistry.

For wildfire sampling, remote platforms are needed to access smoke plumes. This is necessary to maintain safe working conditions and ensure that samples are collected in air parcels dominated by the fires. Ground based sampling is not practical for wildfire studies because adequate planning horizons or sampling sites are not typically available. Even when sites are located, shifting winds often move smoke away from sampling systems. Manned aircraft has been used to collect smoke samples in the past, but this is dangerous and can be prohibitively expensive.

Biomass burning in the Southeast can be a potentially significant source of photochemically active and radiatively important trace gases as well as PM (Barnard and Sabo 2003). Areas burned in the region vary annually but are typically several million acres per year, resulting in trace gas and PM emissions that range from 2 to 15 percent of total emissions from other sources. Little data on emissions from prescribed burning are currently available, and this fire type in particular is projected to increase in the Southeastern United States. Emissions of reduced compounds, many of which are air toxins, are thought to be lower during prescribed fires compared to wildfires covering the same area. This is suspected largely because it is known that wildfires occur typically during excessively dry periods when much of the forest floor is dry and susceptible to smoldering incomplete combustion, the source of many toxic compounds.

Continuous monitoring of O_3, PM, and NO_x have shown that air pollutant concentrations are enhanced by forest fire emissions. In the rural environment, the influence of the forest fire on air quality can be detected, and significantly higher (50 to 150 percent) pollution levels than seasonal median values have been documented (Cheng and others 1998). While fire events can cause high transient air pollutant concentrations, for most criteria pollutants, the fire emissions are a relatively small fraction of the annual emission inventory. For fine PM, however, the annual emission estimates from biomass burning represent a significant fraction of many Southern States' emission inventories, especially in the counties where the emissions are concentrated (Dennis and others 2002). Given the current emphasis by the EPA on particles, it is imperative that real-world emission data be developed from open burning sources.

It is generally thought that emission factors or pollutants are among the more consistent and reliable components of biomass burning emission models. However, comparisons of recent studies suggest that under some conditions, especially where smoldering combustion is important, EFs are still quite uncertain (Andreae and Merlet 2001; Hays and others 2002). Residual smoldering combustion (RSC) emissions from forest floor burns can be produced for up to several weeks after the passage of a flame front and they are mostly unaffected by flames. Fuels prone to RSC include downed logs, litter, and organic soils. These fuels are important in our proposed study area. Limited observations suggest that RSC is a globally significant source of emissions to the troposphere (Bertschi and others 2003). These authors used a model that predicts trace gas EF for fires in a wide variety of aboveground fine fuels. It failed to predict emission factors for RSC. For many compounds, the EF for RSC-prone fuels is different from the EF for the same compounds measured in fire convection columns above forest ecosystems. Some large changes resulted in estimates of biomass fire emissions with the inclusion of RSC. For instance, EF increases by a factor of 2.5 even when RSC accounts for only 10 percent of fuel consumption. This shows that many more measurements of fuel consumption and emission factors for RSC are needed to improve estimates of biomass burning emissions.

Smoke Trajectory and Concentration Modeling

Smoke emissions from wildland fires are one the most important constraints on land mangers conducting prescribed burns. The quantity, duration, time of day, and spatial dispersion of smoke must all be considered when assessing the impacts on human health and safety. Existing smoke models do a poor job of estimating smoke production and duration. This is especially true on the deep organic soils found in the Coastal Plain of the Southeast. Many of the dispersion models in use by wildland mangers today—SASEM (Sestak and Riebau 1988), VALBOX (Sestak and others 1989), VSMOKE (Lavdas 1996), NFSpuff (Harison 1995), TSARS (Hummel and Rafsnider 1995), and CALPUFF (Scire and others 1995)—have been adapted from industrial stack models for use in wildland fires. Smoke models for prescribed burning differ from point-source industrial models due to additional data requirements for pattern of ignition, fuel moisture by size, fuel loading by size, fuel distribution, and local weather that influences burn rates and dispersion. The FARSITE (Finney 1998) model was developed to address these data requirements and is used to model forest fire behavior in variable fuels, terrain, and changing local weather conditions. FARSITE does not model smoke dispersion, but output from the combined models can now be used in smoke dispersion models.

The BlueSky smoke modeling framework (http://blueskyrains.org) is a smoke prediction tool used by land managers to facilitate wildfire containment and prescribed burning programs, which are necessary for ecosystem health, while minimizing impacts to human health and scenic vistas. The BlueSky smoke modeling framework links computer models of weather prediction, fuel consumption and emissions by fire, and smoke dispersion into a system for predicting the cumulative impacts of smoke from prescribed fires, wildfires, and agricultural fires (O'Neill and others 2003, 2005). BlueSky is currently functional over the conterminous United States. While differences exist regionally, each night BlueSky obtains regional meteorological predictions and reported burn information from available private, State, and Federal agencies, merges these data with models of fuel consumption and emissions, and processes dispersion and trajectory models to produce regional estimates of smoke concentrations for the next 1 to 3 days (Ferguson and others 2001). Smoke and fire managers access these predictions via the internet as a tool to aid their "go/no-go" decisions for burning operations and other real-time decision support (Ferguson and others 2003).

Methods

Vegetation Classification and Pre- and Postburn Biomass

We acquired 2004 leaf-off color infrared (CIR) negatives of stereo aerial photography for study areas and collected field data on fuel loads and/or fuel accumulation. Aerial photos were scanned to generate digital data layers and stereo models for interpretation as well as orthorectified mosaics of the study areas. We incorporated existing GIS vegetation data from the U.S. Fish and Wildlife Service and the U.S. Air Force using onscreen stereoscopic techniques to create a digital vegetation database. Vegetation was classified to the Alliance level using the National Vegetation Classification System (http://biology.usgs.gov/npsveg/nvcs.html). Field plots were randomly assigned within each vegetation Alliance. Fire fuel data from field based sample plots, digital photos, and vegetation data were used to develop fire fuel polygons. Additional field data were used to assess the thematic accuracy of the vegetation classification, the positional accuracy of the digital orthophoto mosaic, and the fuel load polygons. Metadata were created for the digital orthophoto mosaics and vegetation and fuel load databases.

We established a permanent plot network on the Alligator River National Wildlife Refuge and the Air Force Dare County Bombing Range modeled on USDA Forest Service FIA P2 and P3 plots to measure and characterize live biomass and pre- and postburn down deadwood (DWD). We used field protocols based in methods establish by the USDA Forest Service in "Field Instructions for Southern Forest Inventory." The collection of DWD data was collected using a line-intersect method to sample down wood along linear transects based on Brown's transects (Brown and others 1982). Plot-level data on the amount, distribution, and characterization of DWD were related to the detailed attribute data for other ecosystem components on the same plot—that is, shrub and herbaceous understory, live and dead herbs (including grasses), and litter. FIA methodology was augmented with additional data on the vertical distribution of DWD for input into the FARSITE fire behavior model. Down deadwood was characterized as coarse woody debris (woody pieces greater than 3.0 inches in diameter), or fine woody debris (small = 0 to 0.24 inch, medium = 0.25 to 0.9 inch, and large = 1 to 2.9 inches, which correspond to 1-hour, 10-hour, and 100-hour fuels, respectively). The depth of the duff layer, litter layer, and overall fuelbed was taken at the 24-ft location on each transect. FIA cluster subplot design with three 24-ft. transects (slope corrected, horizontal distance) were established at each subplot location. All subplot clusters were laid out in a fixed pattern regardless of different condition classes and only the transect segments that fell in the forest condition being sampled. The 6.8-ft radius micro plots were used to estimate the percent cover and height of live and dead shrubs, live and dead herbs (includes grasses) and litter.

These components were used to estimate fire behavior, fire spread, fire effects, and smoke production. Plot-level per-unit-area sums were expanded by the area associated with the inventory plot or averaged across the plots to produce a mean per-unit-area biomass value. Biomass computations for each fuel class have been previously developed in a pond pine/high pocosin forest type. Fuel class biomass algorithms were developed for additional forest species and decay classes in the forest type. Additional micro plots were established for destructive sampling of shrub and herbaceous vegetation to develop biomass equations. Previous equations were developed primarily for Western U.S. species (Brown and others 1982).

Prescribed Burning Emissions Monitoring and Modeling

In order to assess emissions of fine PM from prescribed fire, we investigated emissions from this burning practice during the course of prescribed burns for the fall and spring of 2005 and 2006. Mass balance techniques were used to support flux measurements of dioxin, methyl chloride, methyl bromide, and other compounds. Grab samples—stainless steel canisters for trace gases, filter packs for PM, and polyurethane foam traps for semivolatiles (Hays and others 2002)—were collected in the plumes of the fire during both flaming and smoldering conditions. These samples were then subjected to particle and total gaseous carbon analysis using a thermo-gravimetric analysis and gas chromatography/mass spectroscopy (GC/MS). Total emissions were determined by multiplying emission ratio by the estimate of total fuel carbon consumption. Total fuel carbon by mass is approximately half of the fuel dry weight following the general cellulosic molecular formula of $C_6H_9O_4$.

We sampled air that had cooled to approximately ambient temperature (within 100 m of the fire) to allow partitioning of semivolatiles between the gas and aerosol phase. We sampled directly through $PM_{2.5}$ cyclones using high volume pumps, onto 47 mm quartz (for organic PM components) and Teflon filters (for inorganic ions and elements). These were backed by polyurethane foam plugs for quantitative analysis of semivolatile organic compounds that pass through or are volatilized from the filters. Trace gases (methane, C^2-C^{12} VOC) were characterized separately using Summa stainless steel canisters and GC/MS. Target compounds in the gas and PM phase included saturated (alkane) and unsaturated hydrocarbons, aldehydes, ketones, organic acids, and polycyclic organic hydrocarbons (PAH). We also measured CO via gas filter correlation (Teco 46C) and CO^2 via infrared gas techniques (Licor 7000) to characterize carbon fluxes for the mass balance flux techniques and to characterize the nature of plume dispersion and proximity to the combustion. We used the CO/CO^2/VOC measurements to help us in chemically identifying the flaming and smoldering stages of the fires.

We quantitatively analyzed these samples to determine emission factors for individual trace gases. These were compared with factors from other fuel types. We also compared current source apportionment chemical fingerprints from these fires with those from our laboratory and "burnhut" studies (Hays and others 2002). This allowed us to assess these signatures with *in situ* data. We compared emission factors and fluxes with any available data from wildfire emissions from corresponding forest types.

Smoke Modeling

A forecast of expected weather and smoke behavior was developed before each experimental prescribed burn. On-site meteorological information was gathered to enable a run and test the BlueSky smoke prediction system. The forecast was necessary to help anticipate fire and smoke behavior and to determine the most effective observational configuration. Onsite meteorological information was used to validate and improve the weather components of BlueSky and PB-Coastal Plain. A standard configuration of BlueSky was run to help with preburn forecasting and used to demonstrate the uncertainty in predicting smoke in the region. An enhanced configuration of BlueSky was run with measured information from each experiment to help quantify areas of needed improvement. The meteorological observations included four surface weather stations at strategic points around the fire perimeter to capture surface drift smoke and influencing weather. Each station measured wind, temperature, humidity, and carbon monoxide every 5 minutes. Additional stations—Data-logging Real-time Aerosol Monitors (DataRAM) and Environmental Beta-Attenuation Mass Monitor (E-BAM)—outfitted with a $PM_{2.5}$ sampler were placed in expected downwind locations away from the fire perimeter to capture outflow rates. The location of each sampling station was based on the topographic configuration of the area, expected weather, and anticipated fire and smoke behavior. The meteorological data were monitored during each experiment to ensure quality control. This sampling methodology has been successfully deployed at the FROSTFIRE experimental burn in Alaska (Ferguson and others 2003) and the surface measurements have been tested during experimental burns in Washington, Oregon, and the Piedmont region of northern Georgia with success. Before each experiment a standard configuration of the BlueSky smoke modeling system was run that used the CALPUFF dispersion model. The system was rerun following each experiment in an enhanced mode that adjusts available preburn information with information that was measured during the experiment. The two runs were compared to quantify uncertainty in the modeling system and determine areas of needed improvement.

Results and Discussion

Vegetation Classification and Current Forest Biomass

Six research prescribed burns were monitored during the first 2 years of the study. The following preliminary information characterizes two research burns conducted on March 3 (day 1) and 4 (day 2), 2006 at the Alligator River National Wildlife Refuge and the Air Force Dare County Bombing Range in North Carolina (fig. 1 and 2). Seven vegetation alliances were identified on the research site (table 1). The Pond Pine Saturated Woodland Alliance was delineated as woodland and overstocked woodland for establishment of field plots but were combined for the fuel loading analysis. The Shining Fetterbush-Little Gallberry Shrubland and the Sweetbay-Swampbay Saturated Forest Alliances did not meet the minimum mapping unit size and were not included in the fuel loading analysis.

Preliminary trends in pre- and postburn biomass for North Navy Shell prescribed burns day 1 and day 2 are shown in tables 2 and 3. Fuels were characterized in 12 ft diameter microplots into live and dead herbaceous

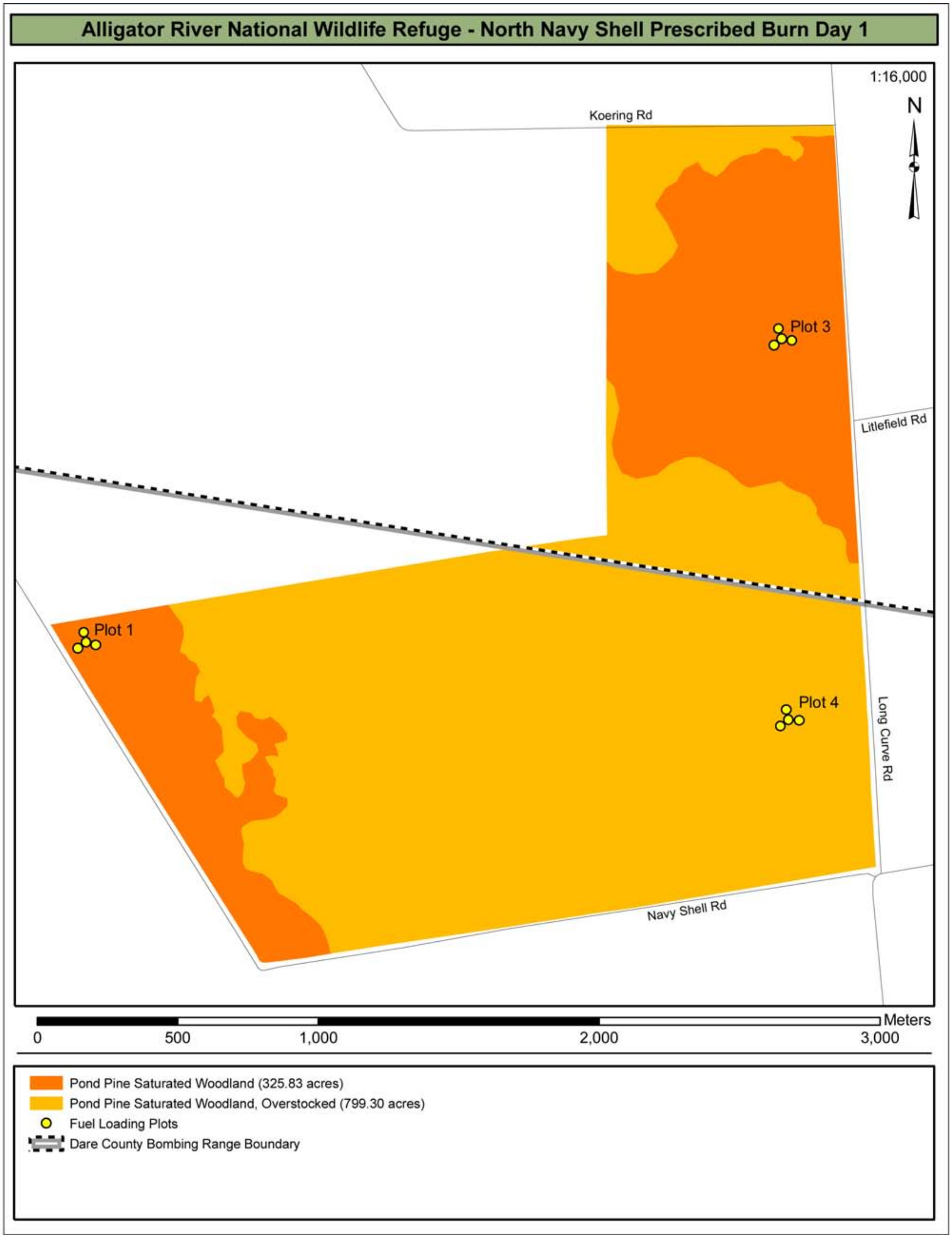


Figure 1—Delineation of vegetation alliances and acres for prescribed burn day 1.

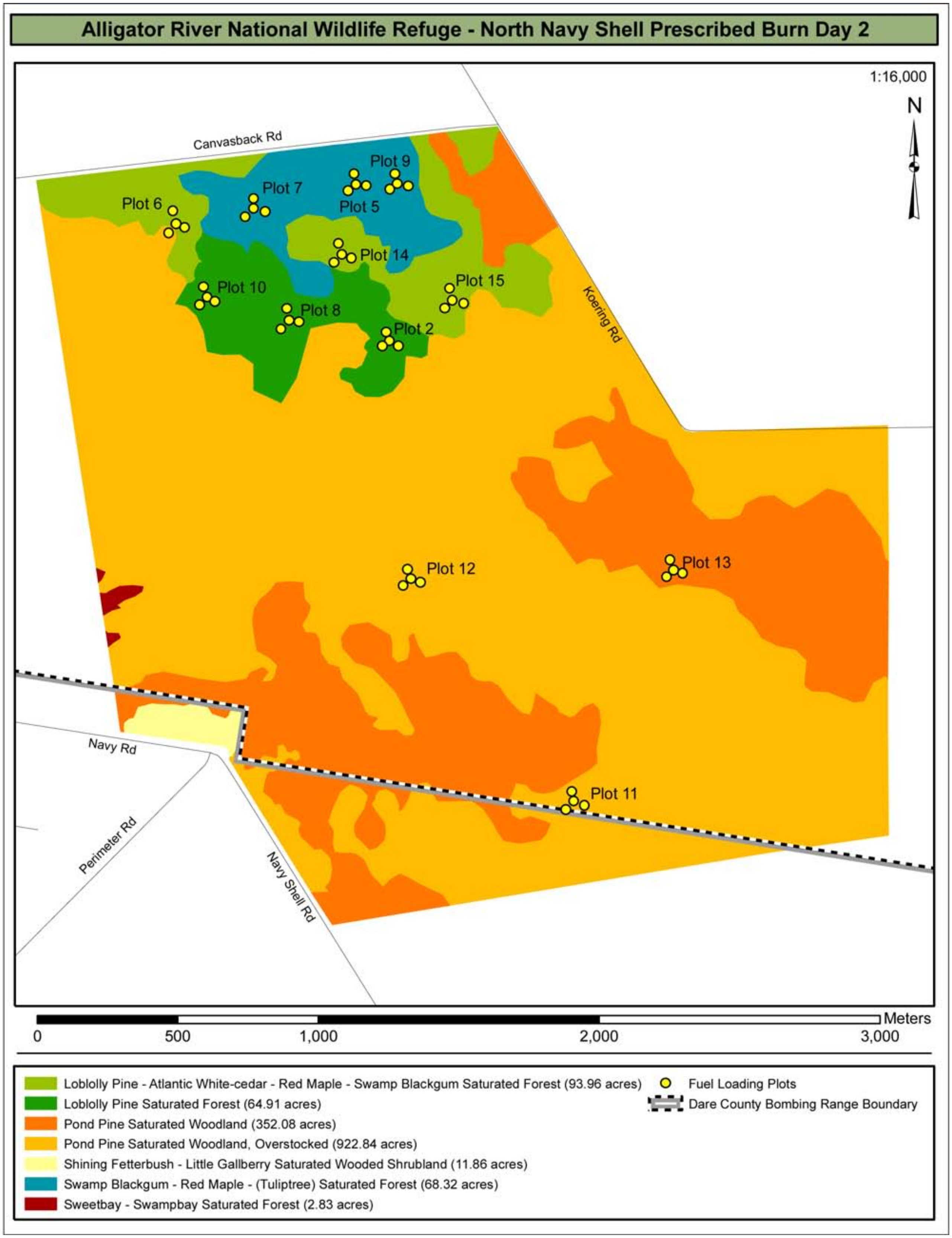


Figure 2—Delineation of vegetation alliances and acres for prescribed burn day 2.

Table 1—Summary of North Navy Shell prescribed burns day 1 and day 2 forest type acres.

Rx burn	Forest type	Acres	Pct.
North Navy Shell day 1	Pond pine saturated woodland	325.83	28.96
	Pond pine saturated woodland, overstocked	799.30	71.04
	Total	**1,125.13**	**100**
North Navy Shell day 1	Loblolly pine-AWC-maple-blackgum forest	93.96	6.19
	Loblolly pine saturated forest	64.91	4.28
	Pond pine saturated woodland	352.08	23.21
	Pond pine saturated woodland, overstocked	922.84	60.84
	Swamp blackgum-swampbay saturated forest	68.32	4.50
	Shining fetterbush-little gallberry shrubland	11.86	0.08
	Sweetbay-swampbay saturated forest	2.83	0.02
	Total	**1516.80**	**100**

Table 2—Summary of biomass for 1,125.33 acres day 1 prescribed burn (March 3, 2006) on the Alligator River National Wildlife Refuge and the Air Force Dare County Bombing Range, NC.

Vegetation alliance		**Duff (Oa)**					**Litter 1 hr fuels**	**Fine woody 1 hr fuels**	**Fine woody 10 hr fuels**	**Fine woody 100 hr fuels**	**Coarse woody 1000 hr fuel**	**Total litter and woody fuels**
			Dead shrub	**Live shrub**	**Dead herb**	**Live herb**	**Litter**	**(0-0.25 in)**	**(0.25-1.0 in)**	**(1-3 in)**	**(>3 in)**	
	Preburn											
Pond pine woodland	tons/acre	334.1	0.36	1.66	0.00	0.03	9.97	0.41	1.41	1.81	1.19	14.79
	total tons	375,972.75	405.12	1,868.05	0.00	33.76	11,219.54	461.39	1,586.72	2,036.85	1,339.14	16,643.63
	Postburn											
Pond pine woodland	tons /acre	334.1	0.36	1.66	0.00	0.03	6.30	0.11	1.22	1.81	1.19	10.63
	total tons	375,972.75	405.12	1,868.05	0.00	33.76	7,089.58	123.79	1,372.90	2,036.85	1,339.14	11,962.26
	Consumed											
Pond pine woodland	tons/acre	0.00	0.00	0.00	0.00	0.00	3.67	0.39	0.30	0.00	0.00	4.36
	total tons	0.00	0.00	0.00	0.00	0.00	4,129.96	337.60	213.81	0.00	0.00	4,681.37

Table 3—Summary of biomass for 1,516.8 acres day 2 prescribed burn on the Alligator River National Wildlife Refuge and Air Force Dare County Bombing Range, NC.

Vegetation alliance		Plot	Duff (Oa)					Litter 1 hr fuels	Fine woody 1 hr fuels	Fine woody 10 hr fuels	Fine woody 100 hr fuels	Coarse woody 1000 hr fuels	Total litter and woody fuels
				Dead shrub	Live shrub	Dead herb	Live herb	Litter	(0-0.25 in)	(0.25-1.0 in)	(1-3 in)	(>3 in)	
Loblolly pine forest	Preburn												
64.91 acres	tons/acre		299.95	0.53	2.22	0.00	0.00	7.70	0.27	1.95	2.20	2.59	14.71
	total tons		454,918.66	803.90	3,367.30	0.00	0.00	11,679.36	409.54	2,957.76	3,336.96	3,928.51	22,312.13
	Postburn												
	tons/acre		299.95	0.50	2.14	0.00	0.00	3.93	0.12	1.49	1.62	2.59	25.12
	total tons		454,918.66	758.40	3,245.95	0.00	0.00	5,961.02	182.02	2,260.03	2,457.22	3,928.51	14,813.92
	Consumed												
	tons/acre		0.00	0.03	0.08	0.00	0.00	3.77	0.15	0.46	0.69	0.00	5.07
	total tons		0.00	45.50	121.35	0.00	0.00	5,718.34	227.52	697.73	879.74	0.00	7,523.33
Pond pine woodland	Preburn												
1,274.92 acres	tons/acre		405.19	0.81	1.02	0.00	0.00	7.23	0.34	1.82	1.80	1.10	12.29
	total tons		614,592.19	1,228.61	1,547.14	0.00	0.00	10,966.46	515.71	2,760.58	2,730.24	1,668.48	18,641.47
	Postburn												
	tons/acre		405.19	0.64	0.99	0.00	0.00	1.38	0.07	1.17	1.66	1.10	5.38
	total tons		614,592.19	970.75	1,501.63	0.00	0.00	2,093.18	106.18	1,774.66	2,517.89	1,668.48	8,160.39
	Consumed												
	tons/acre		0.00	0.17	0.03	0.00	0.00	5.85	0.27	0.65	0.14	0.00	6.91
	total tons		0.00	257.86	45.51	0.00	0.00	8,873.28	409.54	985.92	212.35	0.00	10,481.09
Loblolly pine-AWC-maple-blackgum forest	Preburn												
93.96 acres	tons/acre		226.28	0.53	1.98	0.00	0.00	4.94	0.48	2.10	2.13	17.66	27.31
	total tons		343,221.50	803.90	3,003.26	0.00	0.00	7,492.99	728.06	3,185.28	3,230.78	26,786.68	41,423.79
	Postburn												
	tons/acre		226.28	0.53	1.98	0.00	0.00	4.30	0.48	2.10	2.13	17.66	26.67
	total tons		343,221.50	803.90	3,003.26	0.00	0.00	6,522.24	728.06	3,185.28	3,230.78	26,786.68	40,453.04
	Consumed												
	tons/acre		0.00	0.00	0.00	0.00	0.00	0.641	0.00	0.00	0.00	0.00	0.64
	total tons		0.00	0.00	0.00	0.00	0.00	970.75	0.00	0.00	0.00	0.00	970.75
Blackgum-maple forest	Preburn												
68.32 acres	tons/acre		226.28	0.36	1.05	0.00	0.01	1.83	0.33	1.14	1.67	6.21	11.18
	total tons		343,221.5	546.05	1,592.64	0.00	15.17	2,775.74	500.54	1,729.15	2,533.06	9,419.33	16,957.82
	Postburn												
	tons/acre		226.28	0.32	1.00	0.00	0.01	1.83	0.33	1.14	1.67	6.21	11.18
	total tons		343,221.5	485.38	1516.80	0.00	15.17	2,775.74	500.54	1,729.15	2,533.06	9,419.33	16,957.82
	Consumed												
	tons/acre		0.00	0.04	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	total tons		0.00	60.67	75.84	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

plant biomass, and live and dead shrub biomass. Litter, 1-, 10-, 100-, and 1,000-hour fuels were estimated from line intersects. The large source of carbon emissions was found in the litter layer, followed by 1-hour DWD, 10-hour DWD, and 100-hour fuels.

Emission Factors

The emission factors (EFs) resulting from the samples collected during each phase of the prescribed burn are presented in table 4. $PM_{2.5}$ typically composes at least two-thirds of total PM, and roughly 80 percent of PM_{10} from biomass combustion sources (Andreae and Merlet 2002). Our data are consistent with these relative proportions. The $PM_{2.5}$ and PM_{10} EFs determined using the Met One sensor are lower than the filter based methods, likely because this instrument has a 0.5 µm lower diameter detection limit. A large fraction of biomass burning particles falls below this size cut (Hays and others 2002). CO_2 emission factors are important because they represent the largest carbon component of emissions. The integrated concentration values from the continuous CO_2 emission monitor exceeded or were nearly equal to the concentration determined from the Summa canister during the flaming stages of the fires. It is not known if possible reactions within the canister might affect this comparison. In any case, this method-induced variability in CO_2 concentrations induced an uncertainty in emission factors of all gasses and particles of 0 to 10 percent.

In general, the $PM_{2.5}$ and PM_{10} EFs are lower those published in other open biomass burning studies. Observed NOx EFs are also lower, while those for SO_2 and total NMHC fall within the ranges of previously reported biomass burning studies.

For all of the prescribed fires, emission factors for CO_2 are higher than reported ranges (Andreae and Merlet 2002). The combination of lower PM EFs and higher CO_2 EFs indicates that the prescribed fires exhibited more efficient combustion than wildfires or slash reduction burns. This is likely due to effectively burning primarily fine fuels under prescription conditions,

Table 4—Emission factors derived from smoke samples of the North Navy Shell prescribed burn day 1 (emission factors in g kg (fuel dry weight)$^{-1}$).

Stage*	Time	PM_{10}	PM_{10M}	$PM_{2.5}$	$PM_{2.5Q}$	$PM_{2.5M}$	CO	CO_2	CO_{2c}	NO_X	THC	SO_2
Fl	11:41-13:02	6.49	2.92	6.49	4.87	2.22	44.18	1730	1700	2.07	10.1	0.55
Sm	13:47-16:30	3.38	1.67	2.07	2.41	0.84	34.09	950	920	0.81	303	0.43

Stage* Fl=Flaming stage, Sm=smoldering stage
PM_{10} determined gravimetrically from Teflon filter in single stage impactor.
PM_{10M} determined from Met One detector, measures PM 0.5 to 10 m.
$PM_{2.5}$ determined gravimetrically from Teflon filter in single stage impactor.
$PM_{2.5Q}$ determined gravimetrically from Quartz filter in single stage impactor.
$PM_{2.5M}$ determined from Met One detector, measures PM 0.5 to 2.5 m.
CO determined using TECO 46C continuous emission monitor.
CO_2 determined using GC/TCD analysis on Summa can samples.
CO_{2c} determined using TECO continuous emission monitor.
NO_X determined using TECO 42S continuous emission monitor.
THC determined using TECO continuous emission monitor.
SO_2 determined using TECO continuous emission monitor.

which minimizes consumption of soil organic layers and smoldering of heavy fuels. Combustion of these fuel components often results in higher emission of products of incomplete combustion.

Smoke Trajectory and Concentrations

The BlueSky modeling framework output products include animations of $PM_{2.5}$ concentrations and wind flow patterns at the surface. An example of an hourly image from the animation is shown in figure 3. Fire characteristics are processed through the Emissions Production Model (EPM) to give emission estimates of particulates ($PM_{2.5}$, PM_{10}, and total PM), carbon compounds (CO, CO_2, CH_4, nonmethane hydrocarbons), and heat. The emission estimates from EPM along with meteorology from the fifth generation Pennsylvania State University-National Center for Atmospheric Research Mesoscale Model (MM5) are processed for the CALPUFF dispersion model and the HYSPLIT trajectory model. The BlueSky framework merges meteorology with emission estimates to yield an integrated regional-scale analysis of smoke and aerosol concentrations.

Primary inputs to BlueSky include weather, fire characteristics, and fuels. Predictions of wind speed and direction as well as mixing height are required to determine smoke trajectories and $PM_{2.5}$ concentrations. Weather inputs come from the MM5 mesoscale meteorological model. In order to arrive at an accurate prediction of smoke emissions it is necessary to get detailed information about size, location, and timing of the prescribed burn. Fuel model and fuel loading information is essential to emissions modeling. BlueSky uses general fuel characteristics derived from one of several fuel model systems, including the Fuel Characteristic Classification System (FCCS), but for this

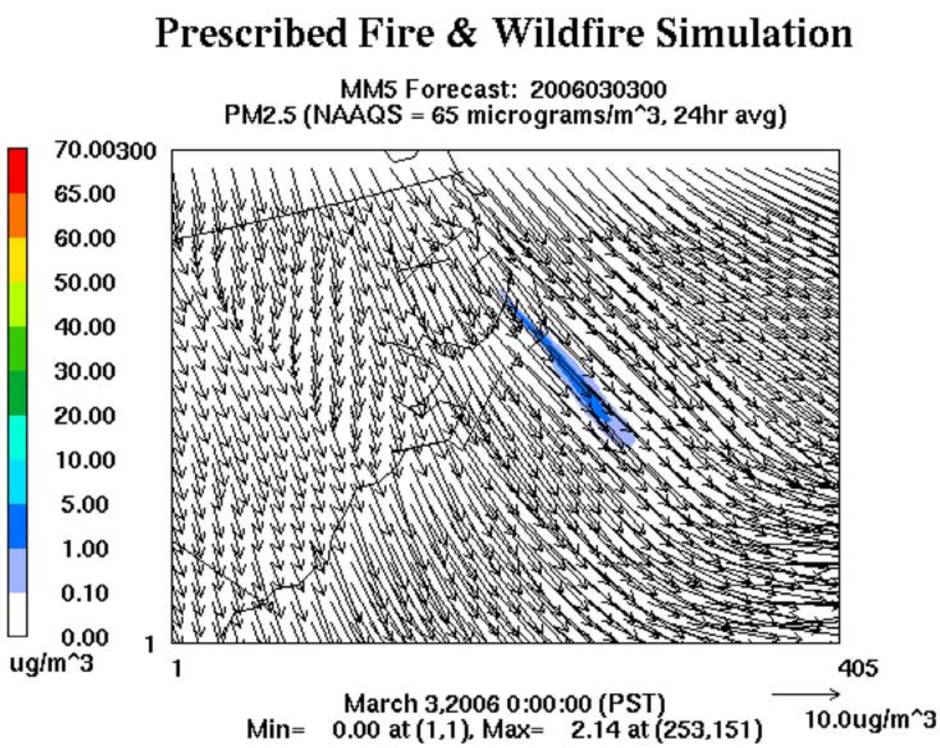


Figure 3—Prescribed fire simulation from BlueSky for North Navy Shell prescribed fire research burn. $PM_{2.5}$ ground concentrations (μg/m^3) and wind flow patterns are shown as houly image. MM5 meterology simulation was done on a 1.33 km resolution.

project detailed pre- and postburn fuel characteristics were collected from permanent field plots. Emissions are computed using Consume/EPM v1.03, which calculates the heat release rate and emissions for particulate matter and carbon compounds as a function of time since fire ignition. These emission values are input data for CALFUFF v5.711 that calculates the dispersion and plume rise. Trajectories are computed using the HYSPLIT model. HYSPLIT uses a full three-dimensional wind field for computational purposes but does not include any heat or buoyancy effects from fire.

The trajectory of the BlueSky smoke plume correlates well with a NOAA GOES satellite image of the smoke plume (fig. 4). The Hazard Mapping System Fire and Smoke Product image is derived from an interactive processing system that allows the trained satellite analysts in the Satellite Analysis Branch (SAB), within the Satellite Services Division (SSD), to manually integrate data from various automated fire detection algorithms with GOES and polar (Advanced Very High Resolution Radiometer; AVHRR), Moderate Resolution Imaging Spectroradiometer Fire Algorithm (MODIS), and Defense Meteorological Satellite Program/Operational Linescan System (DMSP/OLS) images. The result is a quality controlled display of the locations of fires and significant smoke plumes detected by meteorological satellites. Prior to ignition of the prescribed burn, VSMOKE, a computer program for predicting the smoke and dry weather visibility impact of a single prescribed

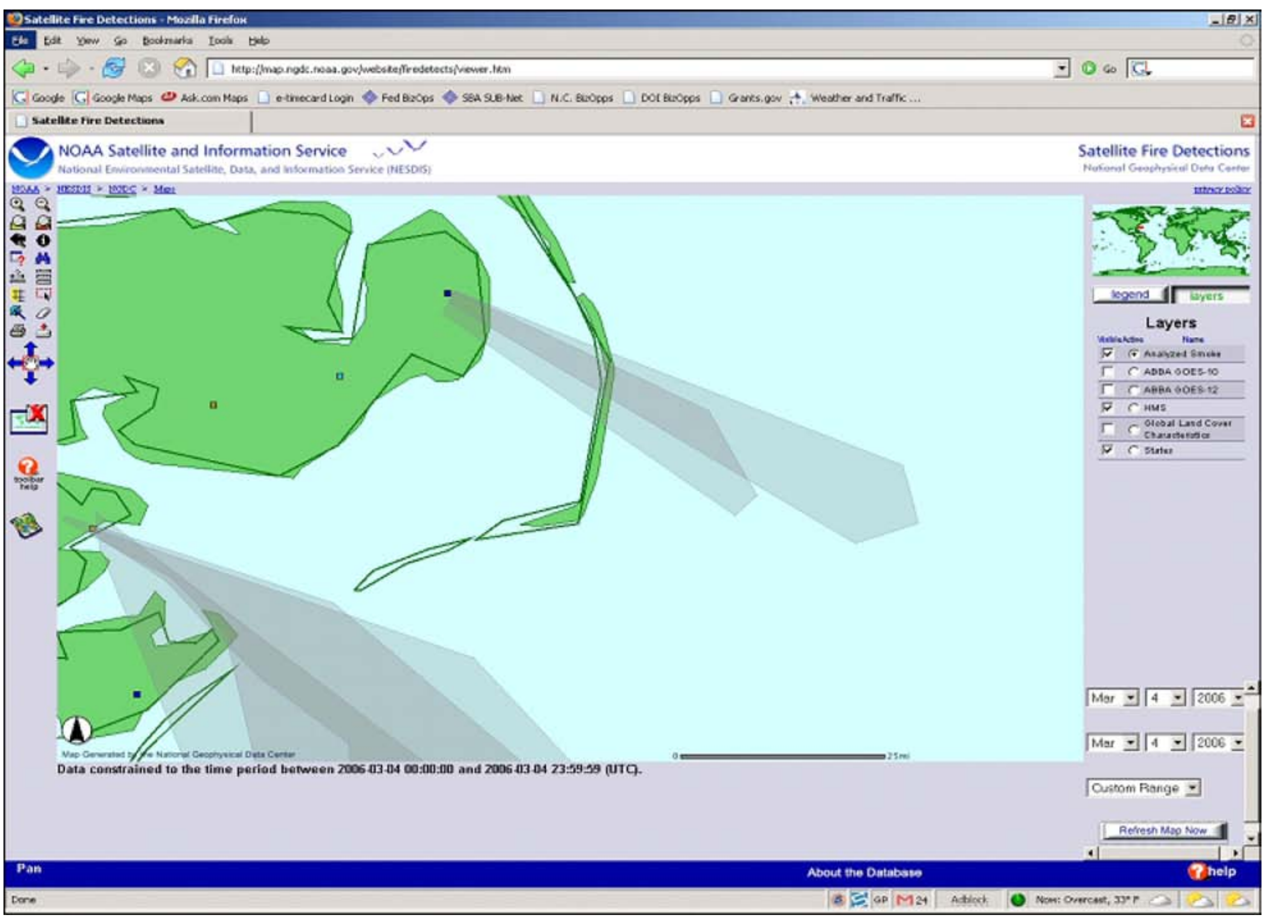


Figure 4—Hazard Mapping System Fire and Smoke Product image derived from various automated fire detection algorithms with GOES and polar Advanced Very High Resolution Radiometer (AVHRR), Moderate Resolution Imaging Spectroradiometer Fire Algorithm (MODIS) and Defense Meteorological Satellite Program/Operational Linescan System (DMSP/OLS) images.

fire at several downwind locations, was run for current weather conditions. Figure 5 illustrates the smoke plume trajectory and visibility impacts. The BlueSky modeled plume trajectory and $PM_{2.5}$ concentrations may result in an accuracy improvement when compared to V-SMOKE predictions. Accurate representation of the wind field and other meteorology parameters within the BlueSky modeling framework may further our understanding of fire behavior and its relationship to smoke management on deep organic soils.

Summary and Conclusions

Land managers in the Coastal Plain of the Eastern United States recognize general fuel types on organic soils and mineral soils. Past fuel and fire behavior research has resulted in only qualitative measures of fuel loads and rates of spread. A more detailed fuel classification based on species composition, standing dead and down deadwood, fuel size classification, understory vegetation, and vertical distribution of fuels would have much more utility than the broad fuel model classification system now in use. Fire in the organic and mineral soil areas of the Coastal Plain centers around the frequent and costly blowup wildfires occurring there and the use of fire as a fuel reduction and habitat management tool. Wildfires in this area can, under certain combinations of fuel and weather, grow from a low intensity burn to a virtually uncontrollable burn until weather conditions change or the fire has run out of fuel. Control efforts are often hampered by inaccessibility, poor soil trafficability on wet organic soils in the area, and fires that tend to burn deeply into the organic soils. A better understanding of the behavior of fires and the role of fuel loading in fire behavior in the pocosins, especially the factors that contribute to the occurrence of major fires, will contribute to the control of wildfires and the use of prescribed fire as a management tool in the region.

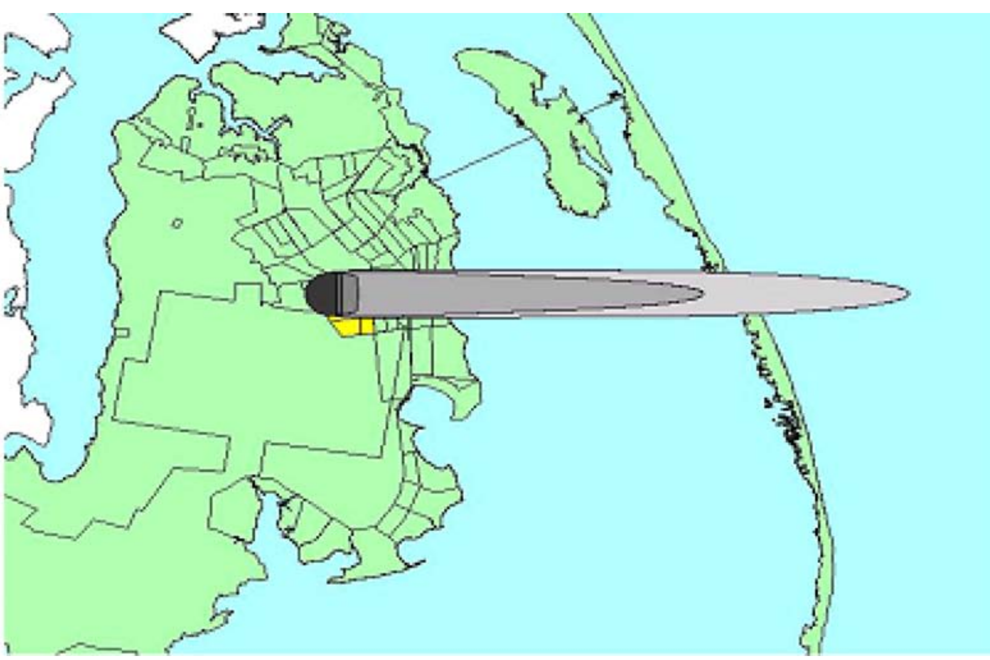


Figure 5—VSMOKE prediction of smoke and dry weather visibility impacts.

The methodology of using modified National Vegetation Classification Alliance level vegetation maps, created from digital photogrammetry and FIA P3 data, shows promise as an approach to fuel mapping. Softcopy photogrammetry, coupled with ground truthing, provides a high level of accuracy for mapping to the association level of the ICEC system. Fuel loads generated from the FIA P3 plots differ from fuel loads estimated using the standard fuel models. These differences could have an impact on the prediction of fire spread and behavior. Fuel loads within fuel size classes did vary between the modified association level classifications. Disturbance history appears to play a significant role in explaining why fuel loads differ and could help in creating more accurate fuel maps. Research of this nature may lead to use of FIA P3 plot data to generate an index of fuel load by ICEC association level vegetation classification. This could lead to a valuable multipurpose tool for land managers and researchers for use in predicting, preventing, and managing forest biomass for wildfire.

The U.S. Environmental Protection Agency (EPA) has implemented new regulations for the management of $PM_{2.5}$, tropospheric ozone, and regional haze. In accordance with sections 108 and 109 of the Clean Air Act, EPA has reviewed the air quality criteria and national ambient air quality standards (NAAQS) for $PM_{2.5}$. Based on these reviews, EPA revised the current primary PM_{10} standards by adding two new primary $PM_{2.5}$ standards set at 15 g m^{-3}, annual mean, and 50 g m^{-3}, 24-hour average, to provide increased protection against a wide range of PM-related health effects. These include premature mortality and increased hospital admissions and emergency room visits; increased respiratory symptoms and disease; decreased lung function; and alterations in lung tissue and structure and in respiratory tract defense mechanisms. Recent proposals would reduce the 24-hour average $PM_{2.5}$ standard to 35 g m^{-3}. Fire generates $PM_{2.5}$ and other ozone precursor gases that reduce visibility. Hence, natural area and agricultural land management, nationwide, may come under increased scrutiny as regulators seek reductions in pollutant emissions that contribute to NAAQS violations.

Little data on emissions from prescribed burning are currently available, and this fire type in particular is projected to increase in the Southeastern United States. We hypothesize that emissions of $PM_{2.5}$ and PM_{10} and gas phase reduced compounds, many of which are air toxics, will be lower during prescribed fires compared to wildfires covering the same area. This is suspected largely because it is known that wildfires occur typically during excessively dry periods, when much of the forest floor is dry and susceptible to smoldering and incomplete combustion, the source of many toxic compounds. It is likely that burning under prescriptions will reduce human exposure and emissions of hazardous air pollutants, and net risk to property and human welfare.

References

Albini, F.A. 1976. Estimating wildfire behavior and effects. Gen. Tech. Rep.INT-30. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest Range Experiment Station.

Anderson, J.R.; Hardy, E.E.; Roach, J.T.; Witmer, R.E. 1976. A land use and land cover classification system for use with remote sensor data: U.S. Geological Survey Professional Paper 964. 28 p.

Andreae, M.O.; Merlet, P. 2001. Emission of trace gases and aerosols from biomass burning. Global Biogeochemical Cycles 15(4): 955-966.

Barnard, W.; Sabo, E. 2003. Review of 1999 NEI and recommendations for developing 2002 VISTA inventory for regional haze modeling. Asheville, NC: North Carolina DENR.

Bertschi, I.; Yokelson, R.J.; Ward, D.; Babbitt, R.; Susott, R.; Goode, J.; Hao, W.M. 2003. Trace gas and particle emissions from fires in large diameter and belowground biomass fuels. Journal of Geophysical Research 108(D13): 1-12.

Brown, J.K.; Oberheu, R.D.; Johnston, C.M. 1982. Handbook for inventorying surface fuels and biomass in the interior west. Gen. Tech. Rep. INT-129. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest Range Experiment Station.

Cheng, L.; McDonald, K.M.; Angle, R.P.; Sandhu, H.S. 1998. Forest fire enhanced photochemical air pollution. A case study. Atmospheric Environment 32(4): 673-681.

Dennis, A.; Fraser, M.; Anderson, S.; Allen, D. 2002. Air pollutant emissions associated with forest, grassland, and agricultural burning in Texas. Atmospheric Environment 36(23):3779-3792.

Ferguson, S.A.; Collins, R.L.; Ruthford, J.; Fukuda, M. 2003. The vertical distribution of nighttime smoke following a wildland biomass fire in boreal Alaska. Journal of Geophysical Research 108 No. D23, 4743.

Ferguson, S.A.; McKay, S.J.; Nagel, D.E.; Piepho, T.; Rorig, M.L.; Anderson, C.; Kellogg, L. 2003. Assessing Values of Air Quality and Visibility at Risk From Wildland Fires. Res. Pap. PNW-RP-550. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 59 p.

Ferguson, S.A.; Peterson, J.; Acheson, A. 2001. Automated, real-time predictions of cumulative smoke impacts from prescribed fire and agricultural fires. In: Proceedings of the Fourth Symposium on Fire and Forest Meteorology, 13-15 November 2001, Long Beach, CA. Boston, MA: American Meteorological Society: 168-175.

Finney, M.A. 1998. FARSITE: Fire Area Simulator-model development and evaluation. Res. Pap. RMRS-RP-4. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Friedli, H.R.; Radke, L.F.; Lu, J.Y.; Banic, C.M.; Leaitch, W.R.; MacPherson J.I. 2003. Mercury emissions from burning of biomass from temperate North American forests: laboratory and airborne measurements. Atmospheric Environment 37(2): 253-257.

Hao, W.M.; Liu, M. 1994. Spatial and temporal distribution of tropical biomass burning. Global Biogeochemical Cycles 8(4): 495-503.

Harrison, H. 1995. A user's guide to PUFFx: a dispersion model for smoke management in complex terrain. WYNDSoft Inc. 42 p.

Hays, M.D.; Geron, C.D.; and others. 2002. Speciation of Gas-Phase and Fine Particle Emissions from Burning of Foliar Fuels. Environmental Science and Technology 36(11): 2281-2295.

Hummel, J.; Rafsnider, J. 1995. User's guide: TSARS plus smoke production and dispersion model, version 1.1. National Biological Service and the Interior Fire Coordination Committee. 107 p.

Lavdas, L.G. 1996. VSMOKE user's manual. U.S. Department of Agriculture, Forest Service, Southern Research Station. GTR-SRS-6. 147 p.

Lavdas, L.; Achtemeier, G.L. 1995. A fog and smoke risk index for estimating roadway visibility hazard. National Weather Digest 20, 26-33.

O'Neill, S.M.; Ferguson, S.A.; Peterson, J.; Wilson, R. 2003. The BlueSky smoke modeling framework. 5th Symposium on Fire and Forest Meteorology. 16-20 November 2003. Orlando, FL. American Meteorological Society: 161-162.

O'Neill, S.M.; Hoadley, J.L.; Ferguson, S.A.; Solomon, R.; Peterson, J.; Larkin, N.K.; Peterson, R.; Wilson, R.; Matheny, D. 2005. Applications of the BlueSkyRAINS smoke prediction system. EM: The Magazine for Environmental Managers. September 2005. Air and Waste Management Assoc.: 42-45.

Rothermel, R.D. 1972. A mathematical model for predicting fire spread in wildland fuels. Gen. Tech. Rep. INT-115. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest Range Experiment Station.

Ryan, K.C.; Noste, N.V. 1985. Evaluating prescribed fires. In: J.E. Lotan, B.M. Kilgore, W.C. Fischer, and R.W. Mutch, Tec. Cord. Proc. Symposium and Workshop on Wilderness Fire. Gen. Tech. Rep. INT-182. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station: 230-238.

Sandberg, D.V.; Ottman, R.D.; Cushon, G.H. 2001. Characterizing fuels in the 1st Century. International Journal of Wildland Fire 10:381-387.

Scire, J.; Strimaitis, D.G.; Yamartino, R.J.; Xiaomong, Zhang. 1995. A user's guide for CALPUFF dispersion model. Doc. 1321-2. Concord, MA: Sigma Research/Earth Tech. 315 p.

Sestak, M.L.; Riebau, A. R. 1988. SASEM, simple approach smoke estimation model. U.S. Bureau of Land Management, Technical Note 382. 31 p.

Sestak, M.L.; Marlatt, W.E.; Riebau, A.R. 1989. VALBOX: ventilated valley box model. Unpublished report on file with: Michael Sestak, Fort Collins, CO: U.S. Department of the Interior, Bureau of Land Management, and Colorado State University, Environmental Science and Technology Center. 32 p.

Taylor, J.A.; Zimmerman, P.R. 1991. Modeling trace gas emissions from biomass burning. MIT Press (Chapter 41): 345-350.

Ward, D.E.; Hardy, C.C. 1988. Organic and elemental profiles for smoke from prescribed fires. APCA/EPA conference.

Acknowledgments

Funding for this study was provided by the Joint Fire Science Program (Project 04-2-1-80). Additional support was provided by the U.S. Air Force Air Combat Command, Richard Lemaire, Dr. Terry Bashore, Bryan Henderson, Joe Lafferty, Scott Smith, and Harry Mann, U.S. Navy. The authors wish to acknowledge the U.S. Fish and Wildlife Service (USFWS) support of Mike Bryant, Kathy Whaley, Tom Crews, Vince Carver, Donnie Harris, Kelley Van Drueten, Greg Suszek, Pete Kubiac, Glen Stratton, the prescribed fire staffs on USFWS Fire District 1, and Gary Curcio and the North Carolina Division of Forest Resources.

Internet VSMOKE: A User-Oriented System for Smoke Management

James T. Paul[1], Alan Dozier[2], and Daniel Chan[2]

***Abstract**—The Georgia Forestry Commission has developed an Internet-based, user friendly version of a USDA Forest Service smoke dispersion model called "VSMOKE." The program provides an easy to use method to quickly evaluate what areas will likely be impacted by smoke from a wild or prescribed fire. This is particularly important in assessing air quality, public safety and health, and visibility along highways. This paper explains the program and use and interpretations, and looks in detail at the example of highway safety.*

Introduction

Smoke from wild and prescribed fire has been an increasing concern in public health and safety over the last few decades. The Georgia Forestry Commission (GFC) encourages safe use of fire on forest lands in Georgia, and provides a number of smoke management tools that may be viewed at: http://weather.gfc.state.ga.us/

A smoke dispersion model was developed at the Southern Forest Fire Laboratory (U.S. Department of Agriculture, Forest Service) and published by Lavdas (1996). It was developed before the widespread use of the Internet and was for the "…smoke management professional" (Lavdas 1996).

In order to encourage the use of prescribed fire with due regard to air quality, the GFC has developed an Internet-based, user friendly version of VSMOKE.

To use the original VSMOKE model one must:

1. Set certain dispersion model parameter
2. Provide fuel loading data
3. Provide emissions data
4. Provide weather data

A number of additions and modifications were required to extend the use of VSMOKE to the general landowner in Georgia. The guiding philosophy in developing the system was ease of use for the general land owner, flexible for use in planning burns, and with sufficient sophistication to appeal to professionals in forestry and smoke management.

In: Butler, Bret W.; Cook, Wayne, comps. 2007. The fire environment—innovations, management, and policy; conference proceedings. 26-30 March 2007; Destin, FL. Proceedings RMRS-P-46CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 662 p. CD-ROM.

[1] President of SciTrans Inc.

[2] Chief of Forest Protection and Meteorologist, respectively, Georgia Forestry Commission. Corresponding author dchan@gfc.state.ga.us

System Components

There are four main components in the system:

1. The INPUT PROCESSOR – Interactive user input.
   FALCON VIEW (http:/falconview.org) extracts the latitude and longitude of the burn from a map mouse click.
   Date and time of burn.
   Acres burned.
   Type of burn – headfire, backfire, flankfire.
   User input options:
      Fuels
         Select fuel and emission information from the best match fuel photograph, or
         Enter basal area, age of rough, height of the understory vegetation, and Society of American Foresters (SAF) cover type, or
         Enter tons of fuel per acre and emission factor.
      Weather
         The program is preset to use weather from the GFC weather database. However, one can elect to manually enter the needed weather data.
2. VSMOKE – Hour by hour dispersion.
3. VSMOKE-GIS (Harmes and Lavdas 1997) – Hourly digital isolines output of concentrations (called each hour by VSMOKE).
4. FALCON VIEW (http:/falconview.org) – Map output of concentrations from VSMOKE-GIS.

The Input Processor

When the GFC Smoke Management System is accessed from the GFC Web site, some choices are required. First, the date and time of the burn, the location of the burn, and firing technique are always required.

Location—A Georgia Tech Research Institute adaptation of FALCON VIEW (http:/falconview.org) is used to aid the user in map location of the burn in order for the system to extract latitude and longitude. The user is presented with a map of Georgia with county outlines and names (fig. 1). The user clicks on the county where the burn will occur, then chooses successively more detailed maps to locate the fire (fig. 2). When properly located, a mouse click on the location will send a latitude and longitude to the system. This is used for generating weather for the location, and for the output plume graphics.

Date and time and other fixed data input—After selecting a map location the user clicks the "SUBMIT BURN LOCATION" bar at the bottom of the page. This will generate the screen to input date, time burn start, time burn end, acres burned, firing method, and fuel photo display option (fig. 3). Date and times are selected from drop down boxes. Acres burned are entered in the labeled box. Firing method and photo display option are selected from radio buttons.

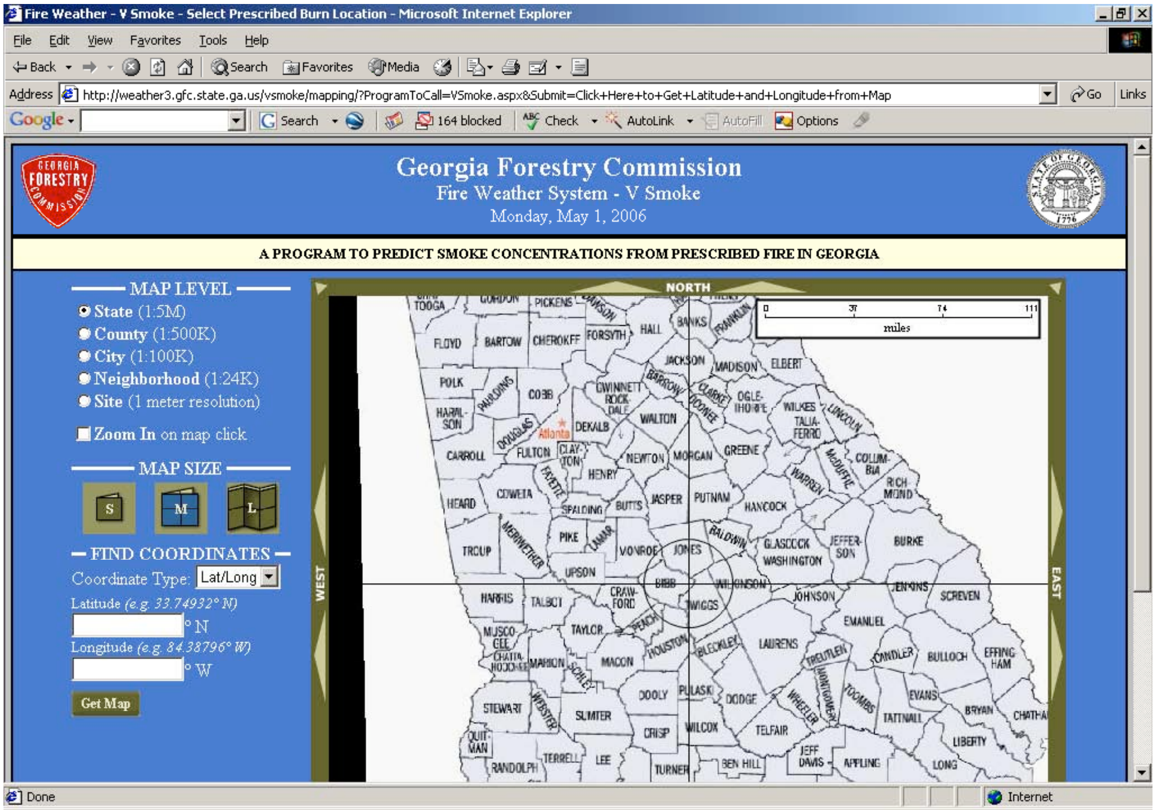


Figure 1—Map with county names for burn site selection in the Georgia Forestry Commission's Web-based VSMOKE.

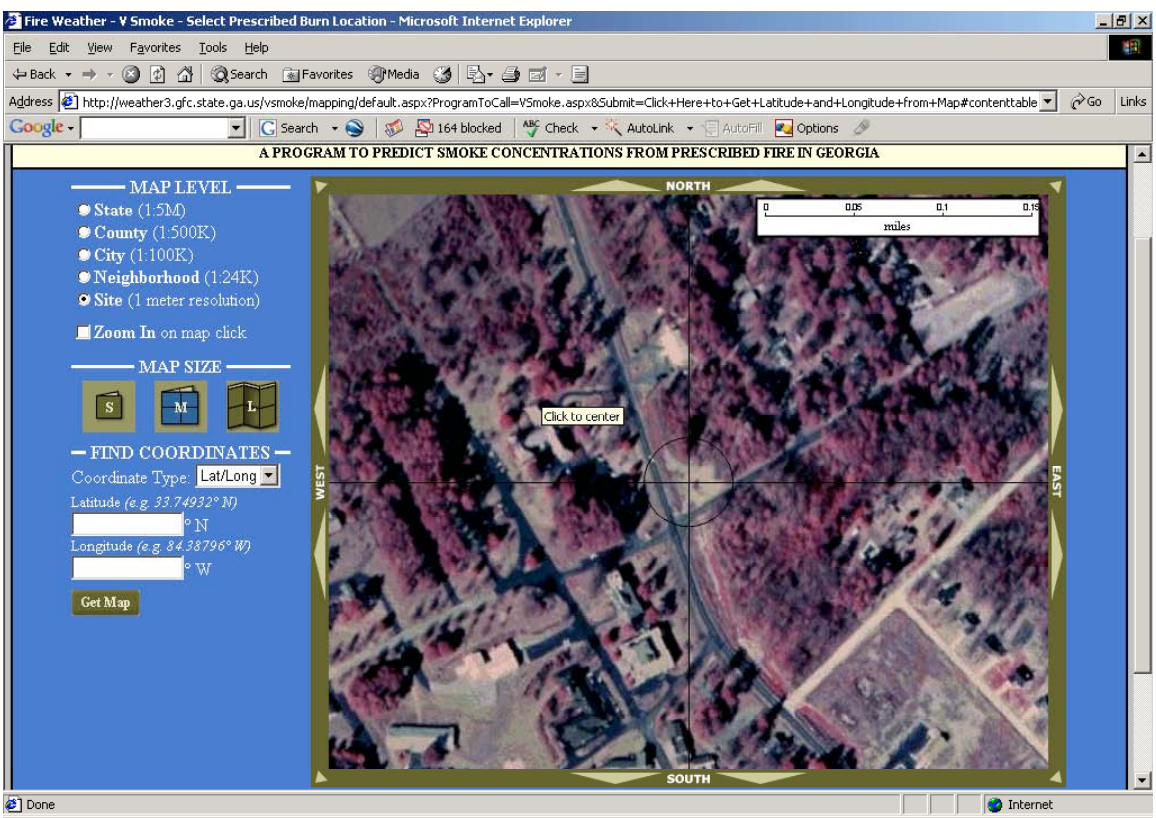


Figure 2—The most detailed site map selection in GFC Web-based VSMOKE. It is an aerial photo of 1 m resolution.

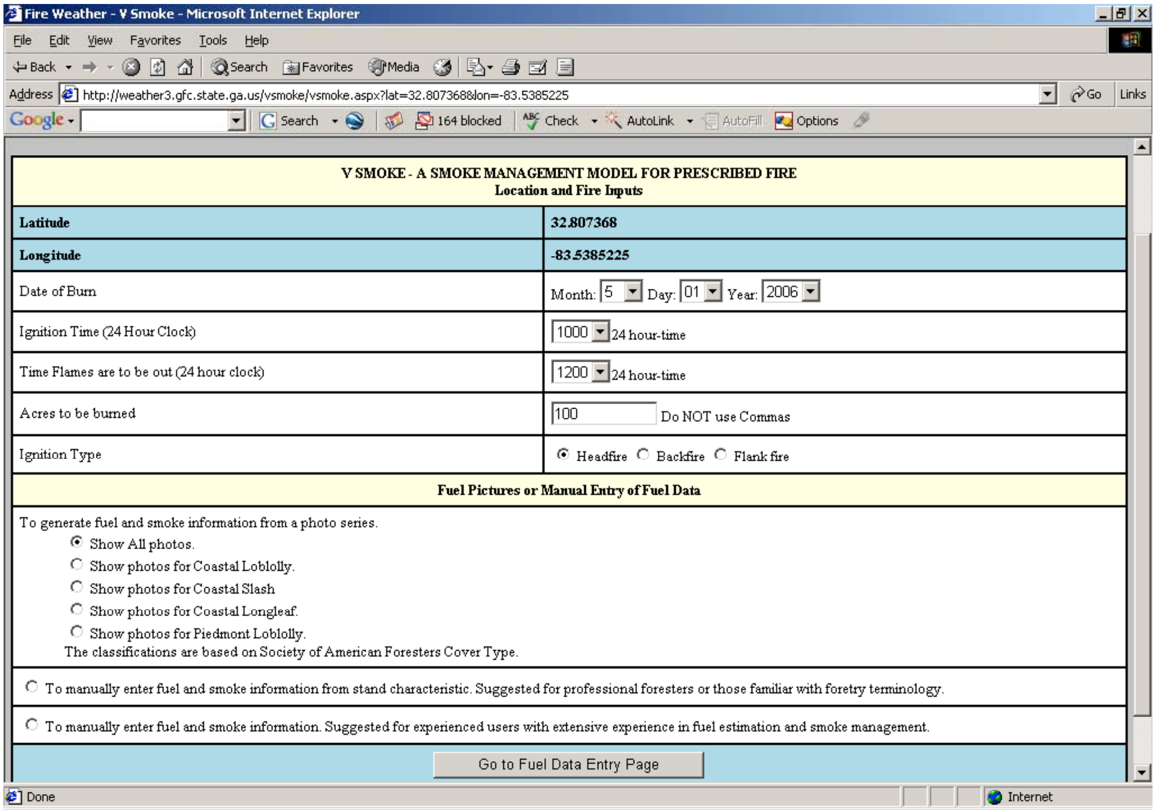


Figure 3—Date of burn, time of burn, acreage burned, firing technique, and fuel data selection screen.

Weather—The user selects either manual weather input, or elects to automatically use weather from the GFC weather system localized to the burn latitude and longitude. The option to manually input weather data (fig. 4) can be used for preburn "what if" planning, or for those cases when the user has a high quality weather data set. The option to have weather automatically supplied by the system is recommended for the general user.

Fuel—There are three options to choose from in the fuels and emissions section. First, the user may choose to match his burn site with a forest scene photo stored on the system (fig. 5). When the best photo match is chosen, the model returns available fuel and emission factor. The second choice is for the user to input SAF cover type, basal area, age of rough, and height of the understory vegetation (fig. 6). When these variables are entered, the system will return available fuel and emission factor. The third option is for the user to directly input emission factor and available fuel (fig. 7). The first option is recommended for the general user. Its advantage is ease of use, and no specialized knowledge of forestry, meteorology, or smoke management is required. The disadvantage is that available fuel computations are not as site specific as other fuel options.

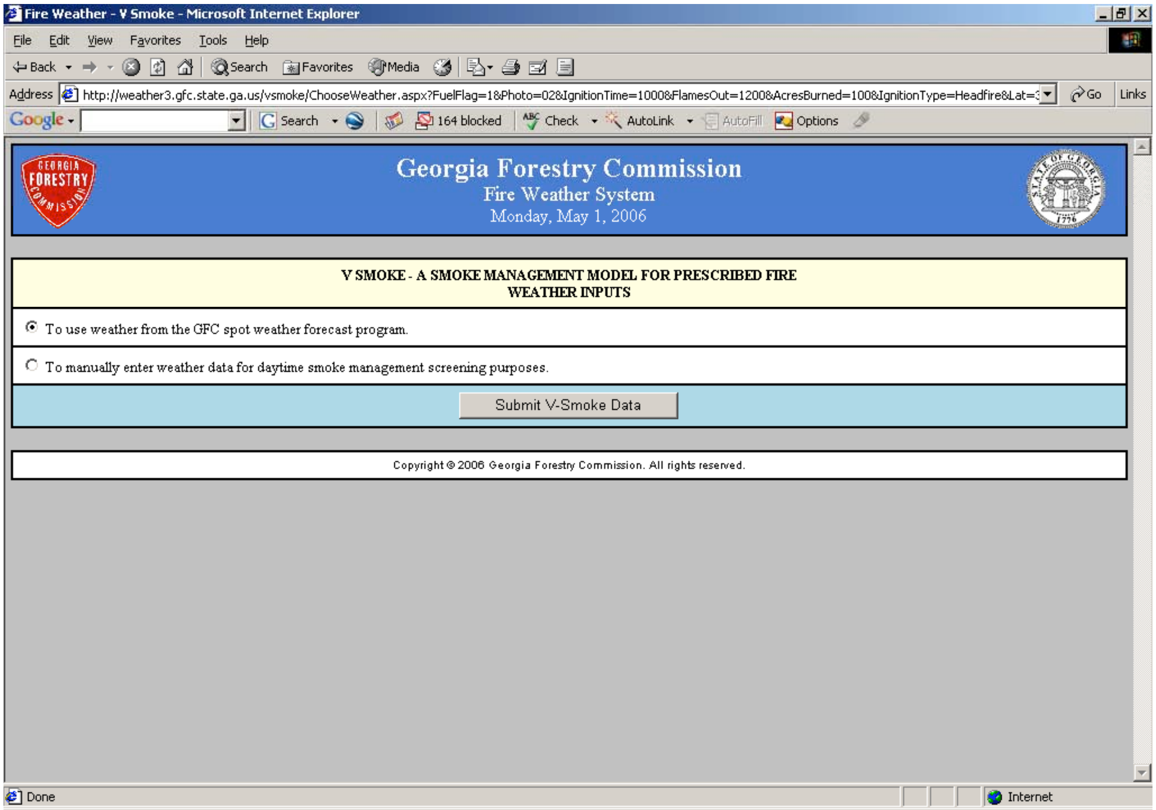


Figure 4—Weather data selection screen.

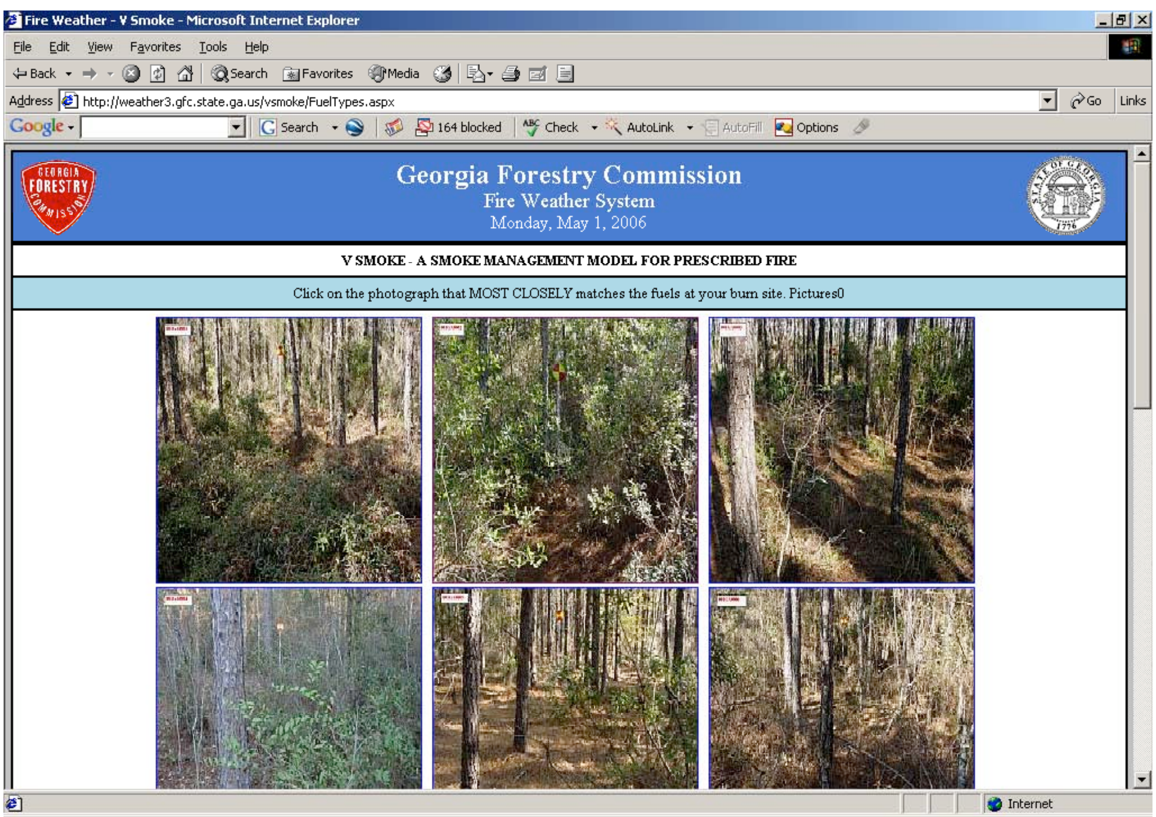


Figure 5—Fuel photo screen for fuel data input.

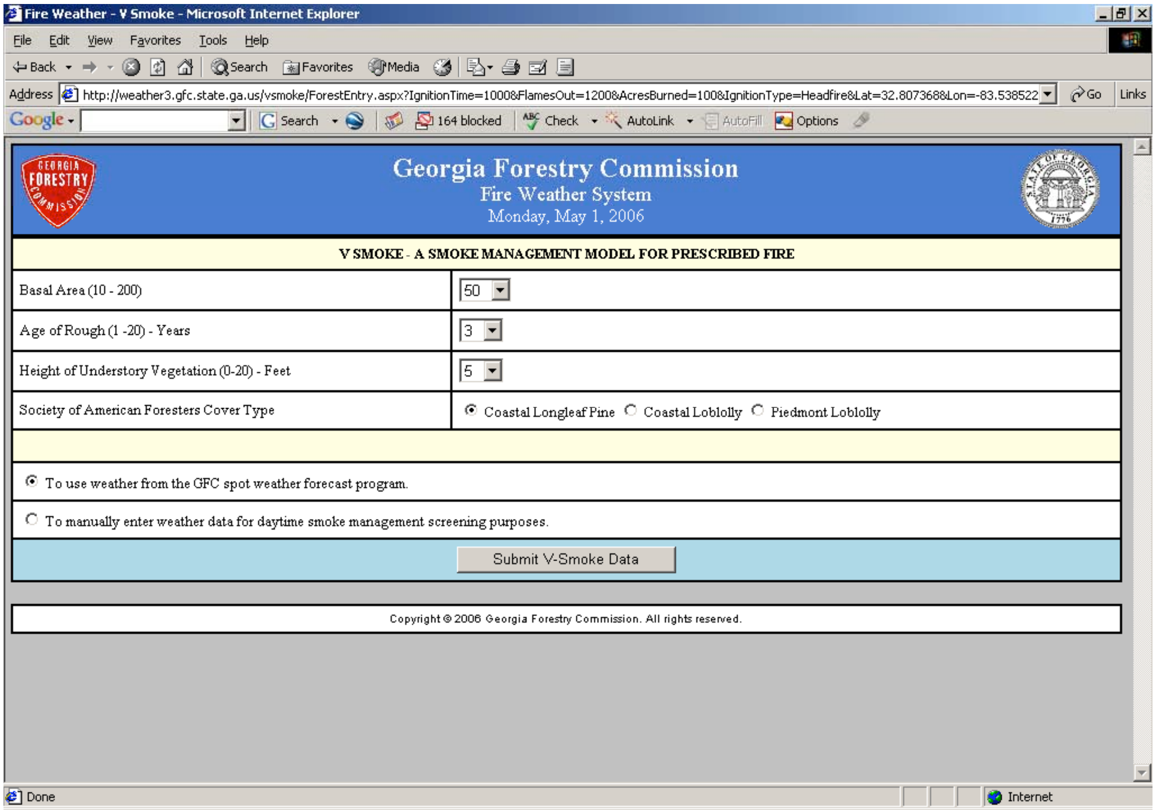


Figure 6—Stand information input.

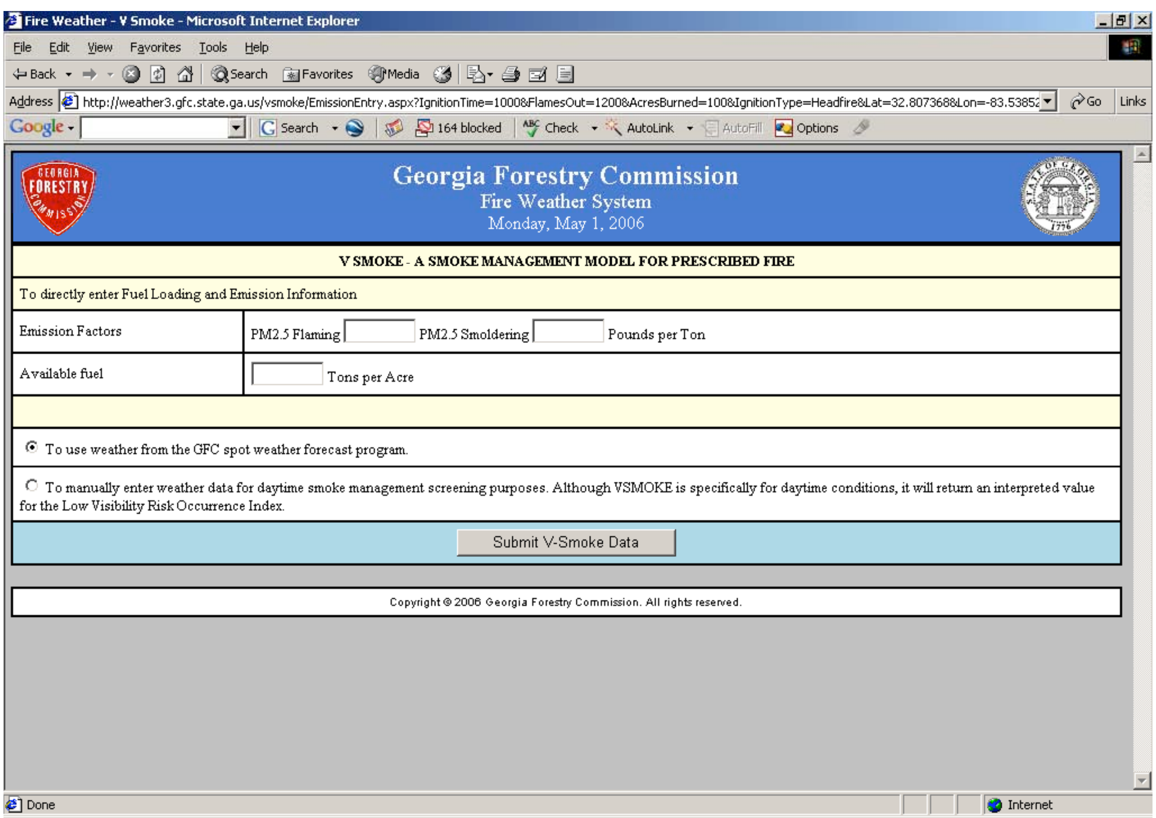


Figure 7—Manual fuel data input.

Output Processor

Running VSMOKE—When all inputs are complete, the user clicks on the "SUBMIT VSMOKE DATA" bar. The input processor then collects all user inputs, and computations based on these inputs, and runs the models.

Hour by hour outputs include:

1. Smoke plume concentrations displayed on a map background. The user may elect to view the output plotted on maps of different scale; figure 8. A plume that tends to be circular indicates most smoke is being lofted upward with associated good dispersion. A long pencil shaped plume indicates poor dispersion with most smoke remaining near the ground.
2. List of most smoke sensitive areas near the burn; figure 9.

Optional output selected from the screen following the plume output display; figure 10.

1. Inputs used by the model; figure 11.
2. Crosswind visibility downwind to 100KM (62.1 miles); figure 12.
3. Centerline smoke concentrations downwind from the fire to 100 km (62.1 miles); figure 13.
4. Low Visibility Risk Occurrence Index (LVORI) from time of fire until 1200 the next day; figure 14. The hours when the LVORI is greater than 7 indicate the atmosphere is conducive to low visibility, and the risk becomes greater as LVORI approaches its maximum value of 10. Values of LVORI less than 7 indicate smoke is unlikely to contribute to low visibility, with the likelihood becoming very small when LVORI reaches its minimum value of 1.

Cautions

Some cautions are in order. First, smoke dispersion models are an attempt to represent concentrations as sets of mathematical equations. Most models in use by the forestry community seem to do an acceptable job of representing this rather complex process. Two sources of error may make a large impact on the results. First, fuel data including emission factor, emission rate, and available fuel are potential sources of error. The authors regard the fuels inputs that were largely gleaned from the literature as being "Best operational available," but recognize this as being an area in need of major improvement. Second, the model is obviously sensitive to errors in forecast wind direction. By inspection of the output plume, one can easily imagine a small change in wind direction might place the plume in an undesired location. Lavdas (1997) in an analysis of National Weather Service forecasts at the Macon, GA, airport, observed wind direction was within plus or minus 22.5 degrees of forecast wind about 38 percent of the time. When the difference was extended to plus or minus 67.5 degrees, the accuracy increased to about 79 percent. He also found that at higher wind speeds (15 mph and greater) accuracy increased by about 15 percent.

In a recent inhouse study, the GFC staff found similar differences in observed versus daily district forecast wind at Dawsonville, GA (table 1). In this case the wind was accurate to within plus or minus 45 degrees 79 percent of the time. These studies draw attention to the need for caution in interpreting the plume impact, especially at low wind speeds.

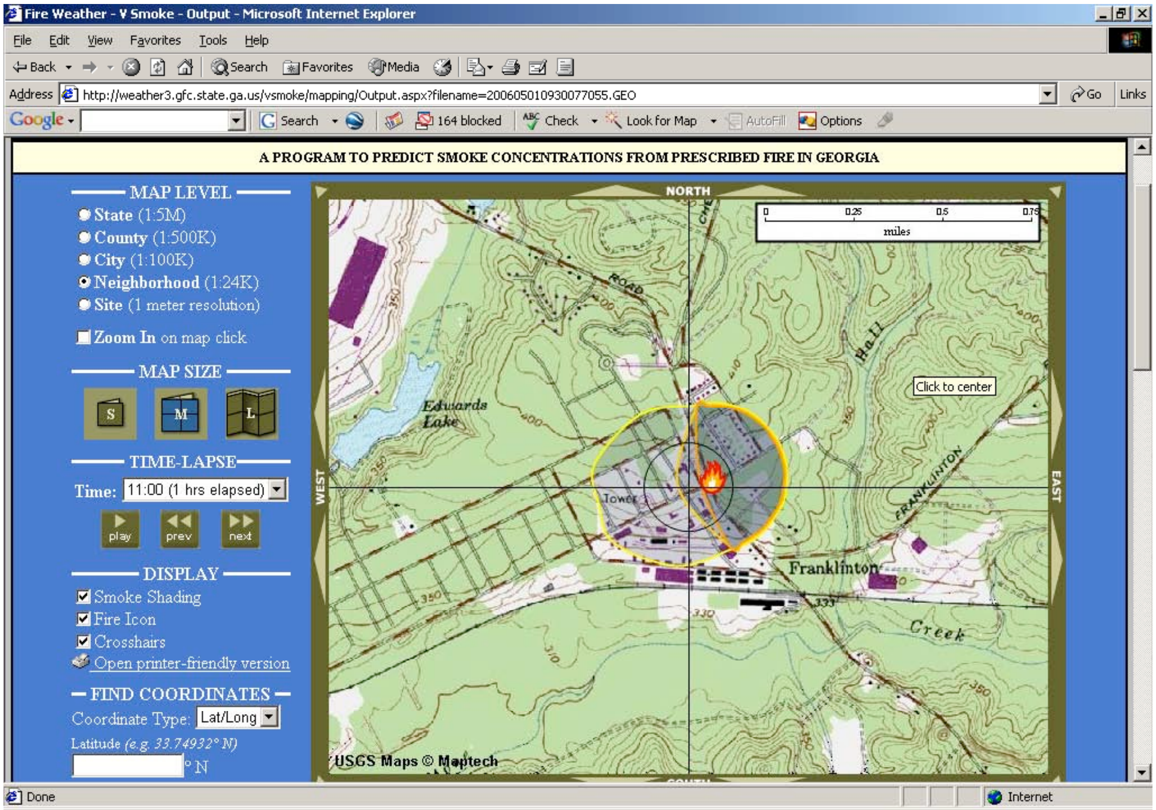


Figure 8—Plume output screen.

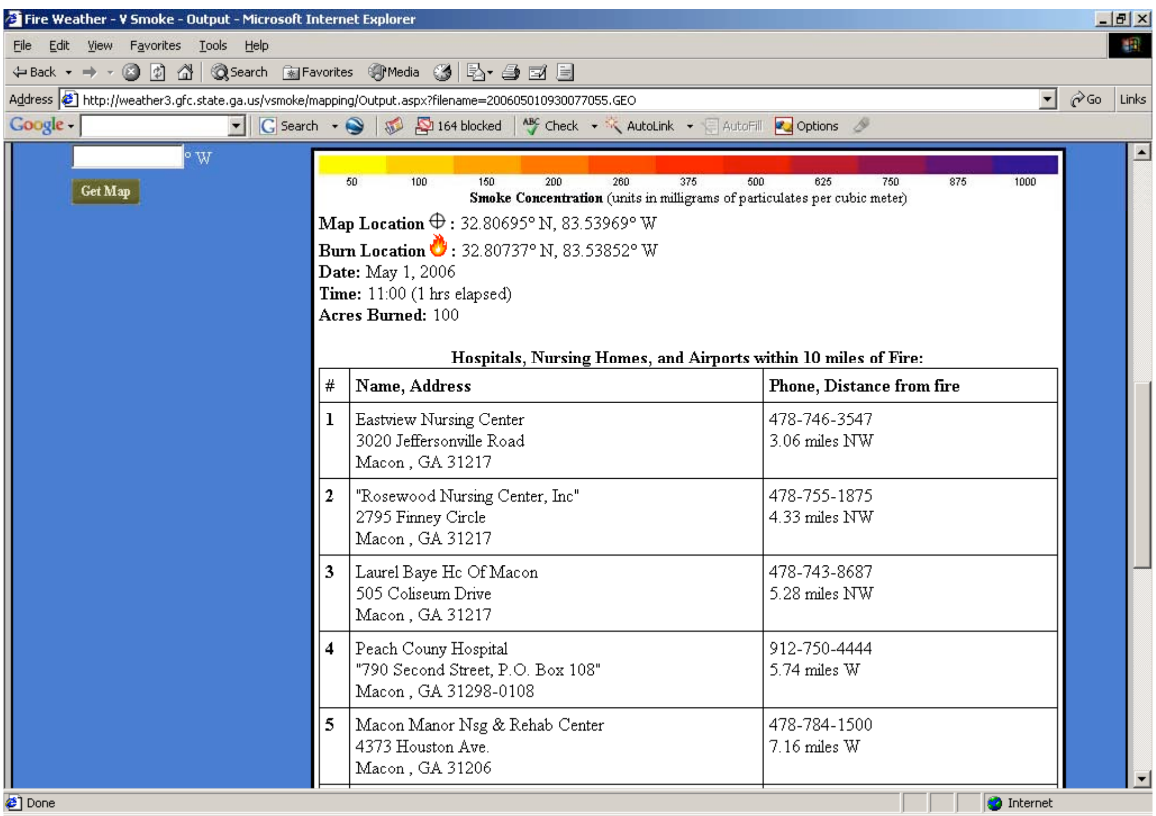


Figure 9—Listing of smoke sensitive areas.

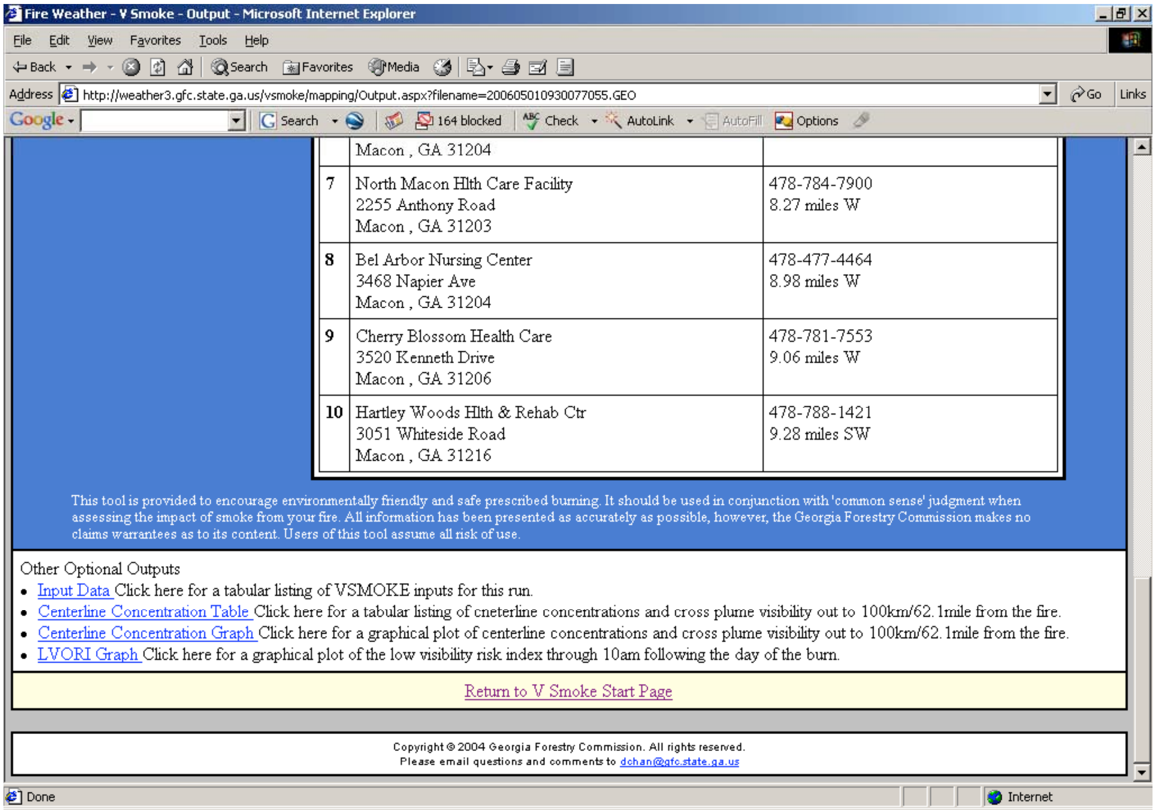


Figure 10—Optional outputs.

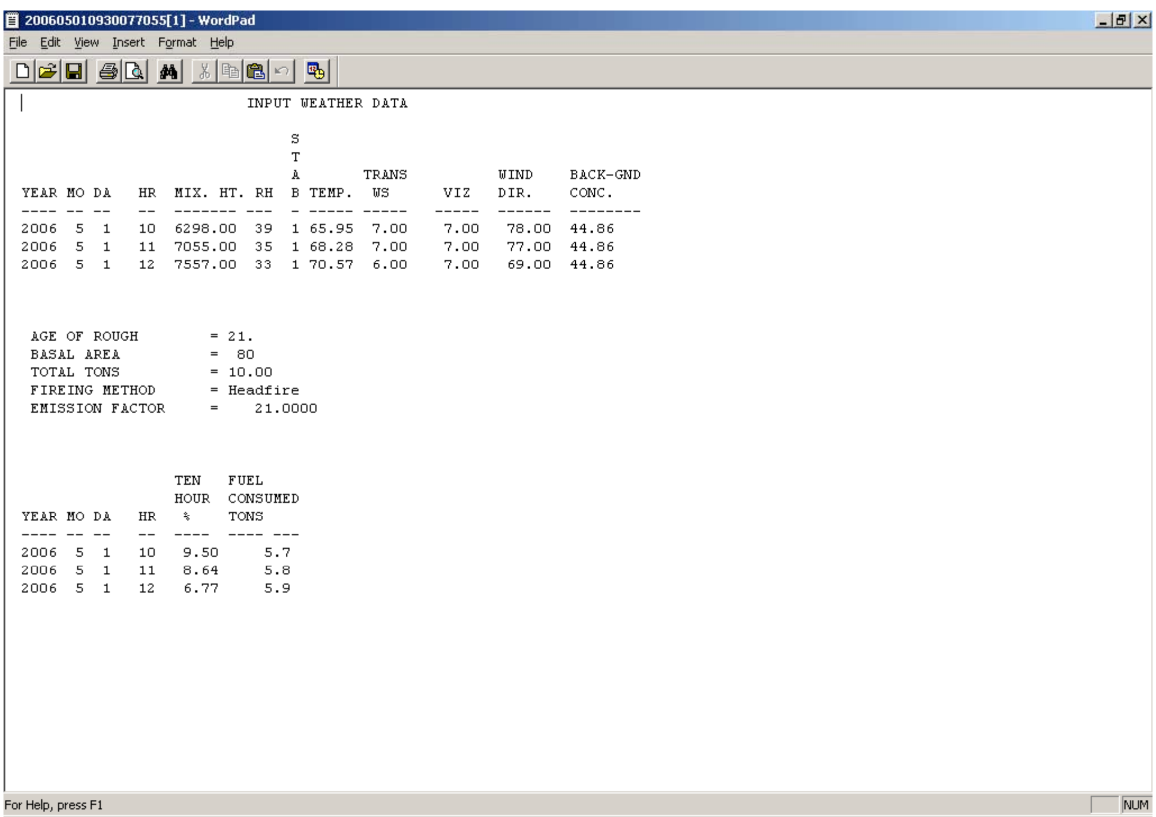
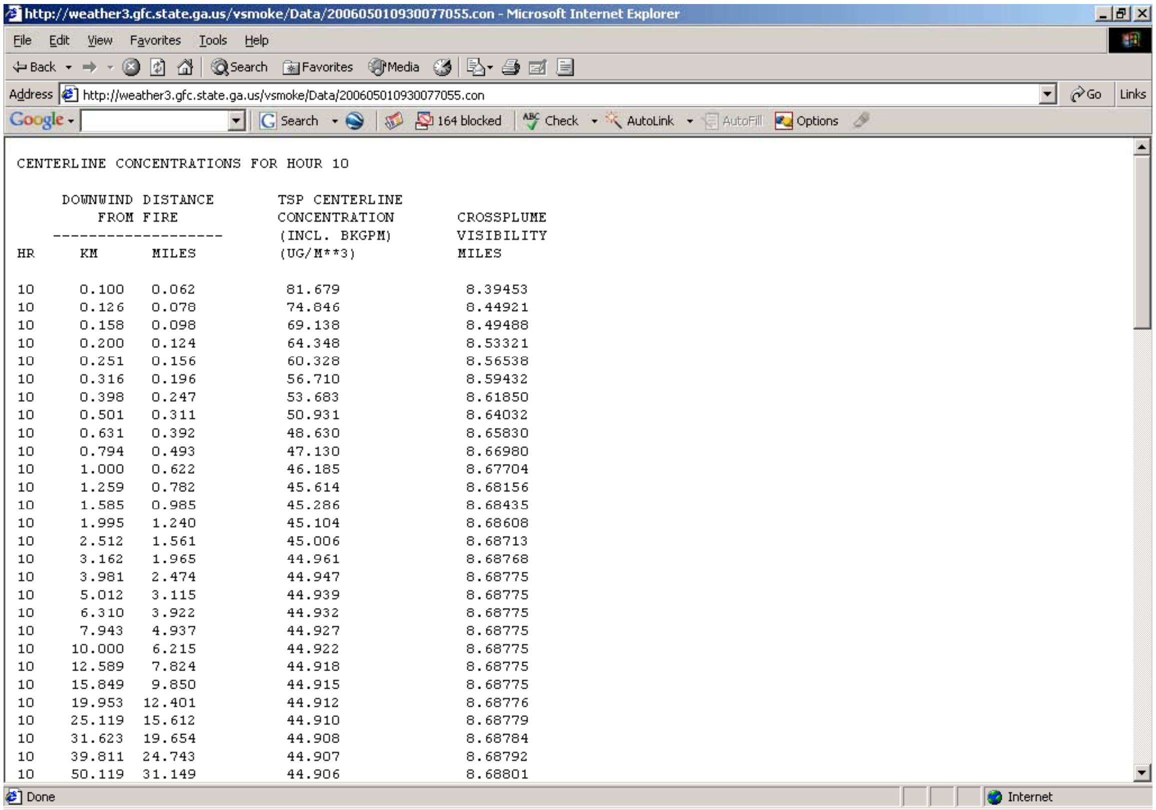


Figure 11—Weather data input used for the application.



CENTERLINE CONCENTRATIONS FOR HOUR 10

HR	DOWNWIND DISTANCE FROM FIRE KM	MILES	TSP CENTERLINE CONCENTRATION (INCL. BKGPM) (UG/M**3)	CROSSPLUME VISIBILITY MILES
10	0.100	0.062	81.679	8.39453
10	0.126	0.078	74.846	8.44921
10	0.158	0.098	69.138	8.49488
10	0.200	0.124	64.348	8.53321
10	0.251	0.156	60.328	8.56538
10	0.316	0.196	56.710	8.59432
10	0.398	0.247	53.683	8.61850
10	0.501	0.311	50.931	8.64032
10	0.631	0.392	48.630	8.65830
10	0.794	0.493	47.130	8.66980
10	1.000	0.622	46.185	8.67704
10	1.259	0.782	45.614	8.68156
10	1.585	0.985	45.286	8.68435
10	1.995	1.240	45.104	8.68608
10	2.512	1.561	45.006	8.68713
10	3.162	1.965	44.961	8.68768
10	3.981	2.474	44.947	8.68775
10	5.012	3.115	44.939	8.68775
10	6.310	3.922	44.932	8.68775
10	7.943	4.937	44.927	8.68775
10	10.000	6.215	44.922	8.68775
10	12.589	7.824	44.918	8.68775
10	15.849	9.850	44.915	8.68775
10	19.953	12.401	44.912	8.68776
10	25.119	15.612	44.910	8.68779
10	31.623	19.654	44.908	8.68784
10	39.811	24.743	44.907	8.68792
10	50.119	31.149	44.906	8.68801

Figure 12—Centerline concentration for each hour in the burn period.

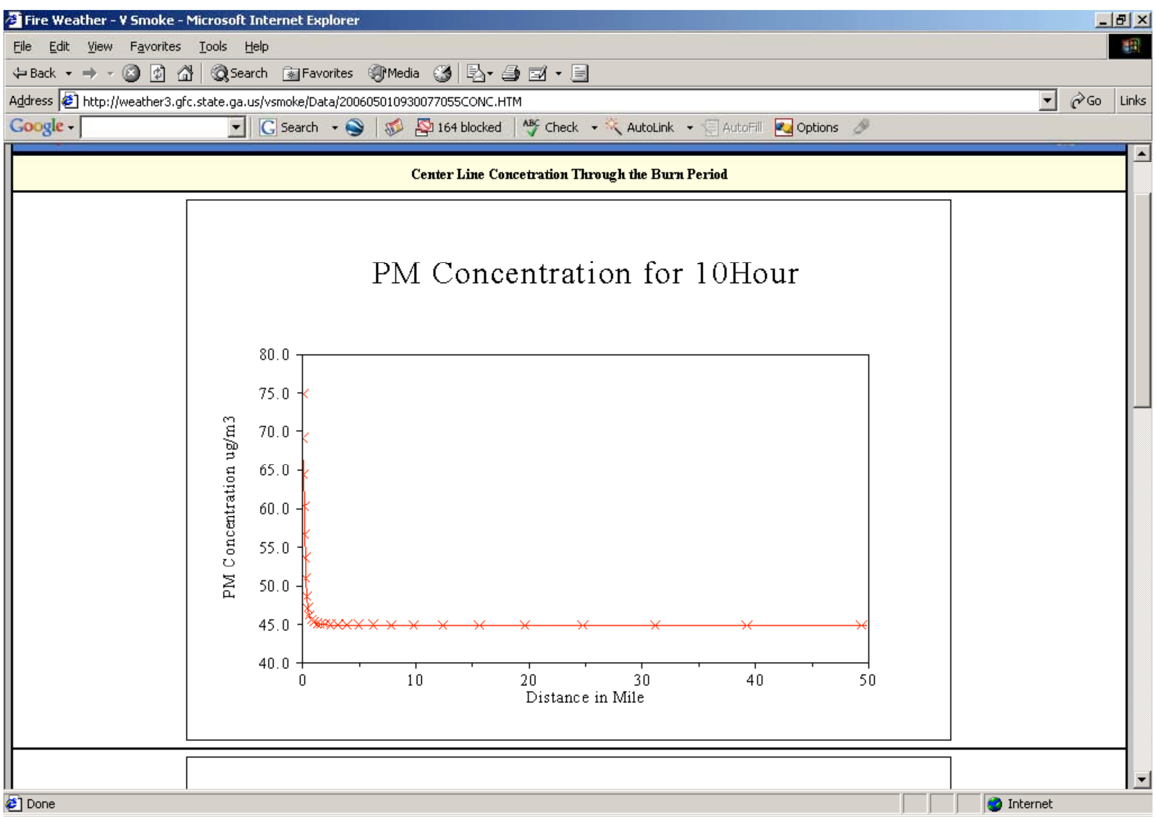


Figure 13—Centerline concentration graph for each hour in the burn period.

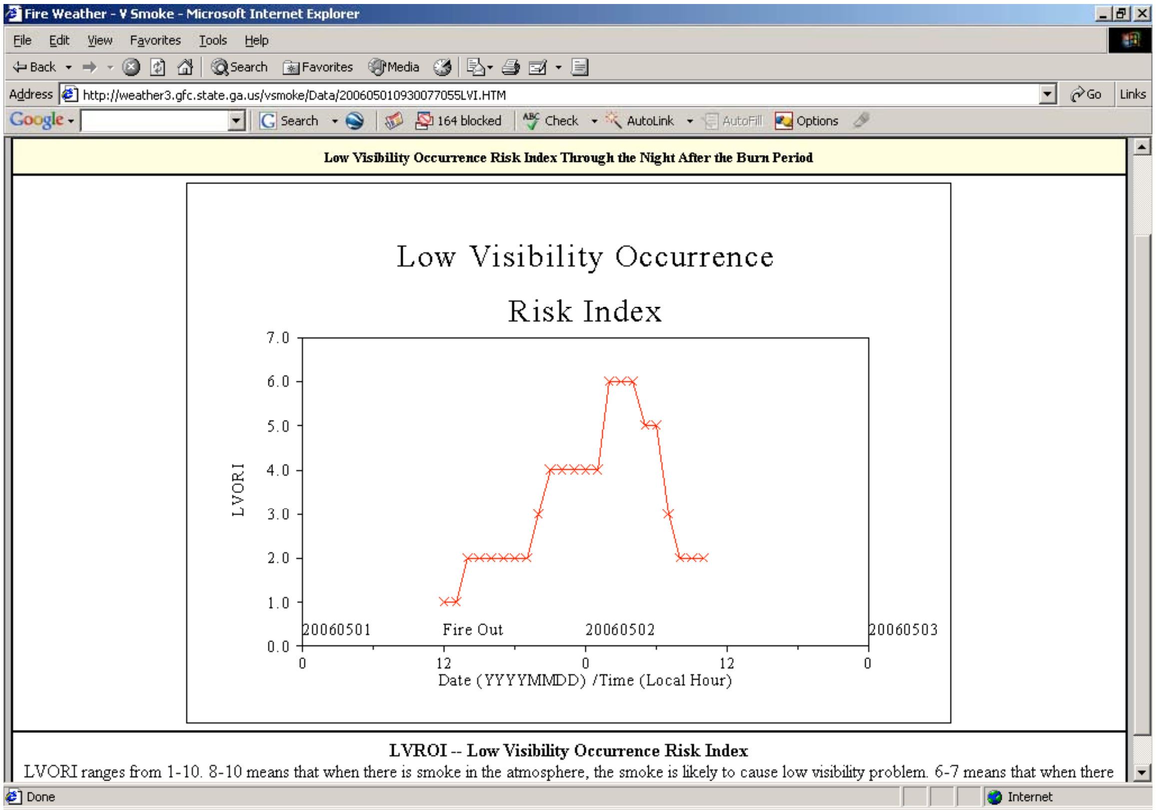


Figure 14—Low Visibility Occurrence Risk Index from the end of the burn to the following morning.

Table 1—Wind direction (observed - forecast) frequencies for the GFC weather station at Dawsonville, GA, from January 2002 to December 2002.

Wind direction (obs–fcst)	**Months**												
Degrees	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOT
-91 <	1	0	2	1	3	2	1	1	1	2	1	1	16
-46 to -90	2	3	5	4	2	0	2	1	1	1	3	1	25
-1 to -45	4	7	9	8	6	2	3	3	3	9	3	6	63
HIT	11	11	6	14	9	14	5	3	7	5	13	14	112
1 to 45	4	7	8	1	2	3	5	5	2	5	3	6	51
46 to 90	0	0	0	1	2	0	2	0	0	2	0	1	8
> 91	4	0	1	0	1	0	0	0	0	3	1	2	12
Total	**26**	**28**	**31**	**29**	**25**	**21**	**18**	**13**	**14**	**27**	**24**	**31**	**287**

Use and Interpretation

The plume depiction provides a method to quickly evaluate what areas will likely be impacted by smoke from a prescribed fire. Unsafe highway visibility resulting from smoke typically extends outward to about 0.25 to 0.50 mile, but under poor dispersion can be much farther. The light to dark gray sections of the plume are the areas of most concern. If this section of the plume impacts a roadway, the burner should defer burning until more favorable conditions occur, or take special precautions such as placing warning signs along the highway, or perhaps paying an off-duty law enforcement officer to monitor the fire on site and reroute traffic or close the road as needed. Additional information concerning concentrations and visibility can be found in the screens following the plume screen. For example, the "Centerline Concentration Table" and "Centerline Concentration Graph" screens provide addition information on concentrations. "The Centerline Concentration Table" also provides estimates of cross plume visibility. These visibility values refer to daytime conditions. Additional information such as the LVORI should be evaluated for nighttime conditions.

The influence of smoke on highway is intuitive because smoke will obviously reduce roadway visibility if present. The question is what constitutes safe visibility? One way to answer this question is to consider automobile stopping distance as a function of speed. In the "Georgia Drivers Manual, 2005," which can be viewed on line at http://www.dds.ga.gov/docs/forms/FullDrivers-Manual.pdf, data are presented that relate stopping distance to speed; these data were used to construct table 2. These numbers are not absolute, and the manual also lists six factors that influence stopping distance. These are:

1. Mental and physical reaction of the driver.
2. Type and condition of the pavement.
3. Kind of tires and tread composition.
4. Chassis (frame) design.
5. Type of brakes, condition, and balance of brakes.
6. Wind direction and velocity.

Suppose one is driving on a State road at the posted speed limit of 55 mph. Rounding this to 60 mph, and using values from table 2, the stopping distance would be between 252 and 372 feet. Next, examine the data from the "Centerline Concentration Table." The first value is at 0.062 mile from the fire with an associated cross plume visibility of 8.39 miles. In this (as in most cases) roadway visibility is not a problem since the estimated visibility is much greater than the stopping distance. However, problems do occur, and using VSMOKE is a good way to evaluate the existence of a problem.

Table 2—Estimated emergency stopping distance by speed. Source: Georgia Drivers Manual, 2005

Driving speed (mph)	Driver reaction distance (ft)	Breaking distance (ft)	Total stopping distance (ft)
20	44	15-22	59-66
30	66	33-50	99-116
40	88	53-107	141-195
50	110	83-167	193-277
60	132	120-249	252-372
70	154	163-327	317-481

The boxed numbers on the map refer to smoke sensitive areas such as nursing homes. It is assumed the burner will make appropriate arrangements when nursing homes and hospitals are within the plumes area.

LVORI is not a perfect indicator of smoke induced low nighttime visibility problems on roadways. LVORI is essentially an estimate of the atmosphere potential to contribute to low visibility. Other factors that should also be considered include:

1. The fire is more than 3 miles from a road. Most nighttime visibility problems occur within 3 miles, but in exceptional cases may extend out to 30 miles from the fire.
2. The vegetation is continuous and heavy between the burn and a road. Heavy vegetation acts as a filter and slows the movement of smoke.
3. Logging roads, power lines, streams, or similar features can provide an unobstructed pathway between the burn and a road.
4. The road is at a higher elevation than the burn.

Future Development

The system is structured as a series of stand alone modules with a master calling routine integrated into the system. Consequently, the fuels, weather, emissions, or dispersion modules can be replaced as desired with a minimum of effort. Possible improvements include output from weather models such as MM5, better ways to estimate fuel loading, available fuel, and improved emission factors.

References

Harms, Mary F.; Lavdas, Leonidas G. 1997. Users guide to VSMOKE-GIS for workstations. Research Paper SRS-6. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 41 p.

Lavdas, Leonidas G. 1996. Program VSMOKE - Users Manual. Gen. Tech. Rep. SRS-6 Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 147 p.

Lavdas, Leonidas G. 1997. Accuracy of National Weather Service wind direction forecasts at Macon and Augusta, Georgia. National Weather Digest Vol. 22 No. 1: 22-26.

Acknowledgments

The authors are indebted to Lee Lavdas for his helpful suggestions during the development of Internet VSMOKE, and for his perceptive and helpful review of this paper.

This
page is
blank
on purpose

Erosion Control and Land Treatments

This page is blank on purpose

Cascading Disaster Models in Postburn Flash Flood

Fred May[1]

Abstract—*A useful method of modeling threats from hazards and documenting their disaster causation sequences is called "cascading threat modeling." This type of modeling enables emergency planners to address hazard and risk assessments systematically. This paper describes a cascading threat modeling and analysis process. Wildfire and an associated postburn flash flood disaster are modeled to serve as examples of the modeling and analysis process. Models are developed for both wildfire and flash flood, and the two models are then linked at a particular threat interface. Additionally, the use of a Federal and State Interagency Technical Team (IAT) for onsite wildfire and postburn flash flood assessment is described. The integration of expert field knowledge held by IAT specialists and agency staff is an essential component in developing credible cascading disaster models. When applied to local hazard mitigation planning, a detailed and systematic picture of local threat, risk, vulnerability, and consequence arises. An example wildfire burn and postburn flash flood is provided as a reference. Additionally, the use of an IAT for onsite wildfire and postburn flash flood assessment is described because this kind of field knowledge is essential in developing credible cascading disaster models.*

Introduction

Scientists commonly think of nature in terms of systems and disaster events occur within natural systems. For some inexplicable reason, disaster practitioners have not typically adopted systems thinking. In current emergency management analysis, disasters are usually studied fragmentally (fragmented), considering one aspect of a disaster at a time. What are considered in disaster assessments are often items arranged in lists or in tables, rather than as component within systems frameworks. Fragmental approaches have public safety shortcomings where extremely dangerous threats hidden within a disaster system may go unnoticed. It is proposed that cascading disaster models be used by emergency practitioners as the basis for conducting hazard and risk analyses and developing those analyses further into plans.

It is proposed herein that methods associated with "systems thinking" about disasters be called disaster systematics. Two kinds of associated information are presented. The first is an explanation of a disaster modeling technique called "cascading disaster modeling" and the second is an explanation of an application of this technique to wildfire and postburn flash flood. Although the concept of cascading disasters is mentioned often in hazard and disaster literature, little has been done in the development of methods for the application of the concept. This author has developed and used a technique for many years both for application in the university classroom (disaster studies) and for application within governmental contexts, including conducting detailed and systematic hazard and risk analyses at the local government level and with State parks.

In: Butler, Bret W.; Cook, Wayne, comps. 2007. The fire environment—innovations, management, and policy; conference proceedings. 26-30 March 2007; Destin, FL. Proceedings RMRS-P-46CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 662 p. CD-ROM.

[1] Associate Professor of Emergency Management, Jacksonville State University Institute for Emergency Preparedness, Jacksonville, AL. fmay@jsu.edu

Defining "Analysis" in Hazard Studies

The definition of the word "analysis" requires that the information being studied represent an intellectual or material whole, such that the constituent parts of the intellectual whole can be studied (see American Heritage Dictionary, Fourth Edition, 2000). Therefore, analyzing a hazard or its associated disaster requires understanding disasters in their entirety so that constituent parts can then be studied

The nature of the "whole" is explained in hazard and disaster management literature in terms of cascading disasters where one event in a disaster is connected through a causal sequence to the next event. Hence, we discover that a disaster consists of interconnected cascading causation sequences, from the initiation of the disaster to its culmination. This satisfies the definition of the whole.

Although a disaster exists as an intellectual or material whole, disasters are rarely studied within the framework of a whole. Hazard and disaster analysts most often study disasters through the use of selected isolated point threats, not related to their constituent cascading threat sequences. As such, according to the definition above, it would be impossible to analyze a disaster (break it into its component parts) through that process. Thus, there is some contradiction among emergency planners when the term hazard or disaster analysis is stated when a fragmental process is actually being used.

Cascading Threat Models

Cascading threat models (also known as cascading emergencies or disasters) have long been mentioned by some authors in the hazard and disaster management literature, but generally as only a vague concept. The concept is that disasters begin with a single primary threat and then occur as sequences of events. These sequences of events are most often referred to collectively as "secondary hazards" without the provision of additional definition or development. In this present paper, cascading is referred to in the context of dynamic disaster systems that consist of branching tree structures from a primary threat or event. To make the point that the concept of disaster systems is actively presented in disaster management literature, some quotes are provided in table 1. However, while such references exist, they lack clarification beyond that provided in the quoted text. Also note that an Internet search for the terms "cascading emergencies or disasters" produces something on the order of 1 million "hits."

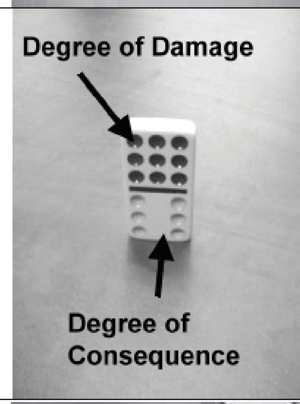
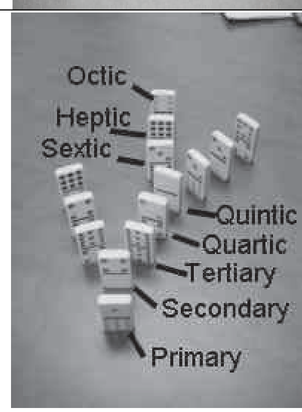
Cascading and Toppling Dominoes Analogy

The concept of cascading disaster events can be illustrated via an analogy involving toppling dominoes. A massive array of dominoes is arranged such that once the initial domino is toppled, striking the next, and so forth, the dominoes then topple in intricate cascading sequences, from beginning to end, often consisting of branching networks. Disasters, as natural systems, operate in much the same fashion. The following examples demonstrate this analogy.

In a disaster, it is not enough to say that there is a primary threat and then all other threats in a sequence are secondary threats. Each threat in a cascading sequence may have its own integral importance, its own degree of damage and degree of consequence. Cascading threat sequences can be identified in Latin as primary, secondary, tertiary, quaternary, quinary, sextenary (or senary), heptenary (or septenary), octenary, nonary, denary, undenary, duodenary, and

Table 1—Examples from disaster management literature.

Reference	Quote
FEMA Independent Study Course, IS 230, Principles of Emergency Management	p. 3.17. Cascading events are events that occur as a direct or indirect result of an initial event. For example, if a flash flood disrupts electricity to an area and, as a result of the electrical failure, a serious traffic accident involving a hazardous materials spill occurs, the traffic accident is a cascading event. If, as a result of the hazardous materials spill, a neighborhood must be evacuated and a local stream is contaminated, these are also cascading events. Taken together, the effect of cascading events can be crippling to a community.
FEMA Independent Study Course, IS 393, Introduction to Mitigation	p. 1-6. Cascading emergencies—situations when one hazard triggers others in a cascading fashion—should be considered. For example, an earthquake that ruptured natural gas pipelines could result in fires and explosions that dramatically escalate the type and magnitude of events.
U.S. Department of Homeland Security National Response Plan, December 2004	p. 4 Additionally, since Incidents of National Significance typically result in impacts far beyond the immediate or initial incident area, the NRP [National Response Plan] provides a framework to enable the management of cascading impacts and multiple incidents as well as the prevention of and preparation for subsequent events.
FEMA for Kids Website, Resources for Parents and Teachers, How Schools Can Become More Disaster Resistant. http://www.fema.gov/kids/schdizr.htm	. . . disasters can have a cascading effect—forest fires can bring mudslides; earthquakes cause fires; tornadoes cause downed power lines.
Resource Materials: Integrating Manmade Hazards into Mitigation Planning Risk Management in a Multi-Hazard World 2003 All-Hazards Mitigation Workshop June 12, 2003 Emergency Management Institute http://www.fema.gov/txt/fima/antiterrorism/resourcematerials.txt	Indirect attacks: infrastructures are really interconnected systems of systems; an attack on one can lead to cascading losses of service (ranging from inconvenient to deadly) and financial consequences for government, society, and economy through public- and private-sector reactions to an attack.
FEMA 428, Asset Value, Threat/Hazard, Vulnerability, And Risk	p. 1-17. Extent of damage is determined by type and quantity of explosive. Effects generally static other than cascading consequences, incremental structural failure, etc.
FEMA 386-7, FEMA State and Local Mitigation Planning How-To Guide, Integrating Man-Made Hazards Into Mitigation Planning. Step. 2, Assessing Risks.	p. 2-11. What is the likelihood of cascading or subsequent consequences should the asset be destroyed or its function lost?
Hazard Analysis and Risk Assessment, 2003 Local Guide, Iowa Homeland Security and Emergency Management Division,	Hazards create direct damages, indirect effects, and secondary hazards to the community. Direct damages are caused immediately by the event itself, such as a bridge washing out during a flood. Indirect effects usually involve interruptions in asset operations and community functions, also called functional use. For example, when a bridge is washed out due to a flood, traffic is delayed or rerouted, which then impacts individuals, businesses, and public services such as fire and police departments that depend on the bridge for transportation. Secondary hazards are caused by the initial hazard event, such as when an earthquake causes a tsunami, landslide, or dam break. While these are disasters in their own right, their consequent damages should be included in the damage calculations of the initial hazard event. Loss estimations will include a determination of the extent of direct damages to property and indirect effects on functional use.
Regional All-Hazards Mitigation Plan, City of St. Louis and counties of St. Louis, Jefferson, Franklin and St. Charles, Missouri, November 2004.	Cascading hazards could include interruption of power supply, water supply, business and transportation.

<table>
<tr><td>A single domino, as shown at the right, represents a point threat, as one might expect were a disaster to be a static event. This standing domino could represent a type of electrical transmission line constructed in an urban wildland interface. It is simply a power line at risk from wildfire, although a wildfire has not happened (domino is not yet toppled).</td><td></td></tr>
<tr><td>Here, at the right, we see the same domino but we consider what might happen if the electrical transmission line were to be damaged by a wildfire. Thus, we may consider a degree of damage and an associated degree of consequence. In this case the degree of damage would be 100 percent, or complete, and the degree of consequence is somewhat more than moderate.</td><td>
</td></tr>
<tr><td>This view, at the right, is of an anticipated dynamic disaster sequence, should the sequence happen. Should the wildfire provide a low level of damage, consequence of even a low level of damage results in a completely negative consequence (see the top number, one dot, on the first domino, which represents the primary threat; see the bottom number on the domino, six dots, which represents the level of consequence). If the primary threat (first domino) happens, then the rest of the cascading sequence may take place, where one threat causes another, and so forth, each with its own relationship between degree of damage and degree of consequence. Numbering is explained in the text.</td><td>
</td></tr>
</table>

so forth. The author proposes using shortened terms to simplify communication: primary, secondary, tertiary, quartic, quintic, sexic, heptic, octic, nonic, decic, undenic, duodenic, and so forth (written communication, Dr. David Larmour, Texas Tech University, 2006). Such nomenclature facilitates communicating about threat sequences. In the illustration above, which shows a branching domino sequence, a disaster analyst could consider how a wildfire would generate a branching set of threat sequences because, for example, the fire spreads because fire support is too far away to provide immediate response. That sequence of events can be analyzed (separated into its constituent parts to be studied). The threat sequence could represent any causation sequence. For example: (1) the delay in response would allow the fire to grow, and (2) the movement of fire support personnel from distant areas could result in traffic accidents, and so forth. Both pathways need to be analyzed.

Multihazard Concept

Cascading threat modeling has its origins in the concept of multihazard events. The term multihazard was introduced by the Federal Emergency Management Agency (FEMA) in 1982-1983 as part of the Utah Multi-Hazard Project. This new concept related multiple hazards to each other through causation sequences. The Utah Multi-Hazard Project included the cities of Provo and Ogden, and Utah and Weber Counties, showing the relationship between earthquake, dam failures, and floods, where a simulated design earthquake would logically cause a dam failure, which would then cause a flood (personal communication, Wes Dewsnup, Utah Multi-Hazard Project, former Program Manager; Utah Division of Comprehensive Emergency Management, July 15, 2006). This concept, though simple, was revolutionary because multihazards lead to multidisciplinary considerations, interactions, and solutions. The concept required diverse groups of specialists from various agencies to work together to solve multihazard problems. Earthquake specialists, dam safety specialists, and flood specialists then needed to work together to solve planning problems that emerged from multiple hazards.

Shortly after the awareness of the multihazard concept, various FEMA publications began to include the term cascading hazards and cascading disasters (see table of references above). It was from this concept of cascading hazards and disasters that this present method of disaster systematics arose in the late 1980s, as both a teaching and planning tool. The initial tool was called a "hazard tree," and authoritative hazard trees were created by members of the Utah Interagency Technical Team (representatives from several agencies working together) for use in conducting local hazard and risk analyses. This tool was used successfully Statewide for such analyses. Hazard trees and the larger concept of disaster systematics was used as early as 1988 in the classroom at the University of Utah, Center for Natural and Technological Hazards, where students were required to develop hazard trees to understand cascading disaster processes for analysis purposes. The author first published a cascading disaster model in 1991 through the National Research Council's publication "A Safer Future, Reducing the Impacts of Natural Disasters," 1991, Chapter 2, Hazard and Risk Assessment.

Modeling Versus Model Analysis

The purpose of creating cascading disaster models is to have credible models available for use in analyses. The models, which often are not complicated, capture the cascading events in disasters. Disasters often consist of many cascading sequences. Computer software can be used to keep track of these sequences, facilitating analysis and even supporting standardized analyses.

Model Development

The human mind cannot recall the amount of sequential information contained within a complex disaster system, but computers can store and display, both in outline and diagram formats, entire disaster systems. Both outline and diagram formats are essential in the development and application of the models. Computers can also store additional text and visual information as background documents within the models through notes and hyperlinked documents of many useful software types (word processing, spread sheets, presentations, Web pages, and so forth). Computers also allow for the creation of aesthetically attractive models suitable for public display and presentation.

Several types of computer software programs are capable of meeting the needs of "cascade modelers," including Inspiration and MindManager. Both of these software programs allow the modeler(s) to work within an outline and or diagram format, and both are powerful and versatile, allowing the modeler(s) to escape the limitations of fragmented hazard and risk thinking–to become disaster systems analysts.

Although completed disaster systems models appear complex and intricate, few of the threat sequences are particularly complex and are often sequences we are familiar with. For example, one sequence from an earthquake model might state that a threat from ground motion causes threat from the shaking of buildings that, in turn, causes threat from falling bricks that, in turn, causes threat from bricks blocking streets that, in turn, causes delaying of emergency vehicles that, in turn, causes threat from the delay of emergency services to people in need of emergency services. But then we notice that falling bricks can cause more than one threat sequence, and that blocking of streets can cause more than one threat sequence. Thus, cascading models branch within themselves, but even the branching sequences are often easy to follow. The team performing an analysis on any of these sequences can perform analyses that range from straightforward to exceptionally complex, and can be multi- and interdisciplinary.

The development of a cascading disaster model must follow a process that provides credibility to the model. Usually, the modeler (generalist), as mentioned, would be an emergency manager or disaster analyst who coordinates a technical team of engineers, geologists, natural resource specialists, fire management specialists, environmental scientists, planners, and others (all specialists) to create a model. Cascading disaster models should be constructed by a team of technical experts who collectively provide best available knowledge into the model. Computer software is used that enables the modeler (generalist) to enter threat sequences directly into the computer during an interview process involving the technical team (specialists). Team members determine model inputs while the modeler enters the information. The software allows the modeler to enter the information (causal sequences) into an outline format/view and display the model as a cascading tree structure in a diagram format/view. The team of specialists collectively determines the threat sequences and the branchings.

Generic and historic models—There are two basic types of cascading disaster models: generic and historic. Generic models are those designed by a modeling team based on their collective experience to document what can happen in a disaster of that type. There is no reference to other disasters in that the model is not intended to reflect any particular disaster event. Generic models have their own threat nomenclature that is written in the present tense. This nomenclature makes the statement throughout the model, from threat to threat, stating that "threat from this causes threat from this that caused threat from this, and so forth." Threat nomenclature is mainly found in the way the verbs are written within the threat symbols (present tense versus past tense). Most example models provided in this paper are representative of generic models. This type of threat nomenclature is either written as "ing" endings or as present tense verbs. See model examples below for these types of endings.

The other basic type of model is the historic model. Historic models are based on research of a particular disaster, and the identified disaster processes (sequences) are captured in that model. The intent is to document what processes happened in that disaster. Because this information documents an event that happened in the past, the threat nomenclature is written in the past tense ("ed" endings or past tense verbs) (fig. 1).

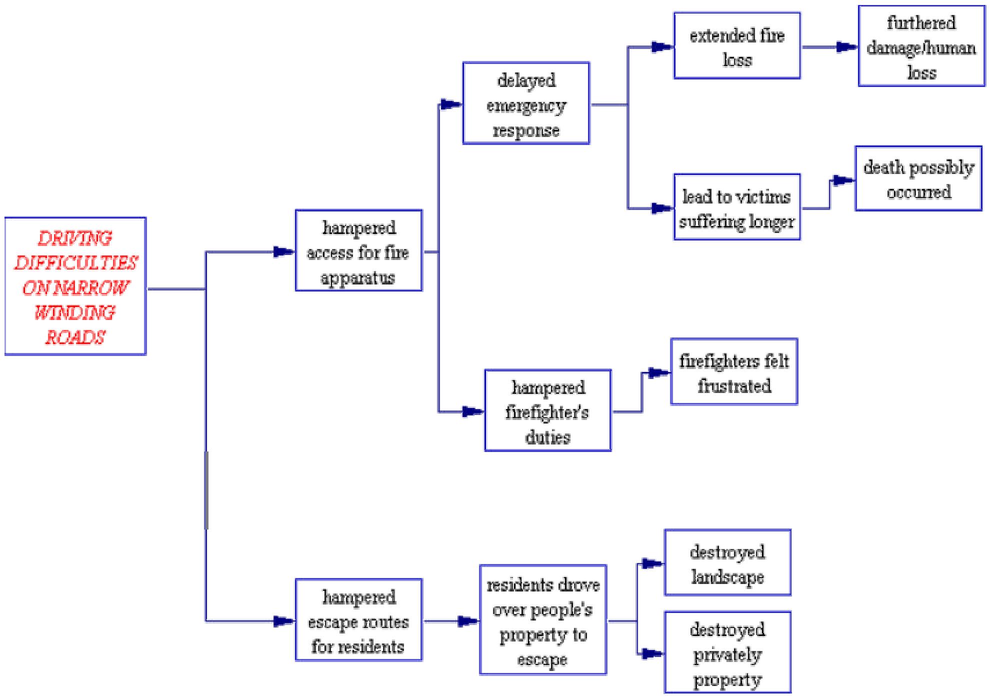


Figure 1—Example of a historic branch of a cascading disaster model of part of the Oakland, CA, wildfire (1991) based on studies of that event.

Threat sequence logic transitions one threat logically to another, depicting the causation sequence. Models must be internally coherent to make sense in their entirety. Thus, one threat must transition logically (causation sequence) and properly (nomenclature) to the next and to the next. This is true if a modeler is developing a generic model (present tense) or a historic model (past tense).

Model geography—Cascading disaster models have **shape, dimension, location, and design**.

The **shape** is that of a branching tree structure, called an index tree. Several graphical examples of a model are provided. Figure 2 is the model for a wildfire. A cascading model for wildfire would begin with a first level index tree, which simply shows our initial sense of what can happen. The fire can then spread uphill, laterally, or downhill, threatening an urban wildland interface community. It can also burn into the community's watershed, introducing the potential for postburn flash flood. The index tree identified the primary and secondary threats that precede the main branches of the model.

The tree can be created and displayed as a top-down tree, a bottom-up tree, a right tree, or a left tree. Experience suggests that either a top-down tree or a right tree functions best. The shape of a tree structure begins with the primary threat, or initial threat that precipitates the cascading sequences of the disaster. Branching sequences follow causing the model to expand. The portion of the tree structure more near the primary threat is termed "proximal," and the portion of the tree structure more distant from the primary threat is termed "distal." At the ultimate proximal end is the primary threat, and at the ultimate distal end are the terminal threats (where the individual model pathways terminate) (fig. 3).

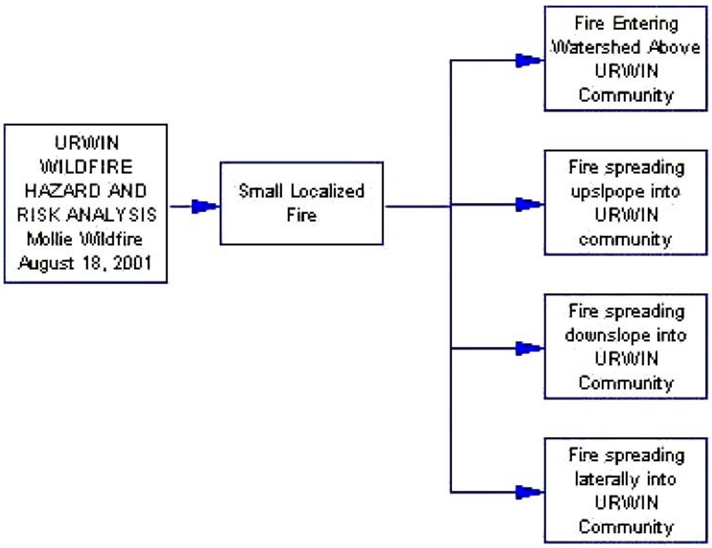


Figure 2—A wildfire begins with the primary threat of a small localized fire. The display of the first few threat layers constitutes an Index Tree, which leads to the rest of an expanded model.

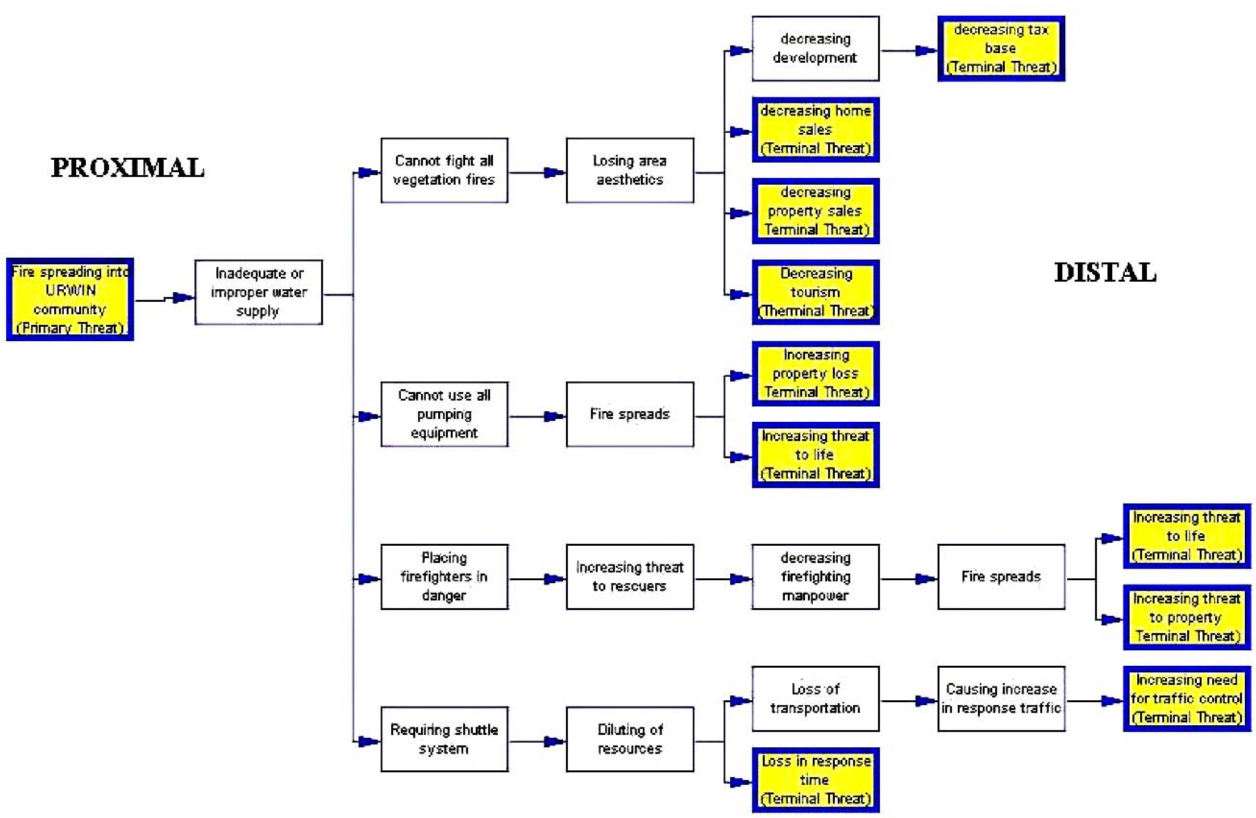


Figure 3—Model branch showing proximal and distal areas and terminal threats.

For **dimension**, the tree has both height and depth determined by the number of branching threat pathways (primary threat to terminal threats). There are as many pathways across the model as there are terminal threats. If the model has 10 terminal threats then the model has a dimension, top to bottom for right trees, of 10 pathways each of which can be analyzed. If the model has 10 pathways, from primary threat to terminal threat, that have, for example, five threats per pathway, then the model is five threats deep, from left to right for a right tree. In this hypothetical example of five threats per pathway, the model would consists of 50 threats, all organized within the 10 pathways. Thus, the model has height (number of pathways - 10) and width (numbers of threats per sequence—a hypothetical number of 10).

There are many threat **locations** within the model. The example in figure 3 depicts 25 threats, each with a unique location within the model that can be identified according to a pathway code. Pathway codes are unique to a particular model, its associated team, and its associated draft date and time. Through the use of pathway codes, team members, or others using the particular model, can communicate about particular threat pathways and understand which pathways they are discussing. Each pathway becomes of interest in a variety of ways: preparedness, response recovery, recovery, training, exercise design, hazard behavior, disaster behavior, and so forth. Given that a pathway consists of a unique threat sequence, then the process of analysis involves studying each threat in its geographic location within the model. It is then important to be able to discuss each threat location with others who may be interested in it. Also note that each individual threat has its own location code.

Figure 4 shows pathway codes for 11 pathways (each terminal threat denotes the end of a pathway) and 24 threats (each box denotes a threat). As shown each threat has a position code number. A threat with two numbers in its code is a secondary threat, and a threat with three numbers is a tertiary threat, and a threat with four numbers is a quaternary threat, and so forth. Numbers are counted from each node between threats and from the top down. The threat position code for a terminal threat is also the pathway code for that pathway (from primary threat at the proximal end of the pathway to the terminal threat at the distal end of the pathway). Thus, in figure 4, one can observe 11 unique pathway codes. As an example of identifying a specific threat, the secondary threat of "inadequate or improper water supply" is located within the box with pathway code "11."

The **design** of the models consists of branches and pathways. Branches are units of a cascading disaster model where two or more pathways originate from a node (that is, the connecting point between two threats). Pathways originating from such a node share design similarities based on the common threat at the proximal end of the branch. Branches that originate from a secondary threat are secondary branches and those that originate from the tertiary threat are tertiary branches, and so forth. Thus, a branch can be discussed by team members as the associated pathways sharing that common characteristic.

Several branches are shown in figure 4. The four pathways of the tertiary branch share the common threat characteristic of "Not Fighting All Vegetation Fires." The two pathways of the quaternary branch share the common threat characteristic of "Fire spreading," which was caused by "Not using all pumping equipment." The two pathways of the sextec branch share the common threat of "Fire spreading."

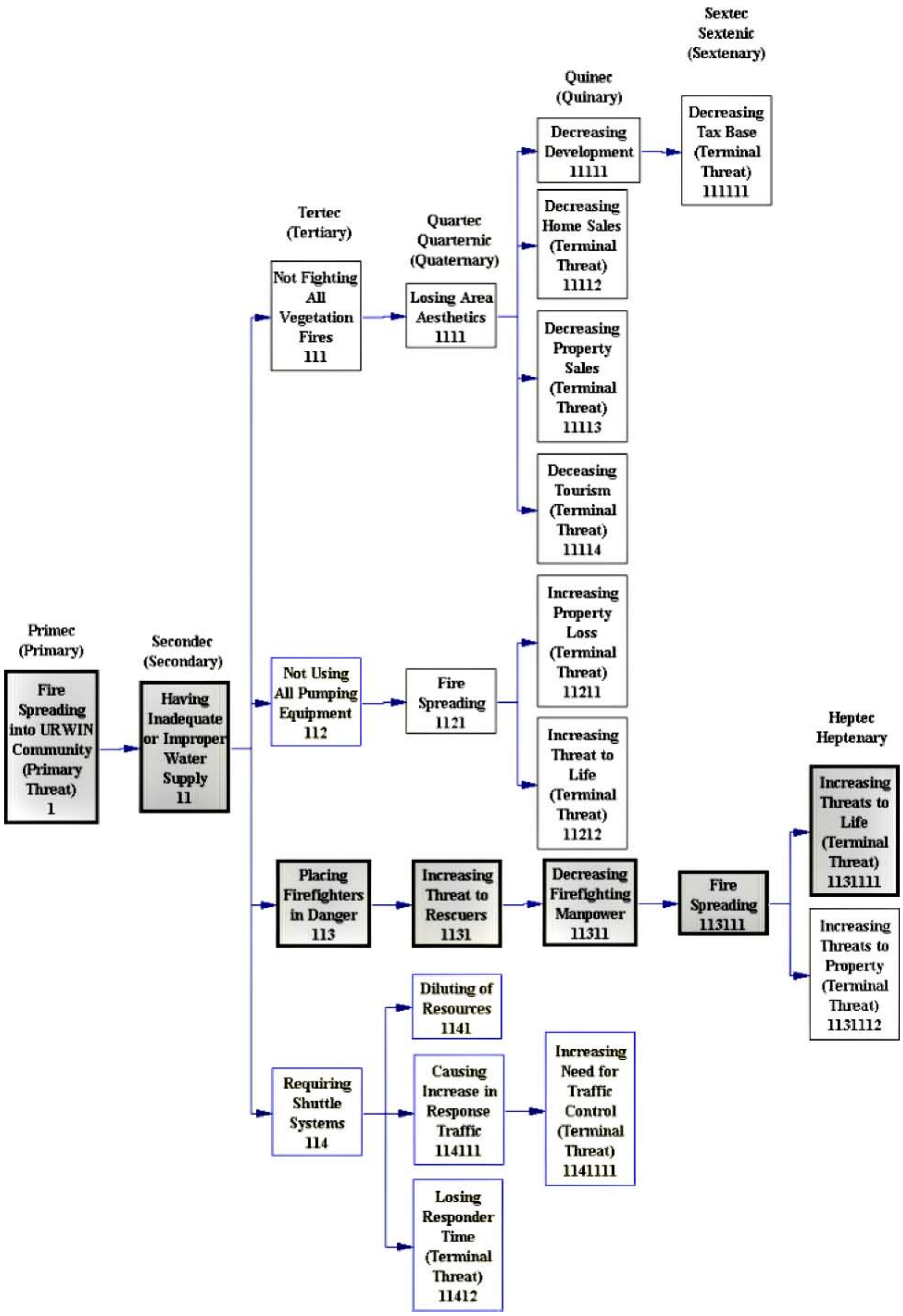


Figure 4—Model branch showing a single pathway highlighted and also showing the unique threat and pathway codes.

Branches can be studied by disaster analysis, but pathways (also referred to as single-file pathways) form the main study unit of a cascading disaster model. Pathways are causation sequences where one threat causes another threat causes another threat causes another threat, and so forth. An example pathway is shown above in figure 4 in the discussion on pathway codes and is separated and shown in figure 5, as well.

Figure 5—Separated single pathway from branch model shown in figure 4.

Single-file causation sequences (pathways) can be studied by a team of hazard and disaster analysts from a variety of perspectives: disaster preparedness, disaster response, disaster recovery, and hazard mitigation. Causation sequences can also be studied from the perspectives of training, exercise design, and so forth. For example, a team of disaster analysts could examine the pathway shown in figure 5 and ask the questions: how might we prepare for, respond to, recover from, or mitigate, such a sequence of events; or how might we train for such a sequence or devise a disaster exercise for such a sequence? In conducting such an analysis, the team might also choose to provide more detail within the model pathway by inserting additional threats.

Antecedent conditions—Cascading disaster models portray disasters and disaster behavior graphically. The same models can also be used to portray hazard behavior by including antecedent conditions—the hazard behaviors that lead to the activation of the primary threat. For example, the presence of propane tanks would also be called a hazard by some disaster analysts. Hazards themselves in these models are simply nouns, or the names of the threats the mind recognizes as hazards to the human built environment and with people themselves.

Figure 6 displays the antecedent conditions that would link a wildfire model to a postburn flash flood model. The antecedent conditions begin with a Damaged Watershed and conclude 11 threats later with a hyperconcentrated flow emerging onto an alluvial fan apex. Antecedent conditions precede the associated disaster, which in this case would be a debris flow disaster associated with the damaged watershed and a significant thunderstorm.

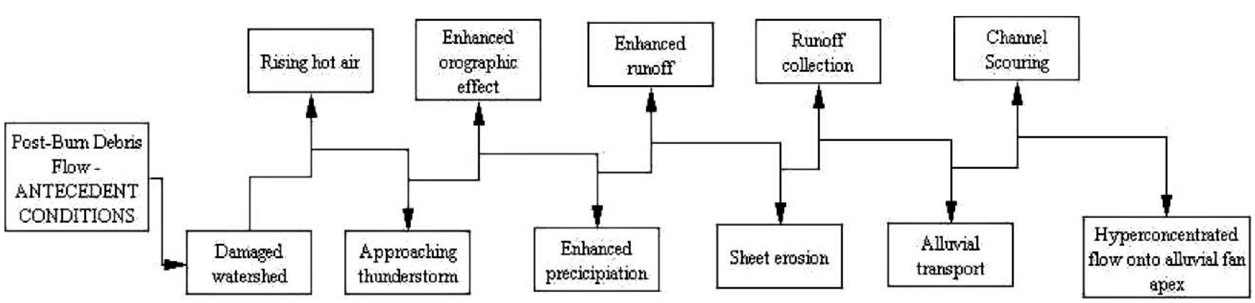


Figure 6—Antecedent conditions that cause the primary threat in disaster genesis.

Model Applications

The value of cascading models has become apparent through several years of application and in a variety of situations.

Cascading models have been used to:

- **Educate community and governmental leaders:** The model as a teaching tool demonstrates to leaders how a particular type of disaster might affect their community, showing generic disaster behaviors as causation sequences, where one threat causes another, causes another, and so forth, or how, through the diagram format, a disaster can “unfold” in their community. The education is meaningful because disasters are commonly thought to happen in random, unpredictable fashion, but in reality leaders learn that disasters happen as systematic processes of causal sequences.
- **Educate IAT members:** Because the human brain is not capable of remembering the details of numerous and complex disaster sequences, the computer-printouts on paper aid team members when they consider what threat pathways are the most dangerous and of highest priority and what strategies might be applied to these pathways to prepare, respond, recover, or to mitigate potential hazard and disaster events.
- **Educate stakeholders and the public:** The process of building community capacity to reduce vulnerability requires public support. The public most often views disaster processes as being too complex to understand and, therefore, tends to avoid gaining an understanding of them. The lay people not versed in hazard and disaster processes and knowledge can understand the logic of cascading disaster model diagrams and, also, the logical threat sequences.
- **Evaluate training:** Models can also be used to identify training needs of the technical team of hazard and disaster managers from the State and Federal agencies, including how to conduct hazard and risk analyses in communities. Team members themselves, in studying a model they created, could identify what knowledge they need in order to understand the sequences in the model.
- **Conduct hazard and risk analyses:** State and local governments are required by Federal law to prepare and submit to the Federal Emergency Management Agency (FEMA, Disaster Mitigation Act of 2000) for approval hazard mitigation plans and emergency operations plans. Such plans are based on hazard and risk analyses. Many agencies of government also conduct these analyses for a variety of needs, or assist local governments in conducting the analyses. Cascading disaster models provide an excellent basis for conducting such analyses that are detailed and systematic. A team of experts can use these models to conduct analyses in a brief period, perhaps 2 hours, considering most any kind of threat that could face a community. Updates to the analyses usually require much less time.
- **Design disaster exercises:** A visual image of disaster as cascading sequences of events provides an excellent basis for designing a disaster exercise. The entire model can be used to develop a comprehensive disaster exercise or it can be used to develop an exercise for selected sequences in a disaster where an exercise would provide the needed training for some aspect of response. The simulated messages (injects) for the exercise could be designed around the threat sequences and relating to the players in the exercise.

- **Conduct planning:** Cascading disaster models can be used for conducting hazard and risk analyses and support the development of response strategies and recommendations. Once a planner comes to the point of adding recommendations, then the hazard and risk analysis becomes more than just an analysis. It begins to look more like a plan. It could become a plan if implementation strategies were also added to the model. Plans, however, are best laid out as text within an outline (table of contents), but the information from the analyses conducted with the model can be transposed into the plan.

Wildfire and Postburn Flash Flood

To relate wildfire to postburn flash flood, refer back to figure 2, which shows a simple view of an index tree including wildfire damaging the watershed. That threat provides the linkage to the cascading threat model for postburn flash flood. City officials too often believe that once a threatening wildfire is contained, the community's vulnerability to disaster is largely over. However, the community then finds itself facing flash flood threat should a significant thunderstorm occur over the damaged watershed (Cornell 1992). In this case, there are now two related cascading disaster models needed, the first for wildfire and the second for postburn flash flood. The two related models would be joined at a terminal threat titled "damaged watershed."

For example, figure 7 displays a wildfire cascading threat model that includes the beginnings of effects of rainfall onto the damaged watershed. Remember that such a model can be as complex as a modeling team wishes to make it. Such threat models, if developed with the assistance of specialized planning teams, gain considerable credibility. This particular model was developed by a combination of wildfire hazard and flood hazard specialists of the Utah Interagency Technical Team in the early 1990s. The process of making a transition from one model (for example, wildfire) to another model (postburn flash flood) introduces the concept of a compound model. (Compound models are caused by a preceding "simple model" and superimpose their own consequences onto the already-existing consequences of the simple, preceding, model. This is a concept too complex to explain in this present paper.) The branching in such a model provides an interesting juncture in the disaster model because it is at this point that the model would actually link to a separate model, representing what happens when the thunderstorm does happen. We then must connect to a debris flow tree modified for the enhanced sediment load. This is a separate model.

Figure 8 presents an index tree for a postburn flash flood cascading threat model. An index tree can be constructed that allows the modeler the option of working with any of the shown pathways, beginning with any of the terminal threats shown. In fact, the entire comprehensive model could be collapsed to the level of the index tree for purposes of illustration.

The Index Tree can be expanded to view a selected branch that would begin with any one of the terminal threats shown in figure 8. This begins the process of analysis. The selected branch provided in figure 9 is an extension from the index tree, diagramming threat sequences arising from the threat of a hyperconcentrated flow impinging onto residential structures. This array of threat sequences shows several aspects of the event that relate to the flow impinging onto residential structures. They all have this one thing in common, which is a characteristic of branches within a cascading disaster model.

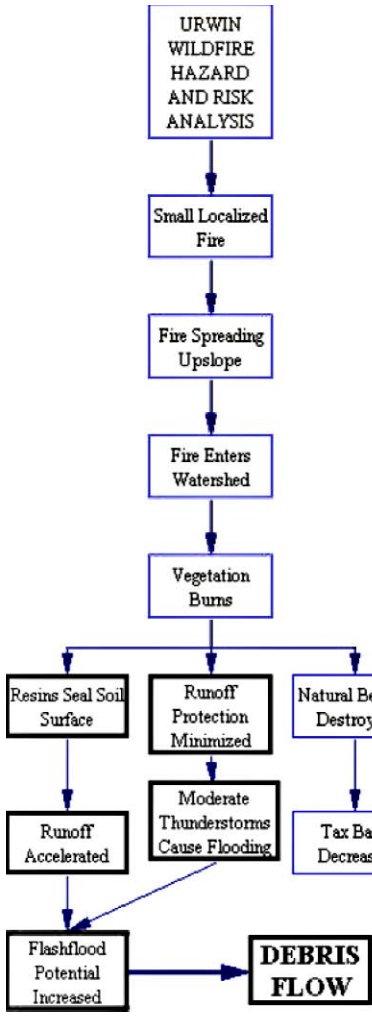


Figure 7—The postburn flash flood (or debris flow/hyperconcentrated flow) model begins at a node within the wildfire model.

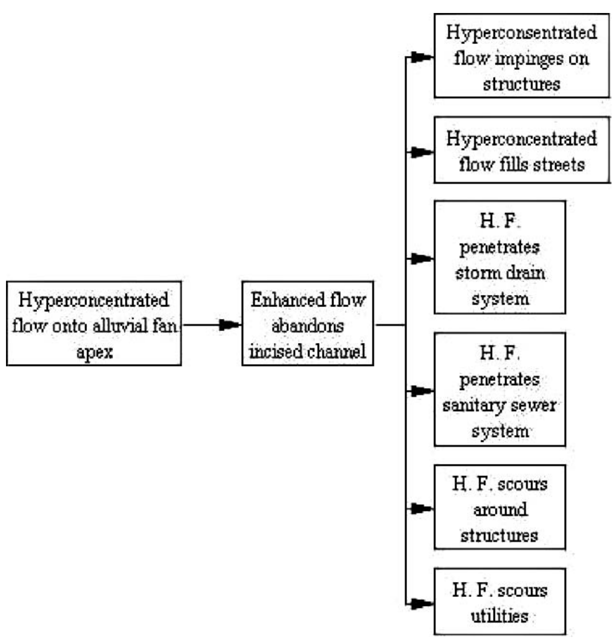


Figure 8—Index tree for postburn flash flood (or debris flow/hyperconcentrated flow).

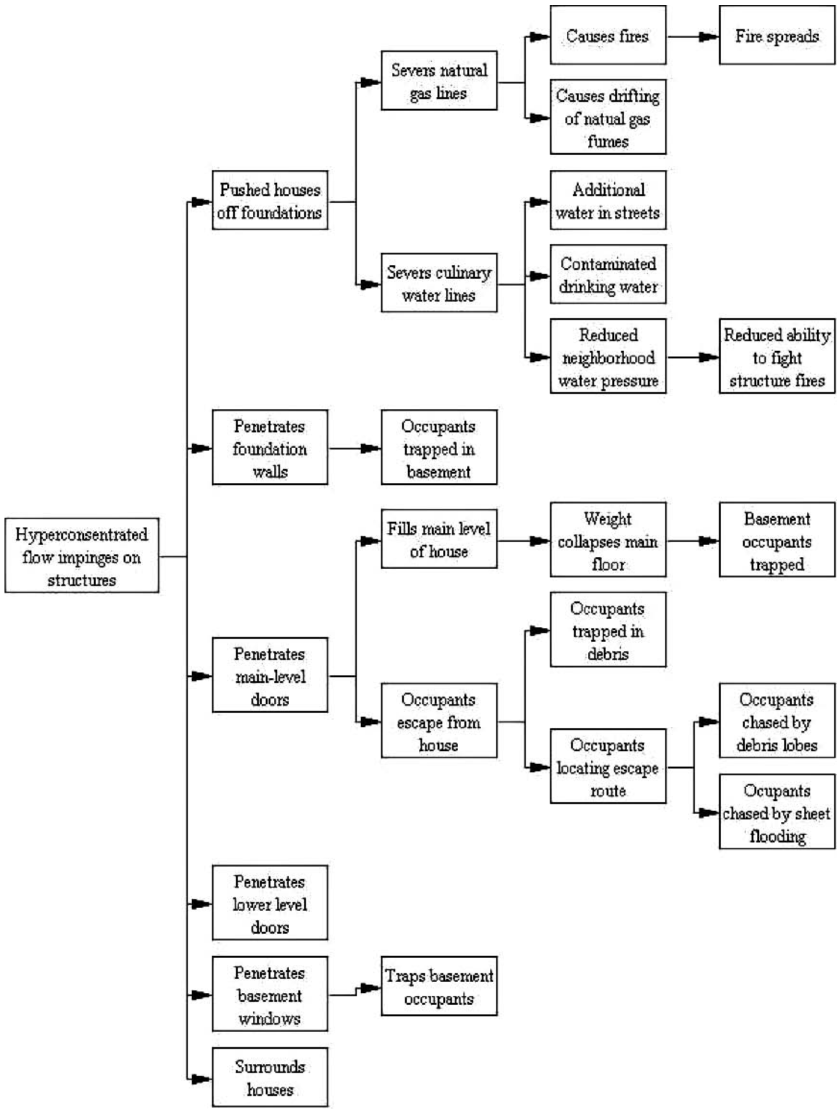


Figure 9—Cascading threat model branch of postburn flash flood stemming from the index tree shown in figure 8.

Branch analysis is useful in determining the variety of sequences that can arise from a single threat node. This could serve as a justification tool for mitigation, which would be an expected objective: to mitigate as many threats as possible with one strategy. Still, the main analytical tools of cascading threat sequences are the single pathways, as the analyst can focus on one particularly interesting or dangerous threat sequence. The single pathway can be displayed, according to the domino explanation provided earlier in this paper, where each threat in a causation sequence has its own degree of damage and degree of consequence. For example, complete damage to a movie theater caused by the flow impinging on the movie theater may have little real consequence for a community, whereas, a small amount of damage to the fire station may have much more consequence. Numerous scenarios of this type (single file pathways) can be identified within the cascading model.

Figure 10—Debris/hyperconcentrated flow causation sequence trapping victims in a basement bedroom.

This single file cascading sequence, shown in figure 10, is a simple three-step pathway regarding water flowing into a basement. As the analyst examines it, however, it becomes apparent that much more study is warranted. Although it is serious enough that adults might be trapped in the basement, one may recognize that children often occupy basement bedrooms and may become victims of the flooding during a night-time postburn flash flood. If the description, in the next section, of the Santaquin, UT, debris flow is correct, that the flow approached silently, then basement rooms would begin filling suddenly with liquefied sediment and other debris without warning. Among debris flow specialists, it is said generally that 6 inches of water flowing over a window well can fill a 10 foot by 10 foot basement room in about 45 seconds, forcing the door closed and making it impossible to open. That being the case, then this single file pathway is worthy of considerable study.

A simple example of an analysis approach for single file pathways is provided in table 2. Notice how the analyst can arrive at a set of mitigation options, addressing each threat in a sequence, and develop an overall mitigation strategy.

Table 2—Example of an analysis approach regarding victims in a basement bedroom.

• Maintain materials for emergency diversion: Prepositioned jersey barriers, straw bales.	• Move children to upstairs bedrooms.	• Use sliding doors for basement rooms.
• Implement home mitigation strategies: deploy sand bags to protect entry points or to divert flows.	• Elevate window wells. • Sandbag window wells. • Board-over window wells. • Fill window wells with bags of gravel to displace water.	• Use delicate door materials that can be easily broken from inside. • Attach basement doors that open in outward direction.
• Build homes at 45 degree angle to uphill slope.	• Construct house without basement windows on uphill side of house.	• Place basement alarms in bedrooms that can be activated by occupants.
• Construct streets in residential area with inverted crowns angled to catch and route flows.	• Use double-pane laminated glass for basement windows.	• Place tools near door so that they are readily available to break door.
• Construct permanent debris basins at apex of flow path.	• Cover window wells with impenetrable plastic shield.	• Remove basement doors until watershed is reestablished.
• Monitor weather, satellite, and Doppler images.	• Tape windows so glass is not easily broken. • Install plastic film to strengthen window panes.	• Place a ladder in occupied rooms.

To conduct such an analysis as shown in table 2, the modeling team of Federal and State hazard and disaster experts meets with a local planning team. The local team being interviewed can view the overall threat model in diagram format (view the tree structure). The analyst leads the local team through the process from branch to branch, even pathway to pathway, determining which branches and pathways have presented problems to the community in the past, or which might present problems in the future. As the local team answers, the analyst types the information into the outline format of the software under each individual threat. The complete interview process, working through an entire model, can take 2 hours, considering that not each threat sequence will apply to the community. Once the analysis is completed with the interview/analysis, then updating the analysis annually will take far less time, based on the local government's interim experience.

To yet advance the analysis into an initial hazard mitigation plan, as the analysis is being conducted, the local team can provide mitigation recommendations as each sequence is discussed. If this is done, then at the end of the analysis, the outline format contains all information provided based on experiences and expectations, and also recommendations for mitigation built within the systematic framework. The overall information can then be transferred to a text document to formulate a hazard mitigation planning document.

Example Scenario: Santaquin, Utah, Postburn Flash Flood

Cascading disaster models are developed based on the real-world experience of interagency technical teams such as the Utah Interagency Technical Team. Since the 1980s, the Utah IAT gained experience working with postburn flash floods of the following locations in Utah: Affleck Park, Emigration Canyon, 1988; Wasatch Mountain State Park, 1991; North Ogden, 1991; Holden, 2000; Orem, 2000; and Farmington, 2003 (State of Utah, Hazard Mitigation Plans). The Mollie Wildfire and postburn flash flood of Santaquin, UT, was an event that was studied in much detail and resulted in much community interaction (fig. 11).

The Santaquin (Utah County) wildfire, named the Mollie Fire, began on August 18, 2001, and produced an 8,000 acre burn directly above the east bench of Santaquin (pop. 4,834). A new development of homes was in proximity to the burn and the wildfire threatened to cause a disaster. Due to the potential for disaster, the fire qualified for a Federal Wildfire Suppression Declaration through the Fire Management Assistance Program of the Federal Emergency Management Agency. By the time the wildfire was contained, it had not burned any homes, due to an excellent fire suppression effort by the State and local fire departments. Some homes had minor damage. At the time of the declaration request, the fire was described as: (1) out of control with conifer vegetation at higher elevations; (2) oak and sage at lower elevations, mixed-in around homes at risk; (3) steep mountain slopes with about 3,000 feet of topographic relief; (4) interspersed rugged canyons; (5) developed areas lie in fire's path within 1 to 3 miles; and (5) threat is to about 900 people and 250 primary residences. In a sense, the entire population on the east side of Interstate 15 was at risk, including 1,315 housing units. These were also at risk from the potential of postburn flash flood. (Mollie Wildfire, BAER Team Report, 2001).

Figure 11—An eastward view across a Santaquin residential area located below a watershed burned by the Mollie Wildfire. The wildfire burned to the ridgeline and the width of the watershed shown here. These residents lived with the daily reminder of a burned watershed and the potential flash flood that could happen with the next thunderstorm or unusual snowmelt.

The composition of an interagency technical team for postburn evaluations for flash flood potential represented several agencies of State and Federal government and enabled the impacted local government to answer most any question and address most any issue. This particular team consisted of the following (Utah Interagency Technical Team ONSITE Report, September, 2001):

- IAT Coordinator, Utah Division of Emergency Services
- Watershed Geologist, USDA. Natural Resources Conservation Service
- Hazards Geologist, Utah Geological Survey
- Engineer/Hydrologist, Division of Water Quality
- Engineer/Hydrologist, Division of Drinking Water
- Engineer/Hydrologist, U.S. Army Corps of Engineers
- Meteorologist, National Weather Service
- Engineer/Hydrologist, USDA Natural Resources Conservation Service, Snow Survey Office

Based on team field assessments, more than 30 field observations were made and those observations resulted in 27 hazard mitigation recommendations relative to wildfire and potential postburn flash flood. This body of knowledge was incorporated into the cascading disaster model for use in future hazard and risk analyses and planning efforts.

In the years following the wildfire, the city of Santaquin experienced two postburn flashfloods. These did not happen immediately after the wildfire, which highlights one of the major challenges of postburn flash flood. Once a watershed is damaged, the threat might remain in effect for up to 6 years while the watershed reestablishes itself. In the meantime, local officials and residents wait for only the possibility of the event.

On the evening of September 12, 2002, just 1 year after the wildfire (August 18, 2001) that damaged 8,000 acres of the watershed above Santaquin, an intense thunderstorm settled onto the watershed. This storm triggered a wildfire related debris flow that damaged houses in the adjacent communities of Spring Lake and Santquin. This debris flow moved and partially buried several automobiles and broke through a wall into a house. It entered other homes through doors of basement windows. Gas meters were torn from their connections, causing leaks and a small fire. Landscaping and property outside of homes were also damaged. The flow also blocked the highline irrigation canal causing additional flooding.

Mayor LaDue Scoville (pers. comm. June 29, 2005) reported that the debris flow that entered the east side of Santaquin entered the neighborhood silently at about dinner time (approximately 6 p.m.). This was unusual in that debris flows have been otherwise described as being noisy, much like the sound of an approaching locomotive. People eating dinner were not aware of the problem until they heard noises of breaking garage doors and the destruction of other doors to their homes. On investigating the sounds, people discovered that mud was flowing in their streets and around their homes. In one case, the mud entered through a main door to the home, breaking it in, and then flowing into the main level. The weight of the mud collapsed the main floor onto the basement, sending a piano through the broken floor. One lady, being forced from her home carrying a baby, was "chased" down the street by the mud flow, but she was able to keep in front of it, escaping. The flowing mix of water and sediment broke through several basement windows filling the basements with the mud. The mayor described the mix as crusty on its surface, but that pressure placed onto it, as with a foot, caused it to turn into a liquid mix and set it to flowing again. The mayor reported that the silent approach of the debris flow made it potentially lethal. Fortunately the debris flow happened early in the evening before people were in bed. The mix filled basement rooms quickly. Had children, or adults, been in basements they likely would have been trapped and killed. This has been a message of emergency managers for at least a decade, that debris flows can fill a basement bedroom in less than a minute, pushing the bedroom door closed and applying such weight as to make it nearly impossible to escape.

No fatalities or injuries occurred, which Mayor Scoville explained as a miracle. The flow surrounded houses and blocked streets, even partially burying automobiles, making it difficult to escape. He explained further that the "liquid mix" remained liquid for days, sealing itself and preventing evaporation of the water. When the city attempted to haul the mix away it liquefied and ran out of the scoops of front end loaders and oozed out the rear gates of dump trucks. This was such a problem that the Utah Department of Transportation would not allow the city to haul the mix on State roads, as it would flow out of the trucks and onto the highway. For several days after the city disposed of the mix in a field, it maintained this fluid consistency.

The city Public Works Director, David Banks, indicated that the debris flow pushed one house off its foundation and separated the natural gas line from the house, causing a leak. The gas company shut off the gas to that neighborhood, but gas remained in the lines. As city workers were digging in the area, underground power lines still had electricity running through them. Excavation by city workers could have severed gas or electrical lines and resulted in electrocution, fire, or explosion; fortunately, such an event did not happen.

Conclusions

Natural disasters are natural systems and happen as cascading causation sequences, and these sequences can be documented using computer software as cascading disaster models. These models can be analyzed according to their branches and single-file pathways. This is a systems approach to analyzing disasters. The opposing method is called the fragmented approach where hazard or disaster concerns to be addressed in assessments are studied from lists and tables. Any technique involving a systems approach should be included in an aspect of disaster science called disaster systematics. It is also proposed that disaster analysts develop and use cascading disaster models when conducting hazard and risk analyses. It is also proposed that fragmented approaches to studying disasters be largely abandoned as they can lead to neglecting dangerous threats that may lie hidden within a disaster system (cascading models).

Although, in this paper, wildfire and postburn flash floods are provided as simplified cascading threat models, the reader's imagination would certainly suggest that complete models can be highly sophisticated/complex based on technical team inputs and model design. The associated analyses would likewise be rather sophisticated if performed by technical teams. Detailed and systematic hazard and risk analyses can be developed with a local government in about 2 hours per hazard (for example: local wildfire hazard and risk assessment), and a mitigation plan with recommendations can also be developed simultaneously.

The example herein makes a strong case for the elimination or greater protection of basement occupancy on alluvial fans below wildfire burn areas, or potential burn areas. The Santaquin, UT, postburn flash flood happened much like other such postburn flash flood events that threaten mountain-front communities. Wildfires are on the increase as development increases in urban wildland interface areas, and postburn flash floods will likely increase as well, similar to the disaster event sequences presented in the Santaquin case. Given the increasing level of vulnerability it would seem necessary from a public safety perspective to examine complete disaster systems rather than fragments of systems (fragmented systems).

References

Ashcroft, Gaylen; Jensen, Donald; Brown, Jeffrey. 1992. Utah Climate. Logan, UT: Utah State University, Utah Climate Center.

Cannon, Sylvester Q. 1930. Torrential Floods in Northern Utah, 1930. Circular 92. Logan, UT: Utah Agricultural Experiment Station, Special Flood Commission.

Case, William. Debris Flow Hazards. Public Information Series 70. Salt Lake City, UT: Utah Geological Survey.

City of Centerville, Geographic Information System, Alluvial Fan Map.

Cornell, Gary. 1992. Urban/Wildland Interface Fires. In: Utah Natural Hazards Handbook. Salt Lake City, UT: Utah Division of Comprehensive Emergency Management, Utah Interagency Technical Team: 23-28.

Dewsnup, Wes. 2006. Pers. comm. concerning origin of multihazard concept through the Utah Multi-Hazard Project, 1982.

Federal Emergency Management Agency. 1982. National Flood Insurance Program, Floodway, City of Layton, Utah (Davis County); Flood Boundary and Floodway Map.

Federal Emergency Management Agency. 1991. National Flood Insurance Program, Flood Insurance Rate Map, City of Bountiful, Utah (Davis County).

Federal Emergency Management Agency. 1991. National Flood Insurance Program, Flood Insurance Study, City of Bountiful, Utah (Davis County). Revised September 27.

Federal Emergency Management Agency. 1992. National Flood Insurance Program, Flood Insurance Study, City of Centerville, Utah (Davis County). Revised, February 19.

Federal Emergency Management Agency. 1992. National Flood Insurance Program, Flood Insurance Study, City of Farmington, Utah (Davis County). Revised: December.

Federal Emergency Management Agency. 1981. National Flood Insurance Program, Flood Insurance Study, City of Kaysville, Utah (Davis County).September.

Federal Emergency Management Agency. 1982. National Flood Insurance Program, Flood Insurance Study, City of Layton, Utah (Davis County). December.

Federal Emergency Management Agency. 1982. National Flood Insurance Program, Flood Insurance Study, City of North Ogden, Utah (Weber County). July 19.

Hatch, Orrin G. 2001. Hatch Announces $1,250,000 in Federal Relief Grants to Help Citizens of Santaquin, Utah Against a Major Flood Threat. United States Senator, News Room, News Items from the Senator. September 27, 2001.

May, Fred. 2005. Cascading Threat/Impact Model Applications Wildfire/Post-Burn Mudflows, Wasatch Front, Utah. Abstract and Conference Presentation. July 18-20, 2006. Boulder, CO.

May, Fred. 2005. Cascading Disaster Model – Post-Burn Mudflows, Wasatch Front, Utah, International Conference on Energy, Environment, and Disaster (INCEED), Charlotte, SC, Conference Presentation, Abstract and Paper on Conference Program CD, July 24-30, 2005. 44 p.

May, Fred. 1992. Introduction, in Utah Natural Hazards Handbook. Salt Lake City, UT: Utah Division of Comprehensive Emergency Management, Interagency Technical Team: 1.

May, Fred. 2001. Interagency Technical Team, ONSITE Report, Santaquin, Utah County, Postburn Flash Flood Evaluation No. 1. September 2.

McDonald, Greg; Giraud, Richard. 2002. September 12, 2002, fire-related debris flows east of Santaquin and Spring Lake, Utah County, Utah. Technical Report 02-09. Salt Lake City, UT: Utah Geological Survey.

National Research Council. 1991. A Safer Future, Reducing the Impacts of Natural Disasters. U.S. National Committee for the Decade for Natural Disaster Reduction, National Academy Press.

O'Brien, Jimmy. 1990. Flood Hazard Delineation on Alluvial Fans and Urban Floodplains. Breckenridge, CO: Lenzotti & Fullerton Consulting Engineers, Inc.

Pickler, Nedra. 2006. Disaster Costs to Swell U.S. Budget. Associated Press. September 16.

U.S. Census. 2000. City of Layton, Utah. Fact Sheet. http://factfinder.census.gov/servlet/SAFFFacts?_event=&geo_id=16000US4943660&_geoContext=01000US%7C04000US49%7C16000US4943660&_street=&_county=Layton&_cityTown=Layton&_state=04000US49&_zip=&_lang=en&_sse=on&ActiveGeoDiv=&_useEV=&pctxt=fph&pgsl=160

Rasely, R.C. 2001. Emergency watershed protection – Mollie fire hazards impacting Santaquin, Utah County, Utah. Unpublished report. Salt Lake City, UT: Natural Resources Conservation Service report to Neil Pellman, State Conservation Engineer. 4 p., 5 attachments.

Richardson, Arlo E. 1971. Estimated Return Periods for Short-Duration Precipitation in Utah. Bulletin No. 1. Logan, UT: Utah State University, Department of Soils and Biometeorology.

Whitworth, Paul; May, Fred. 2006. Disaster Planning For Recreation Areas Via Cascading Models. Special Issue Introduction: The Role of Public Parks and Recreation in Urban Area Homeland Security. Journal of Parks and Recreation. Winter, Vol. 24, no. 4: 1-21.

Assessing the Effectiveness of Seeding and Fertilization Treatments for Reducing Erosion Potential Following Severe Wildfires

David W. Peterson[1], Erich K. Dodson[1], and Richy J. Harrod[2]

***Abstract**—Postfire slope stabilization treatments are often prescribed following high-severity wildfires on public lands to reduce erosion, maintain soil productivity, protect water quality, and reduce risks to human life and property. However, the effectiveness of slope stabilization treatments remains in question. For this study, tests were on effectiveness of seeding and fertilization treatments for increasing total live plant cover and reducing percent bare soil during the first 2 years following wildfire in dry mixed-conifer forests of north-central Washington State. Assessments were made on the effects of four seeding treatments (none, two perennial species mixes, and a winter wheat monoculture) and three fertilization levels (0, 50, and 100 lb N/acre) in factorial combination on percent bare ground, and plant cover using a generalized randomized complete block design at eight sites. Half of the sites also received aerially applied straw mulch. Surveys of vegetation responses during the first two summers following fire showed that seeding, fertilizing, and straw mulching all significantly influenced bare ground and/or live plant cover. Fertilizing alone increased mean live plant cover by 4 to 9 percent in 2005, and by 8 to 12 percent in 2006. Seeding alone increased mean live plant cover by only 1 to 2 percent in 2005 and 0 to 3 percent in 2006. Fertilizing and seeding together increased plant cover by up to 11 percent in 2005 and 20 percent in 2006 and reduced bare ground by up to 13 percent in 2005 and by 21 percent in 2006. Of the seeded species, two native perennial forbs, yarrow (*Achillea millifolium*) and fireweed (*Chamerion angustifolium*), contributed the most to total plant cover. Straw mulching increased litter cover by 10 to15 percent, but had little effect on live plant cover. Our results suggest that fertilization treatments can increase the effectiveness of seeding treatments and stimulate regrowth of surviving native vegetation following wildfires, particularly in forest types with understory vegetation dominated by species that resprout following fire. More work is needed to determine appropriate levels of fertilization and to better identify species and environmental factors that produce better results for seeding treatments.*

In: Butler, Bret W.; Cook, Wayne, comps. 2007. The fire environment—innovations, management, and policy; conference proceedings. 26-30 March 2007; Destin, FL. Proceedings RMRS-P-46CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 662 p. CD-ROM.

[1] Research Forester and Ecologist, respectively, U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Wenatchee, WA. Lead author at davepeterson@fs.fed.us

[2] Deputy Fire Management Officer, U.S. Department of Agriculture, Forest Service, Okanogan-Wenatchee National Forests, Wenatchee, WA.

Introduction

Controlling erosion and water runoff are important objectives for land managers following severe wildfires. High severity wildfires kill vegetation and consume surface organic matter, exposing mineral soils to increased erosion, particularly during intense rainfall events (DeBano and others 1998; Neary and others 2005; Wondzell and King 2003). Fires can also increase hydrophobicity in soils, thereby reducing water infiltration rates and increasing surface runoff, soil erosion, and sediment delivery to streams (Benavides-Solorio and MacDonald 2001; DeBano 2000). These fire-induced effects on soil erosion and water runoff typically diminish as vegetation recovers and replaces lost plant and litter cover (Benavides-Solorio and MacDonald 2001).

Although elevated levels of soil erosion and water runoff are natural ecosystem responses to severe wildfire, they can present unacceptable hazards to human health and property in lower parts of the affected watersheds. Increased sediment delivery to streams and/or loss of forest productivity may also be undesirable, even if human interests are not threatened, if fires are deemed uncharacteristically severe due to previous management activities (such as logging or fire suppression). To reduce erosion and flooding hazards and protect natural resources, land surface treatments are often applied on Federal forest and range lands following wildfires as part of burned area emergency response (BAER) or emergency stabilization and rehabilitation (ESR) efforts (Robichaud and others 2000).

Land surface treatments to reduce erosion and runoff can include seeding, fertilizing, and mulching. Seeding treatments seek to increase plant cover by promoting establishment of new plants, typically from fast-growing species and readily available seed stocks. Fertilization treatments seek to enhance growth and litter production of surviving and newly established plants by enhancing soil nutrient availability. Mulching seeks to directly replace surface organic matter while having little or no effect on vegetation recovery.

Annual costs for BAER/ESR land treatments have increased in recent years due to increased areas burned by high severity wildfires, increased postfire threats to human health and property due to expansion of the wildland-urban interface, and increasing use of costly mulching treatments. Despite escalating expenditures and widespread use, rigorous testing and monitoring of BAER rehabilitation treatments have seldom occurred (Robichaud and others 2000; Government Accountability Office 2003), making it more difficult for agencies to justify continued expenditures.

In this study, we used an experimental approach to examine the effects of seeding and fertilization treatments on plant cover and bare soil at eight sites within the Pot Peak Fire (2004) in the eastern Cascade Range of Washington State. The effects of mulching are also documented as mulch was operationally applied at half of the sites. Study objectives related to this report included:

1. Quantify the effects of seeding, fertilizing, and mulching on vascular plant cover and bare soil cover for 2 years following wildfire.
2. Assess differences among sites in rates of native vegetation recovery and treatment effectiveness after wildfire.

Methods

Study Site

The Pot Peak-Sisi Ridge wildfire complex burned 47,000 acres of coniferous forest along the southwestern shore of Lake Chelan in north-central Washington State during summer 2004. About 45 percent of the area burned was classified as moderate to high severity fire with respect to soil effects, and erosion hazards were considered high for about 90 percent of the total area burned due to combined effects of fire, topography, and soils. Much of the area burned by the Pot Peak Fire, which was the subject of this study, had previously burned in a large wildfire in 1970.

Forests within the Pot Peak Fire area are dominated by ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziesii*) at lower elevations and by lodgepole pine (*Pinus contorta*), Douglas-fir, and subalpine fir (*Abies lasiocarpa*) at higher elevations. Soils generally consist of volcanic ash and pumice deposited over colluvium or glacial till. The climate features warm, dry summers and cold, relatively wet winters. The majority of precipitation falls from October to March (much of it as snow), with occasional intense summer thunderstorms.

We selected eight study sites within areas of moderate and high fire severity, as identified by fire severity maps. The sites were well dispersed and represented a broad range of environmental settings (table 1). At each site, we identified a relatively uniform area of about 1 ha on which we established a grid of 96 study plots. Each plot was 4 m wide and 10 m long, with the long side oriented downslope. We left a 2-m wide untreated buffer between plots to reduce risks of across-plot contamination.

Table 1—Site characteristics for Pot Peak Study, including topographic setting (slope, aspect, and elevation), fire severity (soil effects), operational mulching treatment, mean total plant cover (percent) and shrub cover (percent) on untreated control plots.

Site	Slope (%)	Aspect (°)	Elevation (m)	Fire severity	Mulch†	Plant cover in 2005 (%)	Shrub cover in 2005 (%)
Hug me	35	280	1196	Moderate	No	40	27
Mouse	47	305	1221	High	Yes	9	9
Rainbow	57	360	1297	High	Yes	21	10
Stairway	45	325	1313	Moderate	No	14	13
Beast	68	90	1321	High	Yes	27	25
Big Tree	45	320	1380	High	Yes	3	2
Nice View	12	20	1393	Moderate	No	19	14
Squirrel	43	345	1507	High	No	7	5

† Denotes if mulch was operationally applied to the site.

Treatments

We tested the effects of four seeding treatments and three levels of fertilization in factorial combination on plant cover and bare soil at each site. Seeding treatments included a "warm" seed mix with three grasses and one forb species expected to do well in warmer and drier sites; a "cool" seed mix with two grasses and one forb species expected to do better on cooler and more moist sites; a monoculture of soft white winter wheat (Eltan) that is often prescribed as an operational treatment in this area; and a control treatment with no seeding (table 2). Most of the seeded species were natives (table 2), but local seed sources were not required. We designed the seeding treatments to provide an average of 60 seeds/ft^2 for the cool seed mix (20 seeds/ft^2/species) and the warm seed mix (15 seeds/ft^2/species), and an average of 15 seeds/ft^2 for the winter wheat treatment. By comparison, the local operational seeding treatment with winter wheat called for only six live seeds/ft^2. For the fertilization treatments, we applied an ammonium nitrate-ammonium sulfate (30-0-0-6) fertilizer mix at quantities calculated to provide 0, 50, or 100 lb of nitrogen per acre. The local operational treatment called for fertilizing at a rate of 50 lb N/ft^2. We applied both seed and fertilizer with a hand-held Whirlybird spreader, attempting to produce a relatively uniform application rate. Treatments were applied shortly after snowmelt in the spring following the wildfire.

Table 2—Seeded species information for the Pot Peak Study.

Scientific name	Seed mix	Common name	Lifeform	Origin
Achillea millefolium	Warm	common yarrow	Forb	Native
Chamerion angustifolium	Cool	fireweed	Forb	Native
Elymus lanceolatus	Cool	thick-spike wheatgrass	Grass	Native
Elymus wawawaiensis	Warm	Snake River Wheatgrass	Grass	Native
*Festuca idahoensis**	Cool	Idaho fescue	Grass	Native
*Festuca ovina**	Warm	sheep fescue	Grass	Exotic
*Poa secunda**	Warm	Sandberg bluegrass	Grass	Native
Triticum aestivum	Wheat	common wheat	Grass	Exotic

*Due to difficulties in identification of young plants, *Festuca* and *Poa* species were identified to genera only

In addition to the experimental treatments, four of the sites received aerial application of wheat straw mulch as part of a larger BAER treatment. Contractors applied the mulch by dropping loose bales of straw from helicopters in the fall (shortly after the wildfire) and spring. Although mulching was not an experimentally applied treatment, we made use of spatial heterogeneity in straw cover and depth to evaluate its effectiveness for reducing bare soil cover and its potential effects on vegetation recovery and vegetation responses to seeding and fertilization treatments.

Experimental Design

We used a generalized randomized block design for the study. We randomly assigned treatments in factorial combination so that each possible combination of fertilization and seeding treatments would be replicated eight times per site. Implementation errors on three sites led to as many as 10 replicates or as few as seven replicates for some treatment combinations; however, we still replicated each fertilization treatment 32 times and each seeding treatment 24 times on each site.

Data Collection and Summary

We collected plot data during midsummer (July to August) in 2005 and 2006, when total live plant cover was near its annual maximum. At each plot, we estimated relative cover for each plant species present, as well as cover of bare ground (soil), litter, mulch (straw), woody debris (10 hour fuels and larger), cryptogams, and rock for portions of the plot not covered by live vascular plants so that total cover summed to 100 percent. All cover estimates were based on visual assessment of what a raindrop would hit if falling straight down. In the case of overlapping vegetation, cover was attributed to the taller species. Similarly, plant cover took precedence over litter and so on. We estimated cover values to the nearest whole percent for values over 0.5 percent, and recorded values less than 0.5 percent as "trace" amounts (using a constant value of 0.2 percent cover for subsequent analyses). We summed species cover values to obtain total plant cover for each plot.

Statistical Analyses

Prior to analysis, we chose a Type I error rate of 10 percent ($P < 0.10$) as an acceptable threshold for statistical significance. We accepted a higher error rate than is traditional because we believe that managers are primarily interested in estimated effect sizes and would likely accept a higher false-positive error rate if the potential treatment benefit is high.

We analyzed the effects of seeding, fertilizing, and mulching on bare soil and total plant cover in 2005 and 2006 using mixed statistical models (SAS PROC MIXED, Littell and others 1996). We included the seeding treatment, fertilization treatment, and their interactions as categorical fixed factors in the statistical model, and mulch cover (as measured in 2005) as a continuous covariate. Because plots were measured in two consecutive years, we included "year" as a binary time variable, coding 2005 observations as zero and 2006 observations as one. We also included year-by-treatment interaction terms in the model to test for differences in seeding and fertilization effects between 2005 and 2006. We included "site" and site-by-treatment interactions as random effects at the site level, where at least marginally significant ($P < 0.10$), to test for site effects on mean plant cover (or bare soil) and/or treatment effects. We also included the plot (within site) as a random effect to account for correlations among the repeated measurements. Plant cover data required the use of a square-root transformation to normalize model residuals.

Results

Fertilization significantly increased mean live vascular plant cover during the first two growing seasons following the 2004 Pot Peak wildfire. On untreated control plots, plant cover averaged 15 percent in the first year and 27 percent in the second year. Fertilization alone increased mean plant cover in the first year from 15 percent on controls to 19 percent at 50 lb N/acre and to 24 percent at 100 lb N/acre (fig. 1). During the second year following fire, fertilization increased mean plant cover from 27 percent on untreated control plots to 34 percent on plots receiving 50 lb N/acre and 39 percent on plots receiving 100 lb N/acre (fig. 1). First year fertilization effects were maintained into the second year, but there was no consistent evidence for additional fertilization effects in the second year; there was, however, considerable variability among sites in this regard (see below).

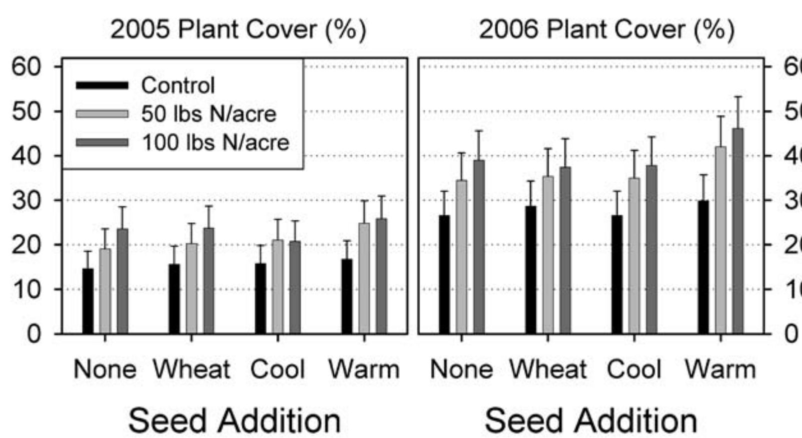


Figure 1—Effects of seeding and fertilization, and their interaction on live plant cover during the first two growing seasons following wildfire (2005 and 2006). Error bars indicate standard errors for the estimated treatment means.

Seeding treatments also increased live vascular plant cover, but the effects were relatively small. Without fertilization, mean plant cover in the first year increased from 15 percent on unseeded controls to 16 percent on plots receiving the winter wheat or cool seed mix and to 17 percent on plots receiving the warm seed mix (fig. 1). In the second year, plant cover averaged 27 percent on untreated controls and plots receiving the cool species mix, 29 percent on plots receiving the wheat seed, and 30 percent on plots receiving the warm species mix (fig. 1).

The most effective treatment combination included seeding with the warm species mix and fertilizing with 100 lb N/acre; it produced a net increase in mean plant cover of 11 percent in 2005 and 21 percent in 2006 (fig. 1). Interactions between the seeding and fertilization treatments were statistically insignificant, indicating that treatment effects on live plant cover could be treated as being additive.

By increasing live plant cover, fertilization and seeding reduced percent cover of bare soil during the first 2 years following fire (2005 and 2006). For plots without active seeding, fertilization reduced average percent bare soil in the first year from 76 percent on unfertilized plots to 71 percent on plots receiving 50 lb N/acre and to 66 percent on plots receiving 100 lb N/acre (fig. 2). In the second year, fertilization reduced bare soil from 56 percent on unfertilized plots to 44 and 39 percent at 50 and 100 lb N/acre, respectively. Unlike plant cover, fertilization produced an additional effect on bare soil in the second year after fire, as indicated by a significant year-fertilization interaction (table 3). Both active fertilization treatments produced an additional net reduction of about 7 percent bare soil in the second year, relative to controls.

As with live plant cover, seeding treatments produced only a small reduction in bare soil in the first year after fire, and no significant additional effect in the second year after fire. Individually, seeded species varied considerably in their effectiveness, although most added little cover. Of all the seeded species, yarrow (*Achillea millifolium*) appeared to be the most effective for increasing plant cover and reducing bare soil. Statistical tests found no evidence for any significant interactions between seeding and fertilization treatments.

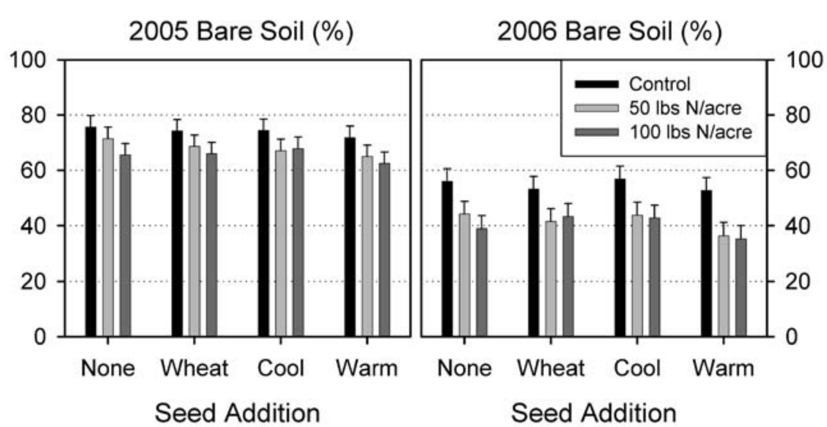


Figure 2—Effect of seeding and fertilization, and their interaction on bare soil cover during the first two growing seasons following wildfire. Error bars indicate standard error for the estimated treatment means.

Table 3—Type 3 tests of significance tests for fixed effects in mixed model analysis of treatment effects on live vascular plant cover.

Fixed effects	Num DF	Den. DF	F-value	Pr. > F
Live vascular plant cover:				
Seeding	3	1168	6.57	**0.000**
Fertilizing	2	15	29.98	**0.000**
Seeding x Fertilizing	6	1168	1.59	0.147
Year	1	7	99.09	**0.000**
Year x Seeding	3	736	1.37	0.251
Year x Fertilizing	2	15	0.67	0.526
Year x Seeding x Fertilizing	6	736	1.62	0.140
Mulching	1	1177	3.01	**0.083**
Year x Mulching	1	743	2.22	0.137
Bare soil cover:				
Seeding	3	1257	4.28	**0.005**
Fertilizing	2	1257	30.42	**0.000**
Seeding x Fertilizing	6	1257	0.75	0.609
Year	1	7	192.81	**0.000**
Year x Seeding	3	33	1.16	0.339
Year x Fertilizing	2	17	5.80	**0.012**
Year x Seeding x Fertilizing	6	717	1.03	0.403
Mulching	1	1246	616.10	**0.000**
Year x Mulching	1	703	117.32	**0.000**

Mulching reduced bare soil cover by 10 to 15 percent in the first year after fire on the four sites receiving the operational mulching treatment. Vegetation cover increased slightly with increasing mulch cover in the first year after fire ($P = 0.083$) but was not affected by mulching the following year.

Site factors significantly influenced first year live plant cover and second year fertilization effects. First year live plant cover varied from 4 to 37 percent and mean bare soil cover varied from 57 to 91 percent (table 1). Fertilization treatment effects on bare soil did not vary significantly among sites in the first year ($P > 0.10$) but did vary significantly in the second year ($P = 0.02$). From 2005 to 2006, reductions in bare soil on unseeded plots ranged 12 to 26 percent at 0 lb N/acre, 21 to 33 percent at 50 lb N/acre and 16 to 31 percent at 100 lb N/acre. Seeding treatment effectiveness did not vary significantly among sites.

Discussion

Fertilization Effects

We found that fertilization accelerated the development of live plant cover following severe wildfire, thereby reducing bare soil cover and, presumably, water runoff and soil erosion. Fertilization effects varied with treatment intensity (0 to 100 lb N/acre), with the 100 lb N/acre treatment increasing plant cover more than the 50 lb N/acre treatment. This indicates that soil N availability was at least partially limiting native vegetation recovery after the Pot Peak wildfire and suggests that higher levels of fertilization may have produced even larger increases in plant cover.

We expected fertilization effects to be greatest on sites with high densities (or cover) of sprouting shrubs and other fire-adapted species that could rapidly take up and use the additional nutrients. However, we found no evidence to support this notion. Fertilization effects were not significantly correlated with first-year plant cover or bare soil, suggesting that plant uptake capacity did not limit the effectiveness of the fertilization treatments, at least on these sites and at these fertilization levels. With only eight sites, however, our power to detect site differences in treatment effects was limited, and there was some evidence to suggest that fertilization effects declined somewhat at higher levels of plant cover.

Fertilization as an erosion control treatment has received little study, and, where it has been studied, results have been mixed (Robichaud and others 2000). In the Interior Pacific Northwest, Klock and others (1975) reported that fertilization increased establishment and cover of species seeded for erosion control. More recently, Robichaud and others (2006) found that fertilization increased total plant cover after the North 25 Fire (close to our study site), with plant cover on fertilized plots being 8 percent higher during the first year after fire and 13 percent higher during the second year, though these effects were not judged to be statistically significant. In Colorado, nutrients applied after wildfire in the form of biosolids also increased plant cover and biomass (Meyer and others 2004).

Results from this study suggest that fertilization could be an effective method for accelerating development of live plant and litter cover and reducing erosion hazards following wildfires. Further study is needed to test the possible additional benefits of higher levels of nitrogen addition, and to test the potential benefits of adding other nutrients, such as phosphorous and potassium. Implementation on sites with diverse soil, climate, and vegetation characteristics would also be helpful to assess the consistency of fertilization effects.

Seeding Effects

Compared to natural vegetation recovery and fertilizer effects, seeding treatment effects on live plant cover and bare soil were small. Some other studies have found seeding to be ineffective at increasing ground cover or reducing erosion (Wagenbrenner and others 2006; Robichaud and others 2006). Yet, there are also examples where seeding has produced larger amounts of cover after wildfire, even to the point of negatively affecting recovery of native vegetation (Beyers 2004; Keeley 2004; Schoennagel and Waller 1999).

Developing a better understanding of the causes of this variability in seeding success is important if seeding is to continue as a land surface treatment. Some variability may be due to uncontrollable variables such as year-to-year variability in precipitation and soil moisture. However, more consistent results may also be attained if seeded species were better matched with biophysical environments or, perhaps, if seeding were restricted to environments where it is generally successful. In this study, yarrow provided greater benefits than winter wheat, the normally prescribed seeding treatment. Is this because yarrow is better adapted to the biophysical settings, established better on burned soils, produced faster initial growth, was less susceptible to seed predation, or all of the above? The answer is unclear. However, further study appears warranted to identify species for seeding that perform consistently well, or to better match seeded species to the environments in which they can be expected to perform well. It will also be important to address questions about tradeoffs between the practical advantages of seeding highly available nonnative species and possible biodiversity benefits of seeding native species (from either local or distant seed sources).

Mulching Effects

Mulching was effective at reducing bare soil cover during the first year after fire, as has been documented previously (Robichaud and others 2000). Our analysis indicated that mulching reduced bare soil cover at a rate that slightly exceeded the rate of mulch application, perhaps due to germination and growth of residual wheat seed in the straw. A potential problem with mulching is that it may affect long-term vegetation recovery by introducing exotic species (Kruse and others 2004) or interfering with plant establishment (Robichaud and others 2000). We found no evidence that mulching reduced live plant cover in either year. However, mulch cover was low overall in this study (less than 15 percent average cover on mulched sites) and may have been below the threshold needed to influence plant cover. We have not yet examined possible mulching effects on plant community composition or exotic species.

Site Variability

In the absence of treatments, first year plant cover is determined by pre-fire plant cover and fire severity (in terms of mortality). In this study, first year plant cover was highly dependent on sprouting shrubs and, on one site, grasses. Understory plant cover generally declined with increasing elevation, probably because lower elevation sites had lower overstory canopy densities that supported higher understory plant cover and biomass before the fire. Low elevation plant communities may also be better able to survive wildfires. Causes for variability in site responses to fertilization are not yet clear but are certainly of interest. We are hopeful that clearer patterns of variation in treatment effectiveness will emerge in the future as results from similar studies on other wildfire areas become available.

Conclusions

Fertilization is a potentially effective treatment for increasing plant cover and reducing bare soil during the first 2 years following wildfire, but more work is needed to determine optimal application rates, formulations, and variability in effectiveness across a range of climates, fire severities, and soil and vegetation types. Seeding was not very effective in this study, suggesting that it may not be the best choice for erosion control in this area. The performance of yarrow, however, suggests that seeding effectiveness may be improved by choosing different species or species mixtures for seeding. Mulching significantly reduced bare soil cover, but it is not clear whether the reductions in erosion risk were large enough to justify the high application costs and elevated risks of exotic species introduction.

References

Benavides-Solorio, Juan; MacDonald, Lee H. 2001. Post-fire runoff and erosion from simulated rainfall on small plots, Colorado Front Range. Hydrological Processes 15:2931-2952.

Beyers, Jan L. 2004. Postfire seeding for erosion control: effectiveness and impacts on native plant communities. Conservation Biology 18(4):947-956.

DeBano, Leonard F. 2000. The role of fire and soil heating on water repellency in wildland environments: a review. Journal of Hydrology 231-232:195-206.

DeBano, Leonard F.; Neary, Daniel G.; Ffolliott, Peter F. 1998. Fire's effects on ecosystems. New York: John Wiley and Sons.

Government Accountability Office. 2003. Wildland fires: better information needed on effectiveness of emergency stabilization and rehabilitation treatments. Report GAO-03-430.

Keeley, Jon E. 2004. Ecological impacts of wheat seeding after a Sierra Nevada wildfire. International Journal of Wildland Fire 13:73-78.

Klock, Glenn O.; Tiedemann, Arthur R.; Lopushinsky, William. 1975. Seeding recommendations for disturbed mountain slopes in north central Washington. Res. Note PNW-RN-244. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 8 p.

Kruse, Renee; Bend, Eric; Bierzychudek, Paulette. 2004. Native plant regeneration and introduction of non-natives following post-fire rehabilitation with straw mulch and barley seeding. Forest Ecology and Management 196:299-310.

Littell, Ramon C.; Milliken, George A.; Stroup, Walter W.; Wolfinger, Russell D. 1996. SAS® system for mixed models. Cary, NC: SAS Institute, Inc.

Neary, Daniel G.; Ryan, Kevin C.; DeBano, Leonard F., eds. 2005. Wildland fire in ecosystems: effects of fire on soil and water. Gen. Tech. Rep. RMRS-GTR-42-vol. 4. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 250 p.

Robichaud, Peter R.; Beyers, Jan L.; Neary, Daniel G. 2000. Evaluating the effectiveness of post-fire rehabilitation treatments. Gen. Tech. Rep. RMRS-GTR-63. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 85 p.

Robichaud, Peter R.; Lillybridge, Terry R.; Wagenbrenner, Joseph W. 2006. Effects of postfire seeding and fertilizing on hillslope erosion in north-central Washington, USA. Catena 67:56-67.

Schoennagel, Tania L.; Waller, Donald M. 1999. Understory responses to fire and artificial seeding in an eastern Cascades *Abies grandis* forest, U.S.A. Canadian Journal of Forest Research 29:1393-1401.

Wagenbrenner, J.W.; MacDonald, L.H.; Rough, D. 2006. Effectiveness of three post-fire rehabilitation treatments in the Colorado Front Range. Hydrological Processes 20:2989-3006.

Wondzell, Steven M.; King, John G. 2003. Postfire erosional processes in the Pacific Northwest and Rocky Mountain regions. Forest Ecology and Management 178:75-87.

Fire and Fire Surrogate Treatments in Mixed-Oak Forests: Effects on Herbaceous Layer Vegetation

Ross Phillips[1], Todd Hutchinson[2], Lucy Brudnak[1], and Thomas Waldrop[1]

***Abstract**—Herbaceous layer vegetation responses to prescribed fire and fire surrogate treatments (thinning and understory removal) were examined. Results from 3 to 4 years following treatment are presented for the Ohio Hills Country and the Southern Appalachian Mountain sites of the National Fire and Fire Surrogate Study. At the Ohio Hills site, changes in forest structure were observed for all treatments, but areas treated with fire showed the greatest increase in herbaceous cover and species richness. These results indicate that fire effects are unique disturbances that are not mimicked by alterations of the forest structure alone. However, at the Southern Appalachian site, fire alone did not produce a response in the herbaceous layer. The combination of fire plus mechanical treatment was necessary to increase cover and species richness.*

Introduction

The herbaceous layer in oak forests typically contains the greatest number of species with perennial forbs and grasses composing the majority of diversity. Many of these species respond positively to disturbance through increased growth, sexual reproduction, and asexual propagation (Whigham 2004). With the exclusion of fire and consequently increased stand density, suitable seedbed habitat and available light become limiting factors for herbaceous species propagation and survival. Eliminating fire disturbance has allowed fire-sensitive, shade-tolerant species to become established leading to changes in forest composition and structure (Abrams 1992; Abrams and Nowacki 1992; Crow 1988; Lorimer 1984; Nowacki and Abrams 1991; Schuler and Gillespie 2000).

The use of prescribed fire in these forests has increased in recent years in efforts to reduce fuel loadings, encourage oak regeneration, and halt the conversion of these stands to forests dominated by mesophytic species. In Ohio, acreage treated with prescribed fire grew from less than 2,000 to almost 20,000 acres from 2001 to 2004 (Mike Bowden, personal communication). Thinning has also been suggested as an alternative method for creating stand structure to promote and sustain oak dominance. While oak regeneration and woody species composition have received considerable attention (for example, Abrams 1992; Albrecht and McCarthy 2006; Barnes and Van Lear 1998; Brose and others 1999, 2006; Elliott and others 2004; Lorimer 1985; Reich and others 1990), only recently has research focused on the herbaceous layer in mixed-oak forest types.

In: Butler, Bret W.; Cook, Wayne, comps. 2007. The fire environment—innovations, management, and policy; conference proceedings. 26-30 March 2007; Destin, FL. Proceedings RMRS-P-46CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 662 p. CD-ROM.

[1] Ecologist, Biological Sciences Technician, and Research Forester, respectively, U.S. Department of Agriculture, Forest Service, Southern Research Station, Clemson, SC. Lead author at rjphillips@fs.fed.us

[2] Research Ecologist, U.S. Department of Agriculture, Forest Service, Northeastern Research Station, Delaware, OH.

Previous studies in oak dominated forests indicate herbaceous cover and abundance typically increase following fire (Elliott and others 1999; Hutchinson 2006; Hutchinson and others 2005), whereas fire effects on diversity vary. Burning may have little effect on diversity (Dolan and Parker 2004; Franklin and others 2003; Hutchinson and others 2005; Kuddes-Fischer and Arthur 2002), or it can significantly increase herbaceous layer diversity (Ducey and others 1996; Elliott and others 1999; Taft 2003). It should be noted the latter studies were conducted in stands that had lower basal area and/or experienced higher intensity fires, suggesting that more intense management than low-intensity burning is required (Abrams 2005; Franklin and others 2003; Ruffner and Groninger 2004).

Many herbaceous species are light limited. Therefore, changes in light availability can cause large responses in plant growth and/or reproduction (Whigham 2004). Altering the structure of oak stands through mechanical thinning increases resource availability and typically results in greater abundance and diversity of herbaceous plants (Bormann and Likens 1979; Elliott and others 1997; Gilliam and others 1995). It has also been shown that different levels of thinning affect the herbaceous layer in significantly different ways (Elliott and Knoepp 2005; Zenner and others 2006). Thus, reducing overstory and midstory stem density may provide suitable conditions for developing and maintaining diversity within mixed-oak forests.

The objective in this paper is to discuss trends resulting from fire and fire surrogate treatments in mixed-oak stands located within the Central and Southern Appalachian regions. Similarities and differences between these sites will be discussed as they relate to land management objectives.

Materials and Methods

Study Sites

Study locations are within the Central Appalachian Plateau and Southern Appalachian Mountains in Ohio and North Carolina, respectively (fig. 1). Both sites are part of the National Fire and Fire Surrogate (FFS) Study and were selected to represent Eastern forest communities that historically sustained frequent, low-intensity fire disturbances (Weatherspoon 2000).

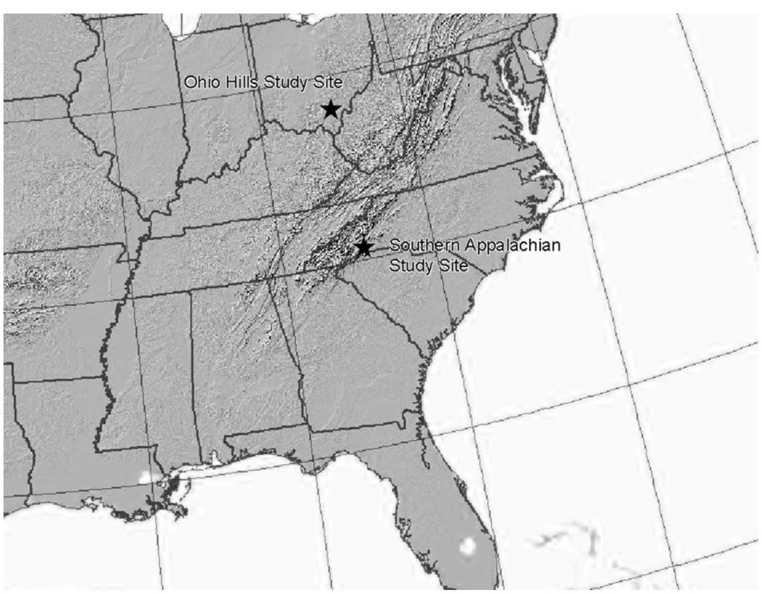


Figure 1—Site locations for the Ohio Hills Country and Southern Appalachian Mountain study sites.

The Ohio Hills Country site is on the Vinton Furnace Experimental Forest, Tar Hallow State Forest, and Zaleski State Forest in the Allegheny Plateau Province of southeastern Ohio. The overstory is dominated by oak: chestnut oak (*Quercus prinus* L.), white oak (*Q. alba* L.), northern red oak (*Q. rubra* L.), scarlet oak (*Q. coccinea* Muenchh.), and black oak (*Q. velutina* Lam.). Other common overstory species include pignut hickory (*Carya glabra* (Miller) Sweet), mockernut hickory (*C. alba* (L.) Nutt ex Ell.), bitternut hickory (*C. cordiformis* (Wangenh.) K. Koch), red maple (*Acer rubrum* L.), tulip poplar (*Liriodendron tulipifera* L.), and American beech (*Fagus grandifolia* Ehrh.). Soils are primarily of the Gilpin series (fine-loamy, mixed, mesic Typic Hapludults) with mixtures of Steinsburg (coarse-loamy, mixed, mesic Typic Dystrudepts) and Germano (coarse-loamy, mixed, mesic Typic Hapludults) soils at two replications and Latham (fine, mixed, mesic Aquic Hapludults) and Wellston (fine-silty, mixed, mesic Ultic Hapludalfs) soils at the third replication.

The Southern Appalachian site is in the Blue Ridge Province of southwestern North Carolina on the Green River Game Lands. Forest composition is mixed-oak with yellow pine on xeric ridges and white pine (*Pinus strobus* L.) in moist coves. Oaks (chestnut oak, scarlet oak, white oak, northern red oak, and black oak) dominated all sites, with other common species including: sourwood (*Oxydendrum arboreum* (L) DC.), red maple, tulip poplar, mockernut hickory, blackgum (*Nyssa sylvatica* Marsh.), and pitch pine (*Pinus rigida* P. Mill.). A dense layer of ericaceous shrubs—mountain laurel (*Kalmia latifolia* L.), rhododendron (*Rhododendron maximum* L. and *R. minus* Michx.), flame azalea (*R. calendulaceum* (Michx) Torr.), and blueberry (*Vaccinium* species L.)—is found throughout. Soils are primarily Evard series (file-loamy, oxidic, mesic Typic Hapludults) with portions of two replications (blocks 1 and 2) of the Cliffield series (loamy-skeletal, mixed, mesic Typic Hapludults). These soils are moderately deep, well drained, mountain uplands (USDA Natural Resources Conservation Service 1998). Elevations range from 366 to 793 m.

Experimental Design and Treatments

Treatments at each study site followed national protocols (Weatherspoon 2000) with accommodations for regional differences. The four treatments included: untreated control (C); a mechanical treatment (M); prescribed burning (B); and a combination of the mechanical treatment plus burning (MB). Treatments were randomly assigned and replicated three times. Herbaceous layer vegetation (herbaceous and woody vegetation less than 1.4 m in height) was measured on 1 m^2 quadrats within larger 0.1-ha rectangular plots randomly placed throughout the treatment areas (and stratified by moisture class at the Ohio site). Within quadrats species composition and abundance were recorded using cover classes: <1, 1-10, 11-25, 26-50, 51-75, >75 percent. Plots were originally sampled in 2000 (Ohio Hills) and 2001 (Southern Appalachian). The first posttreatment sampling occurred immediately following treatment. The second posttreatment occurred 3 (Southern Appalachian) or 4 years after treatment (Ohio Hills).

The mechanical treatment at the Ohio Hills site was a commercial thinning from below whereas the Southern Appalachian site used chainsaw felling of small, suppressed trees (dbh < 10 cm) and all shrubs. Slash created from these treatments was left onsite. Mechanical treatment was completed in the winter of 2000 to 2001 in Ohio and the winter of 2001 to 2002 in North Carolina.

Prescribed burning immediately followed the mechanical treatment at the Ohio Hills site in spring 2001. Temperature and humidity (RH) during the burns ranged from 11 to 23 °C and 23 to 44 percent, respectively. Winds were generally light at 5 to 8 km/hr. Fires were patchy, with the burn-only treatment having greater coverage (acreage burned) and greater intensity than those in mechanical plus burn. Mean maximum temperatures measured by thermocouples were 152 °C in B and 133 °C in MB with flame lengths =1 m. At the Southern Appalachian site, burning was conducted in March 2003, 1 year after mechanical treatment, allowing slash to cure. Ambient temperatures during burns were 17 to 27 °C, the minimum RH was 30 percent, and southwest winds were light (3 to 5 km/hr). Fire intensity in MB was consistently greater than B, as mean maximum temperatures exceeded 370 °C as opposed to 180 °C for B.

Results

Fuel reduction treatments changed species abundance and richness within the herbaceous layer of the mixed-oak forests at both sites. Woody cover increased across all treated areas at the Ohio Hills site but changed only in MB areas at the Southern Appalachian site (fig. 2). Treatments caused a reduction in overstory basal areas for all treated areas at Ohio Hills: M decreased from 29 to 20 m^2 ha^{-1}; B declined from 27 to 24 m^2 ha^{-1}; and MB dropped from 28 to 20 m^2 ha^{-1}. Pretreatment woody cover in the herbaceous layer increased from 17 to 20 percent to greater than 53 percent by the second posttreatment measurement for M, B, and MB in Ohio. Woody cover relative to total herbaceous layer cover increased slightly for C (67 to 70 percent) and M (82 to 84 percent), whereas B and MB showed slight decreases, 77 to 71 percent and 78 to 74 percent, respectively.

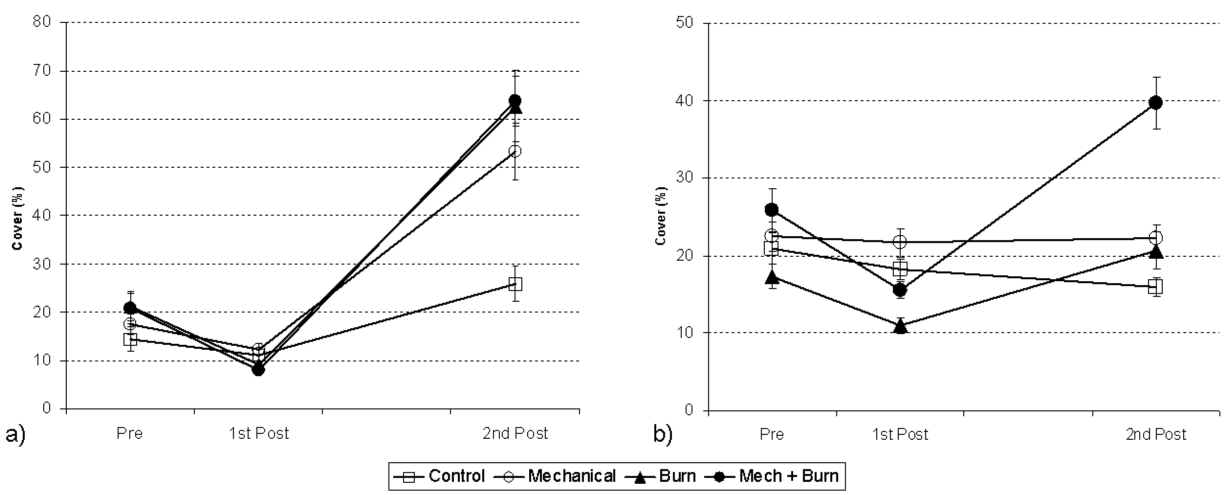


Figure 2—Woody abundance in the herbaceous layer at the Ohio Hills (a) and Southern Appalachian (b) study sites. Vegetation sampling occurred prior to treatment ("Pre"), immediately following treatment ("1st Post"), and 3 (Southern Appalachian) or 4 years (Ohio Hills) following treatment ("2nd Post").

At the Southern Appalachian site, basal area was reduced from 23 to 18 m^2 ha^{-1} in MB, whereas little effects were observed on overstory basal area for the other treatments. Pretreatment herbaceous layer woody abundance averaged 26 percent for MB, but increased to 40 percent after 3 years. Mechanical-only and burn-only were relatively unchanged from pretreatment levels after 3 years, 22 and 20 percent, respectively, while C gradually declined. Relative to total herbaceous layer cover, woody abundance decreased for all areas (C: 83 to 77 percent; M: 92 to 91 percent; B: 82 to 80 percent; and MB: 88 to 76 percent).

Forb abundance showed a positive response to burning at the Ohio Hills site with increases in B and MB from 5 percent to more than 22 and 18 percent, respectively; M differed little from the control after 4 years (fig. 3a). Graminoids followed similar trends with large increases in B and MB and twice as much graminoid cover after 4 years as compared to C and M (fig. 3c). Forbs and graminoids composed almost 30 percent of total herbaceous layer cover in C prior to treatment but cover had dropped to 24 percent after 4 years. The mechanical treatment showed little change in relative cover during the same period. The burn-only treatment increased from 20 to 25 percent in relative cover whereas herbaceous species had a relative cover of 21 percent in MB.

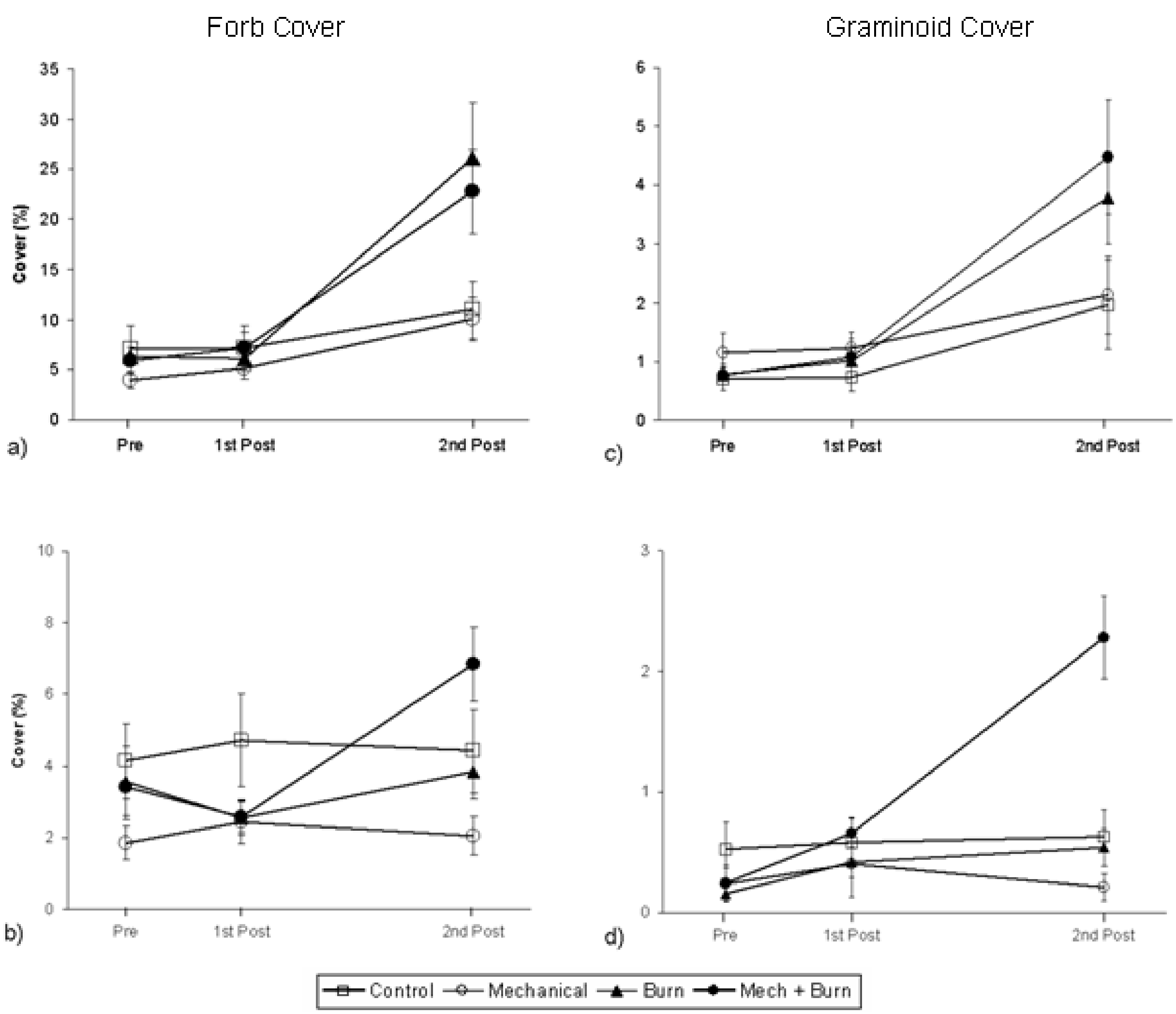


Figure 3—Cover of forbs (a and b) and graminoids (c and d) at Ohio Hills (a and c) and Southern Appalachian (b and d) sites.

At the Southern Appalachian site, forb and graminoid cover were higher in MB as compared to other treatments after 3 years (fig. 3b,d). Forbs recovered to almost twice the pretreatment levels in MB after declining briefly immediately after burns. Graminoids in MB increased immediately, a trend that continued into the third year. In C, M, and B, no differences from pretreatment values were observed after 3 years. Relative cover of forbs and graminoids, combined, increased from 19 to 25 percent in C, in contrast to expected results. The mechanical-only and burn-only treatments had no effect on relative cover for forbs and graminoids after 3 years (9 percent M and 18 percent B). However, relative cover of forbs and graminoids in MB increased from 13 to 20 percent.

Trends for total species richness were similar for both sites as large increases were observed in burned areas (B and MB) immediately after treatment, followed by gradual increases from the first to the second posttreatment sampling (fig. 4a,b). The mechanical-only treatment also increased total species richness at both sites, although these areas contained considerably fewer species than B and MB areas. At the Ohio Hills site, M resulted in more species m^{-2} than the controls, but at the Southern Appalachian site, M still had lower species richness m^{-2} than C after 3 years. However, the differences between C and M lessened over time.

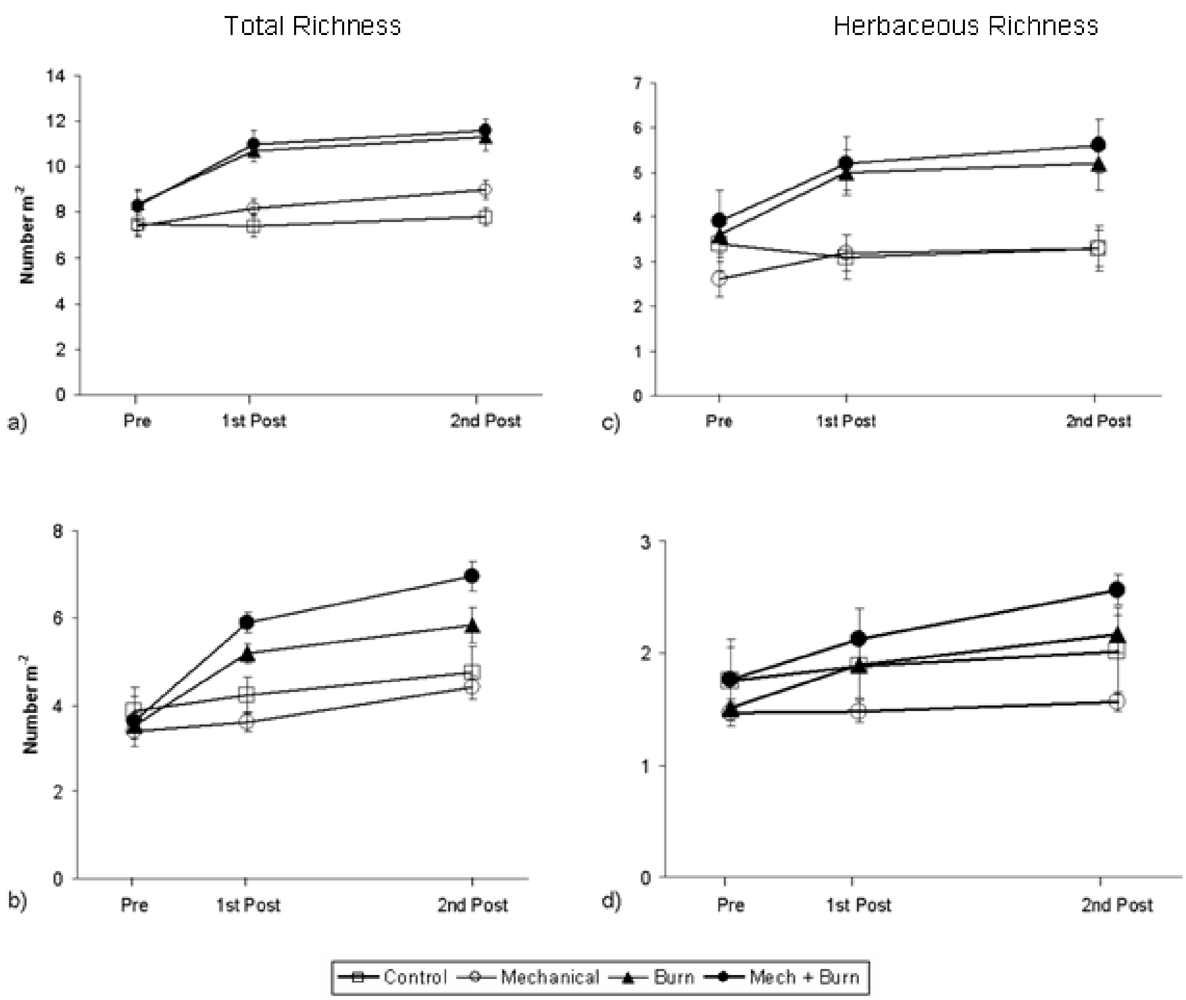


Figure 4—Total richness (a and b) and herbaceous species richness (c and d) for the Ohio Hills (a and c) and Southern Appalachian (b and d) sites.

Burning increased herbaceous species richness at Ohio Hills with almost two more species m^{-2} for burned versus unburned areas (fig. 4c). The mechanical-only treatment also resulted in greater species richness, with little differences between C and M by the second posttreatment measurement. At the Southern Appalachian site, burned areas (B and MB) showed similar trends as immediate increases were observed following burning, whereas unburned areas (C and M) gradually increased over time (fig. 4d). After 3 years MB contained the greatest number of herbaceous species m^{-2}; B and C were similar; and M had the least.

Discussion

Mechanical treatment alone had little effect on herbaceous species at the Ohio Hills site, but it increased woody cover and total richness. At the Southern Appalachian site, there were no significant effects for woody or herbaceous species as a result of mechanical treatment. Structural differences between the mechanical treatments for each location were distinct as basal area and density were significantly reduced at Ohio Hills (Albrecht and McCarthy 2006), whereas few changes were observed for those attributes at the Southern Appalachian site (Phillips and others, in press). Dolan and Parker (2004) reported no changes in herbaceous vegetation in an Indiana oak forest after a mechanical understory reduction treatment similar to that used in the Southern Appalachians, although they observed slight increases in shade-intolerant tree species. Other studies using more intense harvesting practices have shown increasing herbaceous layer abundance and diversity associated with greater intensity harvests (Elliott and Knoepp 2005; Zenner and others 2006). Zenner and others (2006) suggest that until certain harvest intensity thresholds are reached, few effects will be observed. The lack of response for both sites may be partially attributed to the manner in which these treatments were conducted. As specified by treatment prescriptions, all slash was scattered and left onsite. This material may have served as a physical barrier to seed germination and prevented plant growth by limiting light at the forest floor. The changes in forest structure from the mechanical treatments used at the Ohio Hills and Southern Appalachian sites did not promote herbaceous layer richness.

Prescribed fire had positive effects on herbaceous layer abundance and richness at the Ohio Hills site. Abundance and species richness were considerably higher in burned areas than in unburned areas. The prescribed fires in B at Ohio Hills were of sufficient intensity to create canopy gaps, allowing enough light to elicit a response in the herbaceous layer. Changes in the understory environment (for example, consumption of the litter layer, increased available light) provided suitable conditions for seed germination and plant growth. Initial changes in composition richness are typically dominated by establishment of seed-banking, shade-intolerant species; while long-term changes result as perennial forbs and graminoids become established (Hutchinson 2005). Long-term application of fire is necessary to maintain this increased diversity (Hartman and Heumann 2003).

At the Southern Appalachian site, prescribed fire alone had little effect on herbaceous layer vegetation. No differences were observed between B and C after 3 years for herbaceous species abundance or richness, although B had higher total species richness. These results are similar to those of Kuddes-Fischer and Arthur (2002) where a single low-intensity fire produced little differences in herbaceous and shrub cover and slight, nonsignificant increases in richness after 4 years. While mean maximum fire temperatures were greater in the Southern Appalachians than in the Ohio Hills, small declines in overstory basal area and density at the Southern Appalachian site may have been offset by sprouting from ericaceous shrubs. Only minor reductions in the shrub component resulted from the burn-only treatment (Phillips and others, in press); therefore, shading may have limited the light needed for seed germination. Ducey and others (1996) and Elliott and others (1999) indicate that more intense fires are required to reduce mountain laurel abundance (*K. latifolia*) and thus increase herbaceous layer richness and diversity in the Southern Appalachians.

The combination of mechanical treatment plus burning showed similar effects as burning alone at the Ohio Hills site. Greater herbaceous layer cover in addition to increased species richness was observed with lower-intensity fires. Decreased basal area was achieved by mechanical felling of the overstory, while midstory cover and leaf litter were reduced by burning. The combination of mechanical treatment and burning may be less cost-effective than burning alone, but it provides greater control of shade-tolerant species by reducing sprouting vigor through application of multiple disturbances (Albrecht and McCarthy 2006).

In the Southern Appalachians, only a combination of mechanical treatment and burning resulted in increased herbaceous layer cover and richness. Fires within these treatment areas were considerably more intense than the burn-only treatment, resulting in greater mortality of large diameter trees (Brudnak and others, in press) increasing insolation. By using fire after mechanical treatment, sprouts from shade-tolerant species and ericaceous shrubs were further reduced (Phillips and others, in press), allowing herbaceous vegetation to become established.

The lack of response of herbaceous species to mechanical treatment compared to burning indicates that fire may promote processes (that is, nutrient cycling, seed germination, and so forth) that cannot be mimicked by structural alteration alone. Changes to forest structure in some stands, as a result of fire exclusion, may be too extreme to overcome by fire alone (Franklin and others 2003). Reducing stem densities and allowing more light to reach the forest floor, in conjunction with fire, may be necessary to restore diversity to mixed-oak forests, as evidenced at the Southern Appalachian site.

Conclusions

As oak forests decline across the Eastern landscape, prescribed fire and other treatments are being applied to encourage oak recruitment and sustain this forest type. But the intensities of fire and thinning required to restore these communities are not well understood.

These results indicate responses of herbaceous layer vegetation to fire and fire surrogate treatments vary by region and are dependant on pretreatment species composition and structure. Prescribed fire resulted in greater cover and species richness for the herbaceous layer in the Central Appalachian region in Ohio. However, in the Southern Appalachian Mountains in North Carolina, ericaceous shrubs and lack of sufficient light reaching the forest floor required both mechanical treatment and prescribed fire to increase abundance and richness in the herbaceous layer.

References

Abrams, M.D. 1992. Fire and the development of oak forests. BioScience 42(5): 346-353.

Abrams, M.D. 2005. Prescribed fire in eastern oak forests: Is time running out? Northern Journal of Applied Forestry 22(3): 190-196.

Abrams, M.D.; Nowacki, G.J. 1992. Historical variation in fire, oak recruitment, and post-logging accelerated succession in central Pennsylvania. Bulletin of the Torrey Botanical Club 119(1): 19-28.

Albrecht, M.A.; McCarthy, B.C. 2006. Effects of prescribed fire and thinning on tree recruitment patterns in central hardwood forests. Forest Ecology and Management 226: 88-103.

Barnes, T.A; Van Lear, D.H. 1998. Prescribed fire effects on advanced regeneration in mixed hardwood stands. Southern Journal of Applied Forestry 22(3): 138-142.

Bormann, F.H.; Likens, G.E. 1979. Pattern and Process in a Forested Ecosystem. Springer-Verlag, New York, NY.

Brose, P.; Van Lear, D.; Cooper, R. 1999. Using shelterwood harvests and prescribed fire to regenerate oak stands on productive upland sites. Forest Ecology and Management 113(2): 125-141.

Brose, P.H.; Schuler, T.M.; Ward, J.S. 2006. Responses of oak and other hardwood regeneration to prescribed fire: what we know as of 2005. In: Dickinson, M.B., ed. Fire in eastern oak forests: delivering science to land managers, proceedings of a conference. Gen. Tech. Rep. NRS-P-1. Newton Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station: 123-135.

Brudnak, L.A.; Waldrop, T.A.; Phillips, R.J. [In press]. HOBO thermocouple dataloggers: useful applications for prescribed fire research. In: Stanturf, J., ed. Proceedings of the 14th biennial southern silviculture research conference. Gen. Tech. Rep. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station.

Crow, T.R. 1988. Reproductive mode and mechanisms for self-replacement of north red oak (*Quercus rubra*) – a review. Forest Science 34(1): 19-40.

Dolan, B.J.; Parker, G.R. 2004. Understory response to disturbance: an investigation of prescribed burning and understory removal treatments. In: Spetich, Martin A., ed. Upland oak ecology symposium: history, current conditions, and sustainability. Gen. Tech. Rep. SRS–73. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station: 285-291.

Ducey, M.J.; Moser, W.K.; Ashton, P.M.S. 1996. Effect of fire intensity on understory composition and diversity in a *Kalmia*-dominated oak forest, New England, USA. Vegetatio 123: 81-90.

Elliott, K.J.; Boring, L.R.; Swank, W.T.; Haines, B.R. 1997. Successional changes in plant species diversity and composition following clearcutting a southern Appalachian watershed. Forest Ecology and Management 92: 67-85.

Elliott, K.J.; Hendrick, R.L.; Major, A.E. [and others]. 1999. Vegetation dynamics after a prescribed fire in the southern Appalachians. Forest Ecology and Management 114(2): 199-213.

Elliott, K.J.; Knoepp, J.D. 2005. The effects of three regeneration harvest methods on plant diversity and soil characteristics in the southern Appalachians. Forest Ecology and Management 211(3): 296-317.

Elliott, K.J.; Vose, J.M; Clinton, B.D; Knoepp, J.D. 2004 Effects of understory burning in a mesic mixed-oak forest of the southern Appalachians. In: Engstrom, R.T; Galley, K.E.M; de Groots, W.J., eds. Proceedings of the 22nd Tall Timber Fire Ecology Conference: Fire in Temperate, Boreal, and Montane Ecosystems. Tallahassee, FL: Tall Timber Research Station: 272-283.

Franklin, S.B.; Robertson, P.A.; Fralish, J.S. 2003. Prescribed burning effects on upland *Quercus* forest structure and function. Forest Ecology and Management 184: 315-335.

Gilliam, F.S.; Turrill, N.L.; Adams, M.B. 1995. Herbaceous layer and overstay species in clearcut and mature central Appalachian hardwood forest. Ecological Applications 5(4): 947-955.

Hartman, G.W.; Heumann, B. 2003. Prescribed fire effects in the Ozarks of Missouri: the Chilton Creek Project 1996-2001. [Online]. In: Proceedings of the 2nd International Wildland Fire Ecology and Fire Management Congress, Orlando, FL. Available from: http://ams.confex.com/ams/FIRE2003/techprogram/paper_65977.htm [Data accessed: March 15, 2007].

Hutchinson, T. 2006. Fire and the herbaceous layer of eastern oak forests. In: Dickinson, M.B., ed. Fire in eastern oak forests: delivering science to land managers, proceedings of a conference. Gen. Tech. Rep. NRS-P-1. Newton Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station: 136-149.

Hutchinson, T.F.; Boerner, R.E.J.; Sutherland, S. [and others]. 2005. Prescribed fire effects on the herbaceous layer of mixed-oak forests. Canadian Journal of Forest Research 35: 877-890.

Kuddes-Fischer, L.M.; Arthur, M.A. 2002. Response of understory vegetation and tree regeneration to a single prescribed fire in oak-pine forests. Natural Areas Journal 22(1): 43-52.

Lorimer, C.G. 1984. Development of the red maple understory in northeastern oak forests. Forest Science 30(1): 3-22.

Lorimer, C.G. 1985. The role of fire in the perpetuation of oak forests. In: Johnson, J.E., ed. Proceedings Challenges in Oak Management and Utilization. Madison: University of Wisconsin, Cooperative Extension Service: 8-25.

Nowacki, G.J.; Abrams, M.D. 1991. Community, edaphic, and historical analysis of mixed oak forests of the Ridge and Valley Province in central Pennsylvania. Canadian Journal of Forest Research 22: 790-800.

Phillips, R.J.; Waldrop, T.A.; Simon, D.M. [In press]. Third-year responses of understory woody species regeneration to fuel reduction treatments in the southern Appalachian Mountains. In: Stanturf, J., ed. Proceedings of the 14th biennial southern silviculture research conference. Gen. Tech. Rep. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station.

Reich, P.B.; Abrams, M.D.; Ellsworth, D.S. [and others]. 1990. Fire affects ecophysiology and community dynamics of central Wisconsin oak forest regeneration. Ecology 71(6): 2179-2190.

Ruffner, C.M.; Groninger, J.W. 2004. Oak Ecosystem Restoration and Maintenance in Southern Illinois. In: Spetich, M.A., ed. Upland oak ecology symposium: history, current conditions, and sustainability. Gen. Tech. Rep. SRS-73. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station: 177-181.

Schuler, T.M.; Gillespie, A.R. 2000. Temporal patterns of woody species diversity in a central Appalachian forest from 1856 to 1997. Journal of the Torrey Botanical Society 127(2): 149-161.

Taft, J.B. 2003. Fire effects on community structure, composition, and diversity in a dry sandstone barrens. Journal of the Torrey Botanical Society 130: 170-192.

USDA Natural Resources Conservation Service. 1998. Soil Survey of Polk County, North Carolina. U.S. Government Printing Office: 1998-432-697/60527/NCRS.

Weatherspoon, C.P. 2000. A proposed long-term national study of the consequences of fire and fire surrogate treatments. In: Neuenschwander, L.F., Ryan, K.C., Goldberg, G.E., eds. Proceedings Joint Fire Science Conference. Moscow: University of Idaho Press: 117-126.

Whigham, D.F. 2004. Ecology of woodland herbs in temperate deciduous forests. Annu. Rev. Ecol. Evol. Syst. 35: 583-621.

Zenner, E.K; Kabrick, J.M.; Jensen, R.G. [and others]. 2006 Responses of ground flora to a gradient of harvest intensity in the Missouri Ozarks. Forest Ecology and Management 222: 326-334.

**This
page is
blank
on purpose**

Soil Physical Property Response to Prescribed Fire in Two Young Longleaf Pine Stands on the Western Gulf Coastal Plain

Mary Anne Sword Sayer[1]

Abstract—*Prescribed fire every 2 to 4 years is an important component of longleaf pine ecosystem restoration. Under some circumstances, repeated fire could change soil physical properties on the Western Gulf Coastal Plain. The objective of this study was to evaluate the soil bulk density, porosity fractions, and plant-available water holding capacity of restored longleaf pine on the Western Gulf Coastal Plain in response to two vegetation management alternatives that included the application of three prescribed fires over a 6-year period. Soil microporosity and plant-available water holding capacity were influenced by both vegetation management alternatives indicating that a reduction in the perturbation of soil by roots may be a mechanism of soil physical property change. Apparent soil texture effects on plant-available water holding capacity suggest that further research is needed to determine if repeated prescribed fire exacerbates the naturally low plant-available water holding capacity of some soils on the Western Gulf Coastal Plain.*

Introduction

In the late 1800s, longleaf pine (*Pinus palustris* P. Mill.) ecosystems occurred across 37 million ha of the Southeastern United States; today, less than 2 million ha of these forests remain (Landers and others 1995; Outcalt 2000; Outcalt and Sheffield 1996). This decrease in range is attributed to extensive logging followed by unsuccessful reestablishment due to regeneration problems and exclusion of fire as a management tool (Barnett and Dennington 1992; Boyer 1989; Outcalt 2000). Because the native plants and animals of longleaf pine ecosystems are adapted to, and often depend on, the occurrence of fire every 2 to 4 years (Brockway and Lewis 1997; Haywood and others 2001; Landers and others 1995; Outcalt 2000), successful longleaf pine ecosystem restoration is dependent on prescribed fire. Now that fire has been reconsidered as a forest management tool in the South (Brockway and Lewis 1997; Brockway and Outcalt 2000; Gilliam and Platt 1999; Haywood and others 2001), and research has identified successful approaches to regenerate longleaf pine (Barnett and McGilvray 1997; Boyer 1989; McGuire and others 2001; Ramsey and others 2003; Rodríguez-Trejo and others 2003), restoration of this species to portions of its natural range is being realized.

Soil quality will be sustained over a long-term period of repeated prescribed fire if the role of vegetation in controlling soil chemical and physical properties continues. Under some circumstances, however, repeated crown scorch and eradication of understory vegetation may negatively affect various soil physical properties that impact the bulk density and plant-available water holding capacity of Western Gulf Coastal Plain soils. For example, if postfire plant physiological processes are unable to supply the energy needed to maintain

In: Butler, Bret W.; Cook, Wayne, comps. 2007. The fire environment—innovations, management, and policy; conference proceedings. 26-30 March 2007; Destin, FL. Proceedings RMRS-P-46CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 662 p. CD-ROM.

[1] Research Plant Physiologist, U.S. Department of Agriculture, Forest Service, Southern Research Station, Pineville, LA. msword@fs.fed.us

active root growth, both the perturbation of soil by roots and the deposition of organic matter in the soil will suffer. Without adequate perturbation and organic matter, soil bulk density and strength increase (Fisher and Binkley 2000). Where inherent soil physical properties approach root-growth limiting conditions, root system expansion may be dependent on conduits provided by old root channels (van Lear and others 2000). If carbon allocation to root growth is inhibited, the network of old root channels and the potential for soil resource acquisition will be restricted. The soils of longleaf pine forests on the Western Gulf Coastal Plain are characterized as silty and clayey (Peet 2006), with the potential for naturally low subsoil porosity and high bulk density (Patterson and others 2004; Pritchett 1979). Where inherent soil physical property values approach root growth limitations, fire-induced changes could lead to an unnecessary loss of soil quality.

The objective of this study was to evaluate the soil physical properties of restored longleaf pine on the Western Gulf Coastal Plain in response to two vegetation management alternatives that included the application of prescribed fire in spring of 2000, 2003, and 2005. It is hypothesized that repeated fire reduced soil quality by decreasing porosity and plant-available water holding capacity, and by increasing bulk density.

Materials and Methods

Study Location

The study, on the Kisatchie National Forest in central Louisiana, included two replications at latitude 31º 6'N, longitude 92º 36'W on a Ruston fine sandy loam (fine-loamy, siliceous, semiactive, thermic Thermic Paleudults) with some Malbis fine sandy loam (fine-loamy, siliceous, subactive, thermic Plinthic Paleudults) and Gore very fine sandy loam (fine, mixed, active, thermic Vertic Paleudualfs) with a slope of 1 to 5 percent (site 1). Three replications were at latitude 31° 1'N, longitude 92º 37'W on a gently sloping (1 to 3 percent) Beauregard silt loam (fine-silty, siliceous, superactive, thermic Plinthaquic Plaeudults) and Malbis fine sandy loam complex (site 2). A mixed pine-hardwood forest originally occupied both sites. Site 1 was clearcut harvested in 1996 and roller-drum chopped and burned in August 1997. Site 2 was clearcut harvested, sheared, and windrowed in 1991 and prescribe burned in 1993 and 1996. Vegetation at both sites included *Schizachyrium*, *Panicum*, and *Dichanthelium* grass species that are native to western longleaf pine ecosystems (Peet 2006). Grass cover was less at site 2 compared to site 1 due to the prevalence of herbaceous plants such as swamp sunflower (*Helianthus angustifolius* L.), and woody shrubs such as wax myrtle (*Morella cerifera* (L.) Small.

At each location, treatment plots (22 x 22 m; 0.048 ha) were established and blocks were delineated by soil drainage and topography. Three vegetation management treatments were established:

1. Control (C)—no management activities after planting.
2. Prescribed burning (B)—plots were burned using the strip headfire method in spring.
3. Herbicides (H)—herbicides were applied after planting and before age 3 years for herbaceous and arborescent plant control, and recovering brush was cut by hand in 2001 (Sword Sayer and others 2006).

Site 2 was burned in May 1998 and both sites were burned in June 2000, and May 2003 and 2005. Container-grown longleaf pine seedlings from a genetically improved Louisiana seed source (site 1) and Mississippi seed source (site 2) were planted at a spacing of 1.8 x 1.8 m in November 1997 and March 1997, respectively. Treatment plots contained 12 rows of 12 seedlings. Measurement plots contained the internal eight rows of seedlings in each treatment plot.

Measurements

In fall 2002, three saplings of average height per measurement plot were randomly identified. In fall 2004 and spring 2006, a tractor-mounted hydraulic probe was used to extract one long (5.1 cm diameter x 61 cm long) and one short (5.1 cm diameter x 30.5 cm long) soil core 1 m from the base of each selected sapling. Cores were placed in capped plastic liners and refrigerated until processing. Intact soil core increments were excised from the A, Bt1, and Bt2 horizons of long soil cores, and the A horizon of short soil cores. During long soil core processing, the depth to the argillic horizon (Bt1) was visually estimated by color and texture. Specifically, immediately below the darkly colored A horizon, a metal blade was pulled along the core length. The upper Bt horizon was identified as the depth where there were distinct changes in resistance to the blade and the appearance of the blade tracing. The Bt1 core increment was defined as 2 to 12 cm below this depth. Two 1 cm deep core sections each from the A horizon core increment (2 to 12 cm), the Bt1 horizon core increment, and the Bt2 horizon core increment (50 to 60 cm) were excised using a band-saw. Similarly, short soil cores were processed so that two intact 1 cm core sections were excised from the A horizon core increment. In each year, 90 soil cores were processed for A horizon information, and 45 soil cores were processed for Bt1 and Bt2 horizon information.

From the long and short soil cores, two core sections from each soil horizon were placed in plastic rings. One set of rings was positioned on either an equilibrated -0.1 MPa or –1.5 MPa ceramic pressure plate. Bulk density, total porosity fraction, microporosity fraction, macroporosity fraction, and plant-available soil water holding capacity were determined with data generated by the water retention method (Klute 1986) and the core bulk density method (Blake and Hartge 1986). Bulk density (BD) was expressed as core section dry weight (g) divided by core section volume (cm^{-3}). Total porosity (TOP) was calculated by equation 1.

$$TOP = 1-[BD\ (g\ cm^{-3})/\text{particle density}\ (2.65\ g\ cm^{-3})] \quad (1)$$

Microporosity (MIP) was calculated by equation 2 where WATFC is the soil water content of the core section at –0.03 MPa, CSV is the core section volume and SGW is the specific gravity of water.

$$MIP = [WATFC\ (g)/CSV\ (cm^{3})]/SGW\ (1\ g\ cm^{-3})] \quad (2)$$

Macroporosity (MAP) was determined by subtracting MIP from TOP. Percent plant-available soil water holding capacity (PAWHC) was calculated by equation 3 where WATFC and WATWP are the soil water content of core sections at –0.03 MPa and –1.5 MPa, respectively.

$$PAWHC = \frac{\left[(WATFC\ (g)/CSV\ (cm^{3})) - (WATWP\ (g)/CSV(cm^{3}))\right]}{SGW\ (1\ g\ cm^{-3})} \times 100 \quad (3)$$

Statistical Analysis

Values of BD, TOP, MIP, MAP, and PAWHC for each horizon were transformed, as needed, to natural logarithm or square root values to establish normality, and evaluated by analysis of variance using a split plot in time, randomized complete block design with five blocks. Year was the whole plot effect and vegetation management treatment was the subplot effect. Effects were considered significant at $P \leq 0.05$. Means were compared by the Tukey test and considered significantly different at $P \leq 0.05$.

Results and Discussion

All soil physical properties except PAWHC were significantly affected by year in at least two soil horizons (table 1). Values of bulk density in the A, Bt1, and Bt2 horizons were, respectively, 5, 8, and 8 percent lower in 2006 compared to 2004 (table 2). Value of TOP and MAP were greater and values

Table 1—Probabilities of a greater *F*-value for soil physical properties of restored longleaf pine in central Louisiana in response to three vegetation management treatments.

Effect	df[a]	A Horizon	Bt1 Horizon	Bt2 Horizon
Bulk density(BD)[b]				
Block (B)	4	0.0351	0.2296	0.0690
Year (Y)	1	0.0250	0.0172	0.0056
B x Y	4	0.3364	0.1514	0.5146
Treatment (T)	2	0.2789	0.4019	0.7547
T x Y	2	0.5698	0.3928	0.7447
Total porosity (TOP)				
B	4	0.0351	0.2296	0.0801
Y	1	0.0250	0.0172	0.0066
B x Y	4	0.3364	0.1514	0.4829
T	2	0.2789	0.4019	0.7419
T x Y	2	0.5698	0.3928	0.7619
Microporosity (MIP)				
B	4	0.0025	0.0613	0.5435
Y	1	0.1688	0.0455	0.0187
B x Y	4	0.8664	0.1618	0.1960
T	2	0.0047	0.0741	0.0184
T x Y	2	0.7568	0.2509	0.7785
Macroporosity (MAP)				
B	4	0.0167	0.1120	0.1374
Y	1	0.0298	0.0163	0.0039
B x Y	4	0.5552	0.1048	0.1086
T	2	0.0309	0.8419	0.2650
T x Y	2	0.8553	0.4261	0.5020
Plant-available water holding capacity (PAWHC)				
B	4	0.0057	0.0209	0.1167
Y	1	0.5735	0.9603	0.8585
B x Y	4	0.7954	0.0667	0.4637
T	2	0.0063	0.2323	0.5001
T x Y	2	0.6581	0.4449	0.5909

[a] degrees of freedom
[b] A horizon MIP, and A and Bt1 horizon PAWHC were transformed to square root values; BD was transformed to its natural logarithm.

Table 2—Means and standard errors of soil physical property values of restored longleaf pine over a 3-year period in central Louisiana averaged across three vegetation management treatments and two locations. Within a variable and soil horizon, means associated with different letters are significantly different at $P \leq 0.05$ by the Tukey test.

Year	Variable			
	BD[a]	TOP	MIP	MAP
A horizon				
2004	1.44 ± 0.03 a	0.46 ± 0.01 b	0.26 ± 0.01	0.19 ± 0.02 b
2006	1.37 ± 0.01 b	0.48 ± 0.01 a	0.25 ± 0.01	0.23 ± 0.01 a
Bt1 horizon				
2004	1.61 ± 0.03 a	0.39 ± 0.01 b	0.33 ± 0.01 a	0.07 ± 0.01 b
2006	1.48 ± 0.01 b	0.44 ± 0.01 a	0.30 ± 0.01 b	0 14 ± 0.01 a
Bt2 horizon				
2004	1.67 ± 0.03 a	0.37 ± 0.01 b	0.33 ± 0.01 a	0.05 ± 0.01 b
2006	1.54 ± 0.01 b	0.42 ± 0.01 a	0.30 ± 0.01 b	0.12 ± 0.01 a

[a] BD: Bulk density (g/cm^3); TOP: total porosity fraction; MIP: microporosity fraction; MAP: macroporosity fraction.

of MIP were lower in 2006 compared to 2004. The magnitude of these differences increased with soil horizon depth. It is speculated that these effects were caused by soil water content at the time of soil core collection. In 2004, soil cores were collected in fall when the soil was dry; in 2006, soil cores were collected in spring when the soil was wet. The Ultisol soils in this study are characterized by a suite of clay minerals dominated by kaolinite, which exhibits no shrink-swell potential (Buol and others 1980; Kerr and others 1980). However, some soil core expansion was possible after removal from the soil profile due to the influence of organic matter and minor clay minerals such as vermiculite on expansion (Buol and others 1980; Foth 1978). The clay fraction of the soil series in this study increases with soil horizon depth (Kerr and others 1980; Soil Survey Staff 2007). The effect of this clay fraction on soil core expansion may have increased with depth causing annual differences in bulk density, TOP, MAP, and MIP to also increase with depth.

With one exception, all significant effects of vegetation management treatment on soil physical properties were found in the A horizon (table 1). Specifically, MAP, MIP, and PAWHC in the A horizon, and MIP in the Bt2 horizon were influenced by vegetation management treatment. Values of MAP were 25 percent greater on the B plots, and values of MIP were 15 and 18 percent lower, respectively, on the B and H plots compared to the C plots (fig. 1). Values of PAWHC were 18 percent lower on the B and H plots compared to the C plots. In the Bt2 horizon, MIP was 7 percent lower on the B plots compared to the C plots. Bulk density was not significantly affected by either repeated prescribed fire or chemical vegetation control.

Unwanted vegetation was successfully controlled by repeated prescribed fire and chemical vegetation control during seedling establishment. It is likely that the production and activity of roots associated with this unwanted vegetation were also reduced by B and H treatments. These observations suggest that a reduction in the perturbation of soil by roots is a potential mechanism of soil porosity change in response to B and H.

Noncapillary pore space or MAP is the fraction of soil porosity containing both gravitational water and air space depending on the degree of saturation (Kramer 1983). As the soil drains, MAP provides conduits for aeration. The mortality of woody roots as repeated fire weakens or kills unwanted shrubs and small trees may be linked to greater MAP in the A horizon on

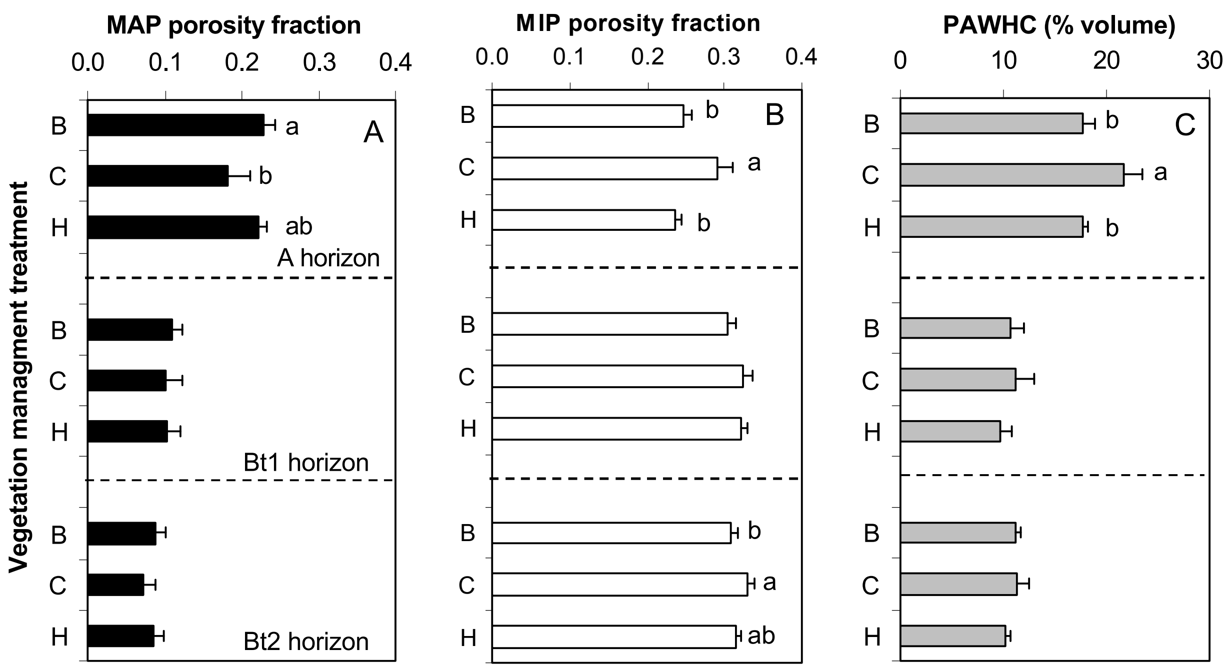


Figure 1—Effects of vegetation management treatment on soil physical properties.

the B plots compared to the C plots. Silty and clayey soils on the Western Gulf Coastal Plain are often poorly drained and remain saturated in winter (Kerr and others 1980). As evapotranspiration increases and these soils dry in spring, perhaps dead root cavities from unwanted shrubs and small trees improve soil aeration on burned sites.

Capillary pore space is the source of water held against gravity at a tension greater than 0.03 MPa. From this, water held at a tension above 1.5 MPa is available for plant uptake (in other words, PAWHC) (Kramer 1983). It is true that unwanted vegetation was successfully controlled by repeated prescribed fire and chemical vegetation control during seedling establishment. However, this was accompanied by 15 to 18 percent reductions in A horizon MIP and PAWHC. Obviously, adequate water is needed to maintain longleaf pine physiology and growth on the Western Gulf Coastal Plain where seasonal drought is common and prolonged drought is possible (Allen and others 1990; Sword Sayer and Haywood 2006). During drought, management-induced reductions in PAWHC have the potential to affect the supply of water to young trees and, therefore, their production. Further research is needed to determine the significance of reduced A horizon PAWHC on the Western Gulf Coastal Plain possibly caused by vegetation control.

Significant block effects were observed for all soil physical property variables in the A horizon, and for PAWHC in the Bt1 horizon (table 1). The separation of some block means suggests that the physical properties at site 1 were distinctly different from those at site 2. The bulk density of the A horizon was variable with a higher value on block 3 compared to most other blocks (fig. 2A). Similarly, MAP was higher on block 4 compared to the other four blocks. It is possible that past management activities such as logging and site preparation introduced variation to the bulk density and MAP of the A horizon.

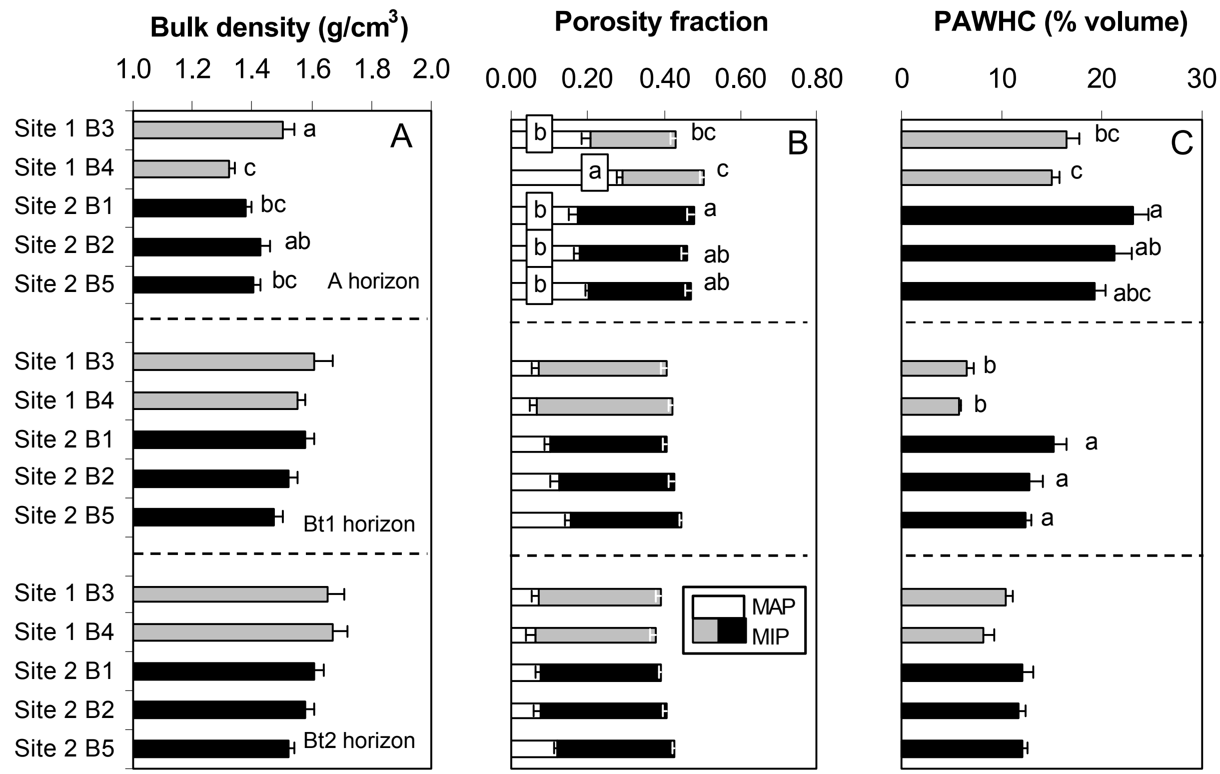


Figure 2—Block effects on the study sites.

For MIP and PAWHC, block means exhibited trends that distinguished site 1 from site 2 (fig. 2B,C). Specifically, A horizon MIP and PAWHC at site 1 were 24 and 26 percent lower, respectively, compared to A horizon MIP and PAWHC at site 2. It is likely that soil texture controlled soil physical property differences at the two sites. Total sand fractions of the A horizon of soils at site 1 and site 2 were similar (Soil Survey Staff 2007). However, the sand fraction of the A horizon of the Ruston soil at site 1 was dominated by fine sand; whereas, that of the A horizon of the Beauregard/Malbis soil at site 2 was dominated by very fine sand (Soil Survey Staff 2007). It is proposed that as sand particle size increased, less MIP contributed to TOP because the larger particle size predisposed porosity to MAP.

Soil texture may have also led to site differences in the Bt1 horizon. The clay fraction of the Bt1 horizon of the Ruston soil at site 1 was greater than that of the Beauregard/Malbis soil at site 2 (Soil Survey Staff 2007). The small particle size of clay enables it to hold more water than sand or silt (Kramer 1983). Small pore sizes associated with clay, however, also result in a large fraction of soil water that is plant-unavailable because it is held at a tension greater than 1.5 MPa. Perhaps greater clay content in the Bt1 horizon resulted in 55 percent less PAWHC at site 1 compared to site 2 (fig. 2C), because the clay fraction of the Ruston soil at site 1 retained more plant-unavailable soil water than the Beauregard/Malbis soil at site 2.

The results of this study suggest that frequent prescribed fire has the potential to affect the soil porosity and plant-available water holding capacity of restored longleaf pine forests on the Western Gulf Coastal Plain. However, soil physical property responses to the application of three prescribed fires over a 6-year period were not severe enough to affect bulk density. Similar trends in MAP, MIP, and PAWHC between the repeated prescribed fire and chemical vegetation control treatments suggest that changes in soil physical properties were associated with altered understory vegetation dynamics. It is hypothesized that vegetation control by prescribed fire or herbicide application reduced soil perturbation by roots, subsequently reducing MIP and PAWHC. Apparent relationships between clay content and soil expansion, and between sand and clay content and PAWHC were noted. Further research is needed to determine if repeated prescribed fire exacerbates the naturally low PAWHC of soils with a higher sand fraction in the A horizon and a higher clay fraction in the Bt1 horizon. This information would help ascertain whether prescribed fire on some Western Gulf Coastal Plain soils influences the supply of water necessary to maintain tree physiological processes.

References

Allen, H.L.; Dougherty, P.M.; Campbell, R.G. 1990. Manipulation of water and nutrients- practice and opportunity in southern U.S. pine forests. Forest Ecology and Management 30: 437-453.

Barnett , J.P.; Dennington, R.W. 1992. Return to longleaf. Forest Farmer 52:11-12.

Barnett, J.P.; McGilvray, J.M. 1997. Practical guidelines for producing longleaf pine seedlings in containers. General Technical Report SRS-14. Asheville, NC: U.S. Department of Agriculture, Southern Research Station. 28 p.

Blake, G.R.; Hartge, K.H. 1986. Bulk density. In: Klute, A., ed. Methods of Soil Analysis Part 1 physical and mineralogical methods. 2nd ed. Madison, WI: Soil Science Society of America, Inc.: 363-375.

Boyer, W.D. 1989. Response of planted longleaf pine bare-root and container stock to site preparation and release: fifth-year results. In: Miller, J.H. comp. Proceedings of the Fifth Biennial Southern Silvicultural Research Conference. General Technical Report SO-74. New Orleans, LA: U.S. Department of Agriculture, Southern Forest Experiment Station: 165-168.

Brockway, D.G.; Lewis, C.E. 1997. Long-term effects of dormant-season prescribed fire on plant community diversity, structure and productivity in a longleaf pine wiregrass ecosystem. Forest Ecology and Management 96: 167-183.

Brockway, D.G.; Outcalt, K.W. 2000. Restoring longleaf pine wiregrass ecosystems: hexazinone application enhances effects of prescribed fire. Forest Ecology and Management 137: 121-138.

Buol, S.W.; Hole, F.D.; McCracken, R.J. 1980. Soil Genesis and Classification. 2nd ed. Ames, IA: The Iowa State University Press. 406 p.

Fisher, R.F.; Binkley, D. 2000. Ecology and Management of Forest Soils. 3rd ed. New York: John Wiley and Sons, Inc. 489 p.

Foth, H.D. 1978. Fundamentals of Soil Science. 6th ed. New York: John Wiley & Sons. 436 p.

Gilliam, F.S.; Platt, W.J. 1999. Effects of long-term fire exclusion on tree species composition and stand structure in an old-growth *Pinus palustris* (Longleaf pine) forest. Plant Ecology 140: 15-26.

Haywood, J.D.; Harris, F.L.; Grelen, H.E.; Pearson, H.A. 2001. Vegetative response to 37 years of seasonal burning on a Louisiana longleaf pine site. Southern Journal of Applied Forestry 25: 122-130.

Kerr, A. Jr.; Griffis, B.J.; Powell, J.W.; Edwards, J.P.; Venson, R.L.; Long, J.K.; Kilpatrick, W.W. 1980. Soil survey of Rapides Parish Louisiana. Baton Rouge, LA: U.S. Department of Agriculture, Soil Conservation Service and Forest Service in cooperation with Louisiana State University, Louisiana Agricultural Experiment Station. 86 p.

Klute, A. 1986. Water retention: laboratory methods. In: Klute, A., ed. Methods of Soil Analysis Part 1 physical and mineralogical methods. 2nd ed. Madison, WI: Soil Science Society of America, Inc.: 635-660.

Kramer, P.J. 1983. Water Relations of Plants. New York: Academic Press. 489 p.

Landers, J.L.; Van Lear, D.H.; Boyer, W.D. 1995. The longleaf pine forests of the southeast: Requiem or renaissance? Journal of Forestry 93: 39-44.

McGuire, J.P.; Mitchell, R.J.; Moser, E.B.; Pecot, S.D.; Gjerstad, D.H.; Hedman, C.W. 2001. Gaps in a gappy forest: plant resources, longleaf pine regeneration, and understory response to tree removal in longleaf pine savannas. Canadian Journal of Forest Research 31: 765-778.

Outcalt, K.W. 2000. The longleaf pine ecosystem of the south. Native Plants Journal 1: 42-53.

Outcalt, K.W.; Sheffield, R.M. 1996. The longleaf pine forest: Trends and current conditions. Resource Bulletin SRS-9. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station. 23 p.

Patterson, W.B.; Sword, M.A.; Brooker, S. 2004. Response of soil physical properties to the application and intensity of prescribed fire in a young longleaf pine (*Pinus palustris* Mill.) stand. In: Conner K, ed. Proceedings of the Twelfth Biennial Southern Silvicultural Research Conference. General Technical Report SRS-71. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station: 74-78.

Peet, R.K. 2006. Ecological classification of longleaf pine woodlands. In: Jose, S, Jokela, E.J.; Miller, D.L. eds. The Longleaf Pine Ecosystem, ecology, silviculture, and restoration. New York: Springer Verlag, Inc.: 51-93.

Pritchett, W.L. 1979. Properties and Management of Forest Soils. New York: John Wiley & Sons. 500 p.

Ramsey, C.L.; Jose, S.; Brecke, B.J.; Merritt, S. 2003. Growth response of longleaf pine (*Pinus palustris* Mill.) seedlings to fertilization and herbaceous weed control in an old field in southern USA. Forest Ecology and Management 172: 281-289.

Rodríguez-Trejo, D.A.; Duryea, M.L.; White, T.L.; English, J.R.; McGuire, J. 2003. Artificially regenerating longleaf pine during a year of drought. Forest Ecology and Management 180: 25-36.

Soil Survey Staff 2007. National Soil Survey Characterization Data [Online]. Lincoln, NE: Soil Survey Laboratory, National Soil Survey Center, U.S. Department of Agriculture, Natural Resources Conservation Service. Available: www.ssldata.nrcs.usda.gov [April 17, 2007].

Sword Sayer, M.A.; Goelz, J.C.G.; Haywood, J.D. 2006. Effects of prescribed fire on production of foliage by sapling longleaf pine. In: Conner K, ed. Proceedings of the Thirteenth Biennial Southern Silvicultural Research Conference. General Technical Report SRS-92. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station: 478-485.

Sword Sayer, M.A.; Haywood, J.D. 2006. Fine root production and carbohydrate concentrations of mature longleaf pine (*Pinus palustris* P. Mill.) as affected by season of prescribed fire and drought. Trees 20: 165-175.

Van Lear, D.H.; Kapeluck, P.R.; Carroll, W.D. 2000. Productivity of loblolly pine as affected by decomposing root systems. Forest Ecology and Management 138: 435-443.

This page is blank on purpose

Innovations

This page is blank on purpose

Fire Behavior Sensor Package Remote Trigger Design

Dan Jimenez[1], Jason Forthofer[1], James Reardon[1], and Bret Butler[1]

Abstract—*Fire behavior characteristics (such as temperature, radiant and total heat flux, 2- and 3-dimensional velocities, and air flow) are extremely difficult to measure insitu. Although insitu sensor packages are capable of such measurements in realtime, it is also essential to acquire video documentation as a means of better understanding the fire behavior data recorded by individual fire behavior sensor packages. Therefore, coupling each sensor pack with a digital video recorder for simultaneous recording of video and insitu measurements allows viewing of the fire behavior as flames approach, envelope, and disperse past individual sensor packs. The limiting factor in this process is the amount of recordable digital video tape, typically 60 to 90 minutes of record time. This raises both tactical and safety-related concerns, requiring researchers to remain in proximity to the advancing fire in order to activate the fire behavior sensor and video packages. A new remote trigger that eliminates the need for human interaction in order to activate data collection hardware and video equipment has been designed and tested. This trigger system allows the fire behavior and video packages to stay in "sleep" mode until a measurable rise in heat flux is detected. The detection activates the fire behavior sensor package to begin logging data and sends a wireless signal to activate the video package. The setup has been tested for range and interference in open and densely treed plots as well as in fire and nonfire settings, effectively and consistently activating the equipment at distances up to 100 yards.*

Background

Insitu fire behavior measurements are an integral part of fire behavior research (Butler and others 2004). Fire behavior research often starts as an idea that evolves to practical, reproducible experiments in the laboratory setting. Many of the models currently being used by fire managers are tools that were developed in this way.

Models developed in this manner are often calibrated and validated in a controlled environment by changing the key factors that influence fire behavior. Under experimental conditions, air temperature, relative humidity, wind speed, fuel loading, and fuel moisture are systematically changed in order to define and parameterize fire behavior models under various fire conditions. Examples of fire behavior models developed in this manner include Behave (Andrews 1986), Farsite (Finney 1998), and FireStem (Jones and others 2004).

Even though it is possible to manipulate the internal environment within the burning chamber and wind tunnels at the Fire Sciences Lab (Forest Service, Rocky Mountain Research Station), it is often quite different from the outside world. To further calibrate and validate fire behavior models

In: Butler, Bret W.; Cook, Wayne, comps. 2007. The fire environment—innovations, management, and policy; conference proceedings. 26-30 March 2007; Destin, FL. Proceedings RMRS-P-46CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 662 p. CD-ROM.

[1] Chemical Engineer, Mechanical Engineer, Physical Science Technician, and Research Engineer, respectively. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Missoula, MT. Lead author at djimenez@fs.fed.us

developed in the lab, *insitu* measurements are often gathered on prescribed and wildland fires using ruggedized fire behavior sensor packages (FBP). These packages are equipped with heat flux, air temperature, and air flow sensors contained in a compact field setup able to withstand the extreme fire environment (see fig. 1 for FBP details).

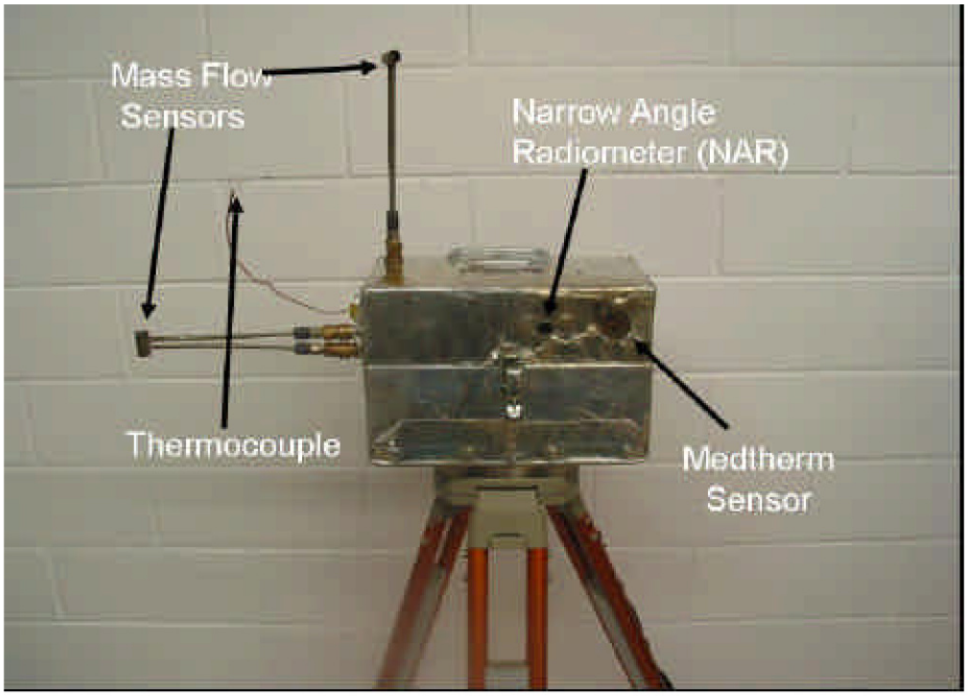


Figure 1—View of fire behavior package with sensors labeled.

Although the *insitu* sensor packages are capable of detailed measurements in real time, the researcher's ability to understand and interpret the data is greatly enhanced when digital video footage of the specific fire behavior at the sensor location is provided. Therefore, each FBP sensor pack is typically coupled with a digital video recorder for simultaneous recording of video and *insitu* measurements. This coupling allows researchers to see video footage of the fire behavior as flames approach, envelope, and continue past individual sensor packs (see fig. 2 for video box and camera details). Collection of this field data is vital to the model calibration and validation process.

Unfortunately, the success of field campaigns is often marginal due to the inherent logistical and safety issues and difficulty associated with anticipating the spread of the fire. The limiting factor in most of these efforts is the short record time associated with the digital video tape, which is typically on the order of 60 to 90 minutes. These short record times often make it too risky for researchers to manually turn on the video cameras when the fire is within an hour or less from burning over the sensor locations. This marginal success rate and increased risk to field personnel lead to the design, testing, and development of a wireless triggering system that eliminates the need for human involvement once the equipment is placed.

Figure 2—View of digital camera enclosure and camera mounting plate.

Materials and Methods

A field deployable ground based sensor package and digital video camera provide *insitu* time resolved measurements of radiant and convective energy transfer from the fire, horizontal, and vertical air flow, air temperature, and digital video footage. The data and video are critical to the success of the field experiments. Research efforts have provided the opportunity to improve these sensors through a series of field trials. The result is a system that is not only robust, but also easy to operate, simple to deploy, fire proof, and light weight. Two packages have been developed:

- **Fire Behavior Flux Package (FBP)—**These packages measure 27 cm by 15 cm by 18 cm and provide an insulated protective enclosure for the data logger, sensors, and other electronics. The standard instruments consist of radiometers that measure total and radiant energy fluxes, small-gauge thermocouples (nominally 0.13 mm diameter wire) to sense flame and air temperature, and pitot-static type velocity probes that detect the magnitude and direction of airflow before, during, and after the fire passes. The packages are typically deployed so that the sensors are directed toward the oncoming fire front. The data loggers are capable of logging more than 1 million samples, which translates to a maximum logging duration of 30 hours at a 1 second sampling rate The most recent version of the packages includes a wireless transmitter that allows the data logger to send a signal to turn on a nearby video camera and begin recording.

- **Video Acquisition Box (VID)**—Digital video imagery is an integral component of our field campaigns. Digital video is acquired by camera(s) housed within 10 cm by 18 cm by 19 cm fireproof enclosures. The camera boxes are designed to be lightweight and compact in order to minimize bulk; they are constructed of 1.6 mm aluminum, weigh approximately 1.0 kg. The boxes have a double lens configuration of high temperature Pyrex glass and a second lens of hot mirror coated glass (Edmund Optics). This multilayer dielectric coating reflects harmful infrared radiation (heat), while allowing visible light to pass through. The cameras can either be turned on manually or can be set to trigger and record through a wireless link to the FBP data loggers. The system has been used throughout a full range of fire size and intensity, from slow moving surface fires to full scale crown fires. Analysis of the visual video images provides an objective method for measuring flame height, flame length, flame depth, flame angle, and fire rate of spread.

Currently four of the latest generation fire behavior/digital camera packages have been manufactured to collect *insitu* measurements in wildland fire environments. Table 1 provides details about individual sensors and their engineering specifications.

Recognizing the need to reduce risk to research team members and improve use and reliability of the instrument system, efforts were directed at developing a safe, ruggedized low cost data logger/camera triggering system. The development of this technology was not trivial and required a constant level of effort over a significant amount of time to develop, construct, and test various trigger methods and designs. Some of the options considered included radio frequency, infrared technology, handheld remote, and automatic systems.

The end result was a wireless trigger design based on the SONY proprietary LANC camera control technology (thus, the system is only compatible with SONY cameras). While any digital video camera that meets the size requirements can be used in the VID boxes, presently only SONY cameras are compatible with the automatic trigger system. The preferred model is the SONY PC-1000 HandyCam digital video camera. These cameras were chosen for their relatively high quality construction, image capability, availability, and associated hardware (such as batteries, cables). The system allows users to trigger the recording mechanism of the camcorder remotely by using its own unique internal computer source code. Although the LANC connector is wired directly to the camcorder, by reverse engineering the signals within the LANC system we were able to determine how to remotely trigger the on/off switch using Radio Frequency (RF), much like a remote garage door opener. Radio frequency was chosen over Infra Red (IR) technology due primarily to line-of-sight and interfering reflectance issues. In order to incorporate the wireless technology into our FBP design each package needed to be fitted with a RF transmitter and likewise the video boxes needed to be fitted with a RF receiver. This equipment was designed and assembled in-house using off the shelf supplies (see fig. 3 and 4). The transmitter and receiver operate off the internal 12V battery power sources available in the FBP and VID cases. Once the FBP and VID boxes are deployed the trigger system is armed from readily accessible switches in the respective enclosures.

Table 1—*Insitu* fire behavior package (FBP) specifications.

Narrow angle radiometer	
Sensor	Thermopile (Meggett Avionics)
Spectral band of sensor	0.15 – 7.0 μm with sapphire window
Field of view	~4.5º controlled by aperature in sensor housing
Transient response	Time constant of sensor nominally 30 m sec
Units of measurement	Calibrated to provide emissive power of volume in FOV in kW-m^{-2}
Total energy sensor	
Sensor	Schmidt-Boelter thermopile
Spectral band of sensor	All incident thermal energy
Field of view	~130º controlled by aperature in sensor housing
Transient response	< 290 m sec
Units of measurement	Total heat flux incident on sensor face in kW-m^{-2}
Hemispherical radiometer	
Sensor	Schmidt-Boelter thermopile (Medtherm Inc)
Spectral band of sensor	0.15 – 7.0 μm with sapphire window
Field of view	~130º controlled by window aperature
Transient response	< 290 m sec
Units of measurement	Radiant energy incident on sensor face in kW-m^{-2}
Air temperature	
Sensor	Type K bare wire thermocouple, new, shiny, connected to 27ga lead wire
Wire diameter	0.13 mm
Bead diameter	~0.16-0.20 mm
Units of measurement	Degrees celsius
Air mass flow	
Sensor	SDXL005D4 temperature compensated differential pressure sensor
Pressure range	0-5 in H_2O
Sensor design	Pressure sensor is coupled to custom designed bidirectional probe with ±60º directional sensitivity
Units of measurement	Calibrated to convert dynamic pressure to velocity in m-s^{-1} assuming incompressible flow
Sensor housing dimensions	150× 180 × 270 (mm)
Housing weight	7.7 kg
Power requirements	12V DC
Power supply	Rechargeable internal battery
Data logging	Campbell Scientific Model CR10X
Sampling frequency	Variable but generally set at 1 Hz
File format	ASCII

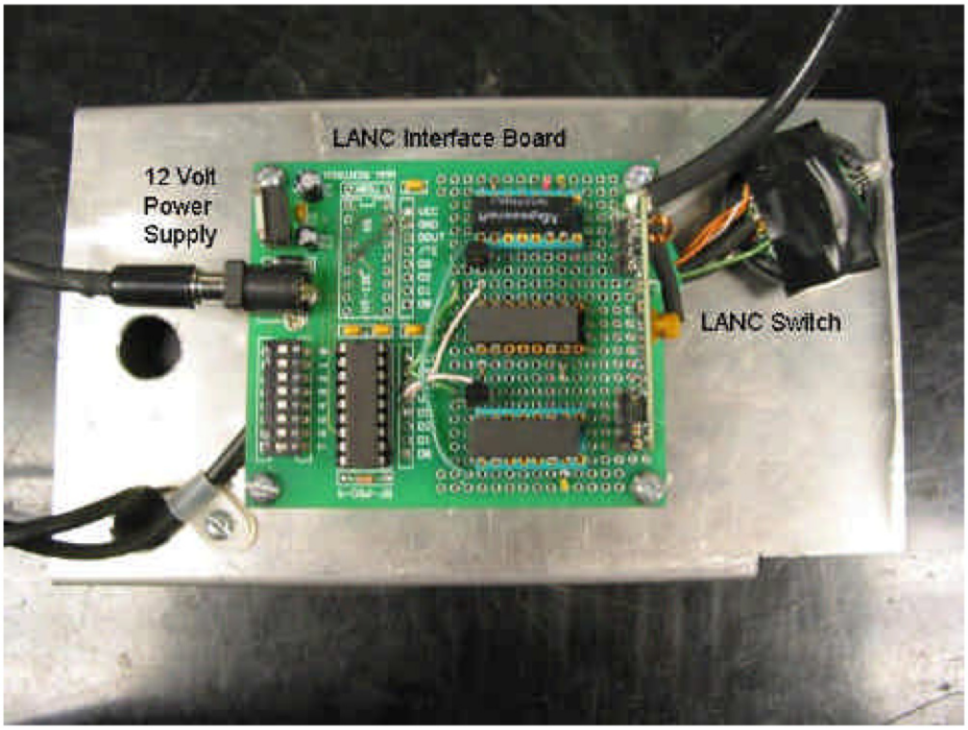


Figure 3—View of RF electronics for automatic camera trigger function.

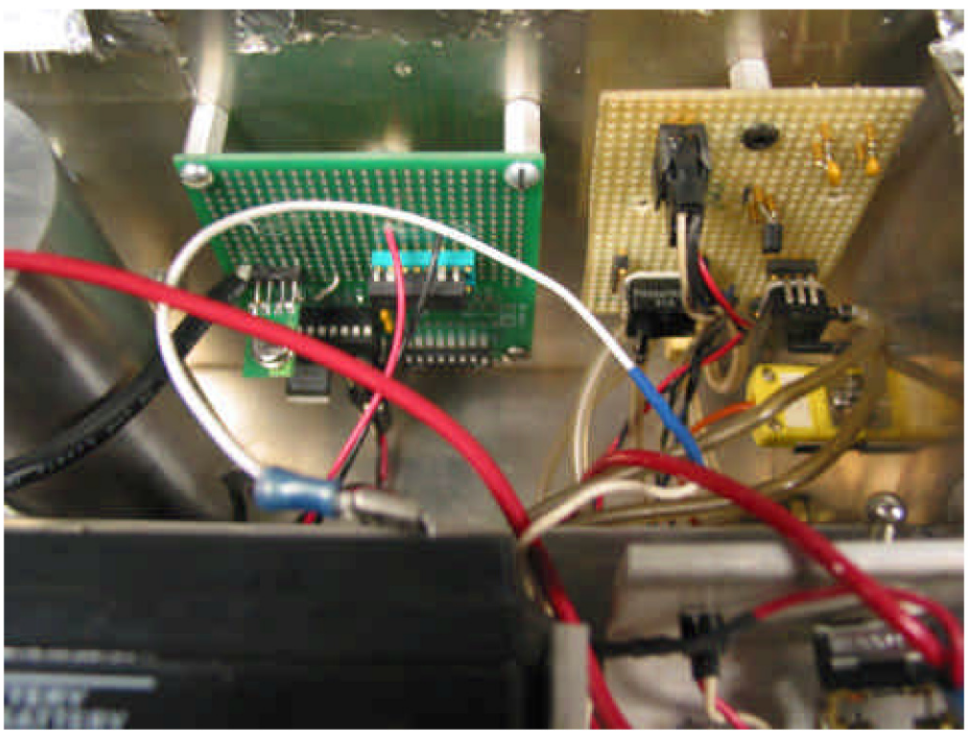


Figure 4—View of trigger electronics mounted in fire behavior package.

Results

This new trigger system allows the fire behavior and video packages to stay in “sleep” mode until a measurable rise in heat flux or air temperature is detected. The detection activates the fire behavior sensor package to begin logging data and sends a wireless signal to activate the video camera package into record mode. The unique capability and hardware have been tested for range and interference over wide range of fire intensities and fuel types in open and densely treed plots as well as in fire and nonfire settings. In all the cases the system effectively and consistently activated the equipment at distances up to 100 yards. The result is a system that is reliable, able to withstand the high temperatures of fires and provides researchers and managers with the capability to quantify fire intensity and behavior safely and effectively. The components required for this conversion cost approximately US$100.

These systems have been used to collect quantitative fire information for support of fire spread models, fire-induced plant and tree mortality studies, firefighter safety zone studies, crown fire transition studies, and for comparing ecosystem management methods and techniques. The systems have been deployed on prescribed and natural fires from Alaska to Florida in the United States, and in Europe and Australia. The designs can be adapted to fit other sensors and data loggers. The FBP enclosures can be constructed for approximately US$300 per box plus cost of data loggers, and sensors. The VID enclosures can be constructed for US$450 per box plus cost of cameras. Users of the hardware and designs include Dr. Bret Butler (Manager of the USDA Forest Service Fire Behavior Team), JoAnn Fites-Kaufman (Manager of the USDA Forest Service Adaptive Management Services Enterprise Team), Dr. Matthew Dickinson (Research Ecologist with the USDA Forest Service Northeastern Research Station), Dr. Miguel Cruz (Research Ecologist with Australian CSIRO Forestry Research Group in Canberra, Australia), Jason Simmons (USDI Bureau of Land Management Fire Ecologist for experiments at Knife-River Village in North Dakota).

Acknowledgments

Funding for this project was provided by the U.S. Department of Agriculture, Forest Service and the Joint Fire Science Program.

References

Andrews, P. 1986. BEHAVE: fire behavior prediction system and fuel modeling system - burn subsystem, part 1. Gen. Tech. Rep. INT-194. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station.

Butler, B.W.; Cohen, J.; Latham, D.J.; Schuette, R.D.; Sopko, P.; Shannon, K.S.; Jimenez, D.; Bradshaw, L.S. 2004. Measurements of radiant emissive power and temperatures in crown fires. Canadian Journal of Forest Research 34:1577- 1587.

Finney, M. 1998. FARSITE: fire area simulator - model development and validation. In: Res. Pap. RMRS-RP-4. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Jones, J.L.; Webb, B.W.; Jimenez, D.; Reardon, J.; Butler, B.W. 2004. Development of an advanced one-dimensional stem heating model for application in surface fires. Canadian Journal of Forest Research: 20-30.

This page is blank on purpose

Fire History and Age Structure Analysis in the Sherburne National Wildlife Refuge: Establishing Reference Conditions in a Remnant Oak Savanna Woodland

Kurt F. Kipfmueller[1] **and Tim Hepola**[2]

Abstract*—Oak savanna woodlands were once a dominant ecotone throughout the upper Midwest. These ecosystems represented a transitional zone between prairie communities to the west that eventually graded into Big Woods forest. Most of the oak savanna landscapes of most of the Midwest were extensively homesteaded and farmed during the middle 1800s and few intact savanna landscapes remain today. Given the current interest in preserving, maintaining, and restoring these systems, it is imperative that the natural factors that have shaped these areas are investigated. This research investigates the potential of developing reference conditions in a relatively intact oak savanna in the Sherburne National Wildlife Refuge, Minnesota. This research provides a context for current management activities centered on maintaining and restoring oak savanna ecosystems.*

Introduction

Oak savanna woodlands were once a dominant ecotone in southwestern Minnesota and throughout the upper Midwest. These ecosystems represented a transitional zone between prairie communities to the west that eventually graded into Big Woods forest. Most of the oak savanna landscape of southern Minnesota (and indeed most of the Midwest) were extensively homesteaded and farmed during the middle 1800s and few intact savanna landscapes remain today.

The structure, origin, and factors that have maintained presettlement oak savanna have not been well documented or established. Fires are thought to have maintained these landscapes, perhaps ignited by Native Americans, but the disturbance regime of these landscapes prior to widespread Euro-American impact remains elusive. Given the current interest in preserving, maintaining, and restoring these systems, it is imperative that the natural factors that have shaped these areas are investigated. Prescribed fires have become an important tool in this regard, but the fire management activities can be better implemented if the natural role of fire is known.

Reconstructing the historic fire regime in oak savanna woodlands is challenging because few are of sufficient age to extend to periods before appreciable impacts by human activities. However, this information is critical for establishing reference conditions that can be utilized to guide restoration activities and initiate management activities.

In: Butler, Bret W.; Cook, Wayne, comps. 2007. The fire environment—innovations, management, and policy; conference proceedings. 26-30 March 2007; Destin, FL. Proceedings RMRS-P-46CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 662 p. CD-ROM.

[1] Assistant Professor, Department of Geography, University of Minnesota, Minneapolis, MN. kurt@umn.edu

2 Federal Cooperator and Regional Fire Ecologist, Region 3, U.S. Fish and Wildlife Service, Fort Snelling, MN.

This research will investigate the potential of developing reference conditions in a relatively intact oak savanna in the Sherburne National Wildlife Refuge, Minnesota. Vegetation plots will be established throughout the remnant to determine the variability in savanna structure and composition. Fire scars will be collected throughout the remnant to determine the variability in fire frequency and associated changes in savanna age-structure and composition related to fire activity.

This research provides a context for current management activities centered on maintaining and restoring oak savanna ecosystems. The principal questions to be answered include:

- What is the fire frequency of the oak savanna remnant and how much variation exists over space?
- How has fire frequency changed over time?
- Are there particular time periods where fire is more/less prominent?
- Are forest compositional and structural characteristics related to fire frequency?
- Has the seasonality of fire changed over time?

Identifying the historic fire regime of oak savanna landscapes, the associated forest structures, and spatial variations is critical to developing sound management guidelines for the restoration of these landscapes. Since this study area is one of the few old-growth remnants of this ecosystem in the refuge, information developed in this study will be useful to management of other parts of the refuge. Few detailed investigations of oak savanna fire history and age structure have been completed. This research will add substantially to our understanding of the vegetation dynamics and disturbance regime that characterize this landscape.

The information in this paper is taken from the study's "Progress Report, Spring 2007."

Field Sampling

Field sampling for age structure and compositional patterns was completed during summer 2006 at 55 points within the study area. Our sampling used an alternating pattern of grid points. At every other grid point we collected increment cores for age determination. Each grid point was inventoried for compositional attributes. Age structure data were collected from 28 points.

Our original design included sampling of 65 grid points. However, some points fell in wetland areas with little or no tree cover and some points were omitted due to their proximity to a cemetery, road, or other impediment to sampling.

Age and composition data collection is complete for the study area; however, we have not collected fire-scar samples as of March 2007. Fire scar samples will be collected during spring and summer 2007 outside the time period where oaks are susceptible to oak wilt.

Stand Composition

A great deal of variation in stand composition exists across the study area (table 1). This is mostly manifested as differences in relative amounts of pin and bur oak as stem density and basal area are quite variable. The study area is largely composed of northern pin oak that dominates both basal area and stem density (and therefore species importance) with lesser amounts of bur oak. In fact, only a limited number of sites are dominated by bur oak. Of the grid points sampled, 92.7 percent contained pin oak and/or bur oak. Aspen and sugar maple were also present at a few sites, sometimes in large numbers.

Table 1—Species identification code for tree species located in plots. Number inventoried indicates the number of each species present in all plots combined. Codes are used in figures in this paper.

Four-letter code	Scientific name	Common name	Number inventoried
QUEL	*Quercus ellipsoidalis*	Northern pin oak	1,386
QUMA	*Quercus macrocarpa*	Bur oak	515
POTR	*Populus tremuloides*	Quaking aspen	241
POGR	*Populus grandidentata*	Big-tooth aspen	15
ACSA	*Acer saccharum*	Sugar maple	75
ACRU	*Acer rubrum*	Red maple	18
FRPE	*Fraxinus pennsylvanica*	Green ash	31
FRNI	*Fraxinus nigra*	Black ash	43
ULAM	*Ulmus Americana*	American elm	9
OSVI	*Ostrya virginiana*	Eastern hophornbeam	5
PRPE	*Prunus pensylvanica*	Pin cherry	7
PRVI	*Prunus virginiana*	Choke cherry	7
PRSE	*Prunus serotina*	Black cherry	14
SASP	*Salix sp.*	Willow	1

Stem density (fig. 1, 2) and basal area (fig. 3, 4) appear to have no spatial pattern at a landscape level. That is, there does not initially appear to be any clustering of large/small values (fig. 5). However, basal area and stem density appear greatest south of the road running east-west through the study area. This has not been investigated using a spatial autocorrelation or variogram approach as of yet to determine if there are spatial patterns that can be quantified.

Tree diversity is generally higher south of the road and includes sugar maple, ash, and cherry in greater abundance than are found elsewhere within the study area (fig. 6). *Corylus sp.* is present in high abundance at nearly every sampled grid point (note we have not yet summarized sapling/shrub data). There are places that have less *Corylus* than others. This may be related to some aspect of the environmental conditions within a stand but more likely reflects fire history to some degree. We suspect that those areas that are burned most frequently might be enabling hazel to germinate readily from root stock. This has led to enormously high stem densities in some areas of the savanna at the sapling/shrub level.

Stem Density Information

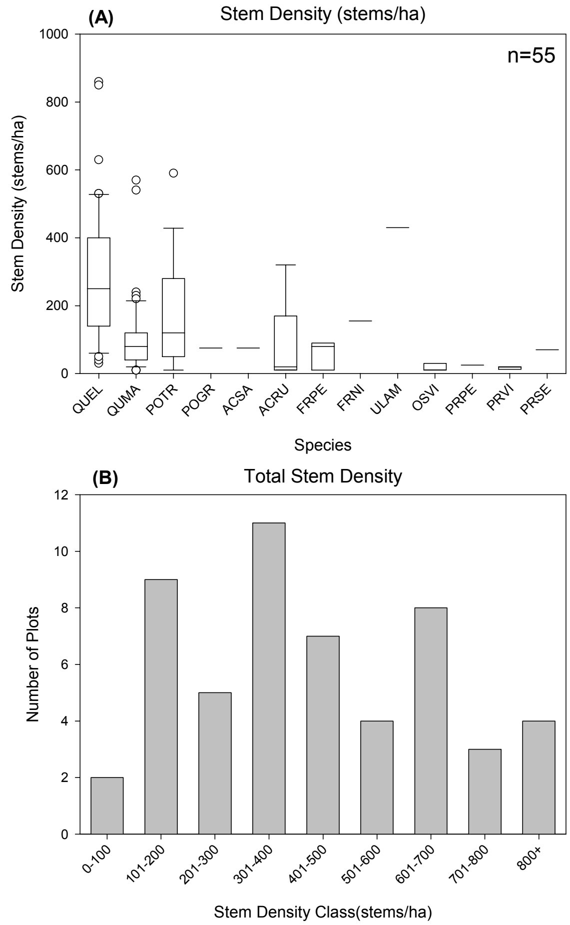


Figure 1—Stem density of sampled forest structure plots in the Sherburne National Wildlife Refuge. (A) Box and whisker plots of stem density of individual species where present in a plot. Horizontal line in each box represents the median value. Each outliner is depicted as an open circle. (B) Total stem density determined in individual plots.

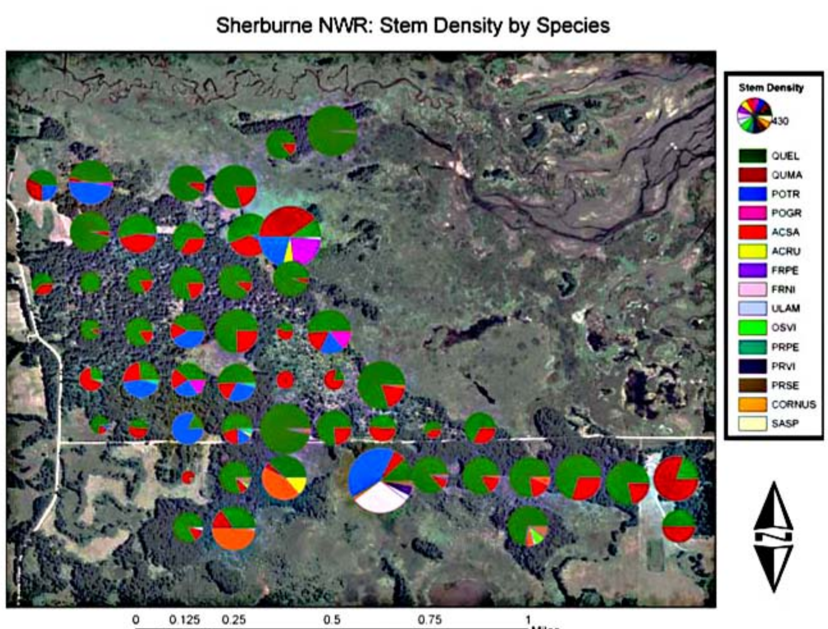


Figure 2—Stem density by species across the landscape. The relative size of each circle reflects the total stem density of each plot.

Basal Area Information

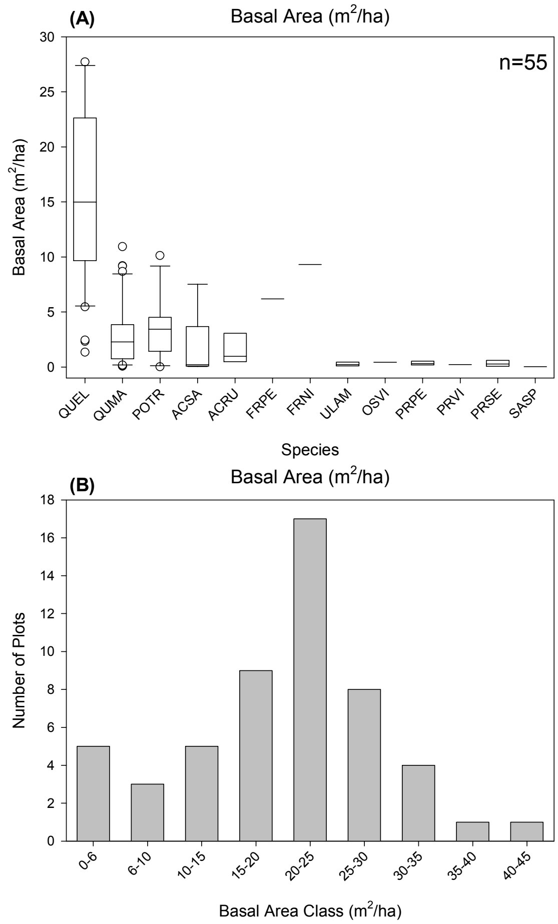


Figure 3—Basal area of sampled forest structure plots in the Sherburne National Wildlife Refuge. (A) Box and whisker plots of basal for individual species where present in a plot. Horizontal line in each box represents the median value. Each outlier is depicted as an open circle. (B) Total basal area determined in individual plots.

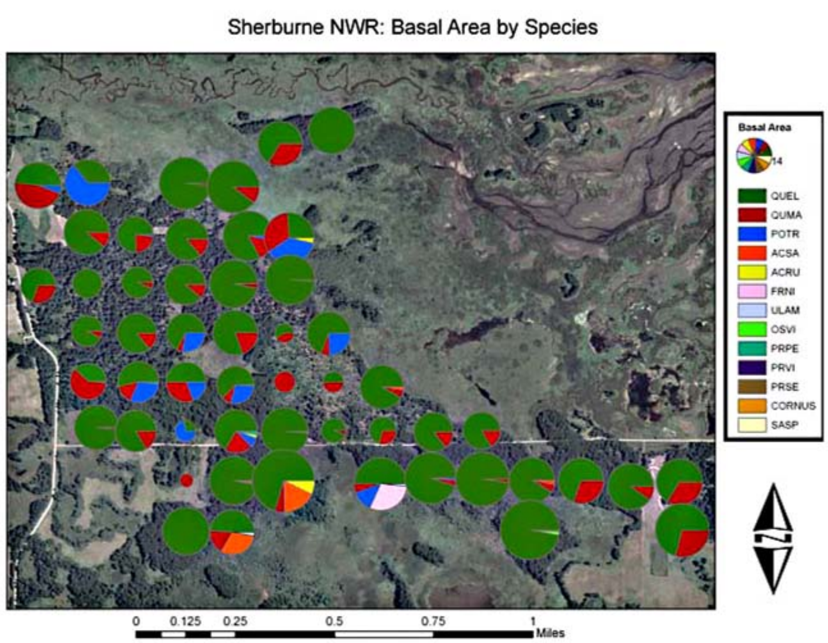


Figure 4—Basal area by species across the landscape. The relative size of each circle reflects the total stem density of each plot.

Species Importance Values

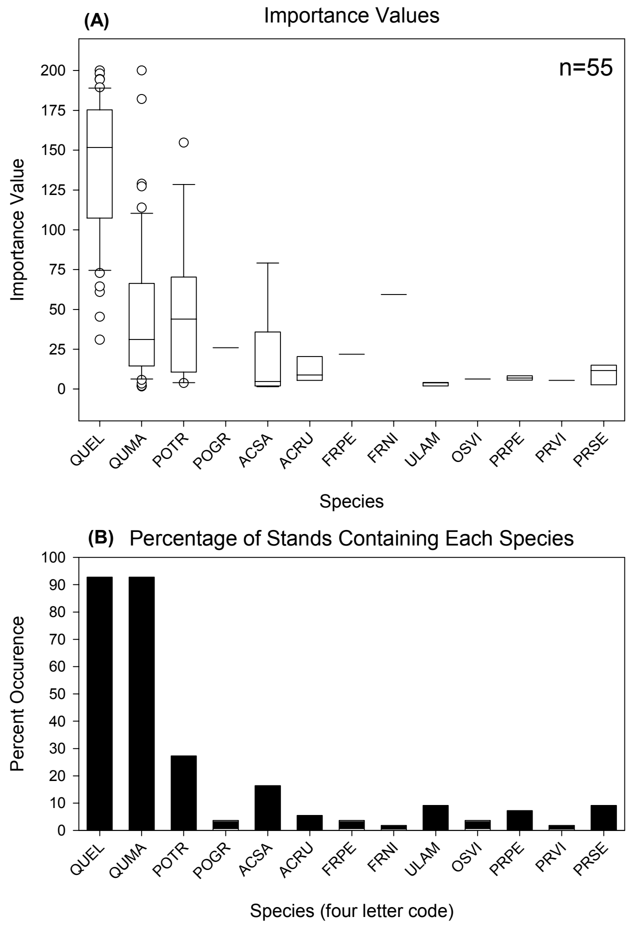


Figure 5—(A) Box and whisker plots of importance values for individual species where present in a plot. Importance value is calculated by adding together the relative density and basal area of a given species (B) after first multiplying each by 100. Importance values range from 0 to 200, with 200 indicative of a stand that is composed of only one tree species. Horizontal line in each box represents the median value.

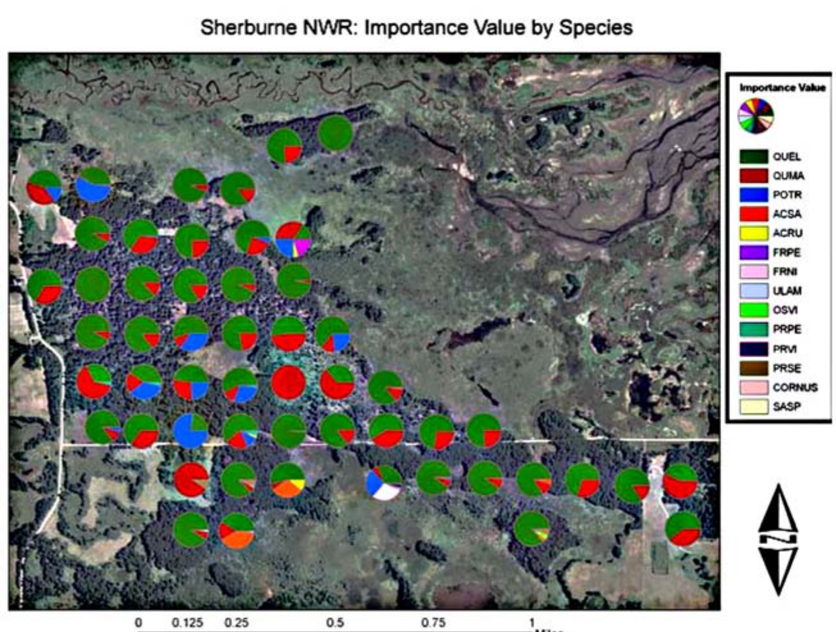


Figure 6—Basal area by species across the landscape.

Age Structure Data

We are processing increment cores for determination of age-class patterns. We hope to use the age-structure information to refine our search for fire-scarred trees. We will concentrate our search effort for fire scars near areas that contain older trees to help extend the fire history further back in time.

Preliminary analyses indicate that most of the sampled trees germinated in the mid 1900s. There appears to be a dramatic pulse in regeneration during the early 1950s. The oldest trees dated so far have inner-ring dates in the middle 1800s with a few that extend further into the past.

The low density area near the center of figure 7 contains trees dating to the early 1800s (1801 is the oldest so far). Increment cores from these trees were collected separately from the age-structure grid points for a dendrochronology class during fall 2006. Older trees also appear to be near the outer edges of the study area.

We have not assessed the relative ages of bur oak versus pin oak in a formal sense, but it appears the oldest trees are mostly bur oak.

Figure 7—Oldest sampled trees by species.

Tree Size Observations

In nearly every plot where both *Quercus ellipsoidalis* and *Q. macrocarpa* were present, *ellipsoidalis* was larger in diameter on average (fig. 8). However, initial examination of the age data suggests that *Q. macrocarpa* were nearly always older.

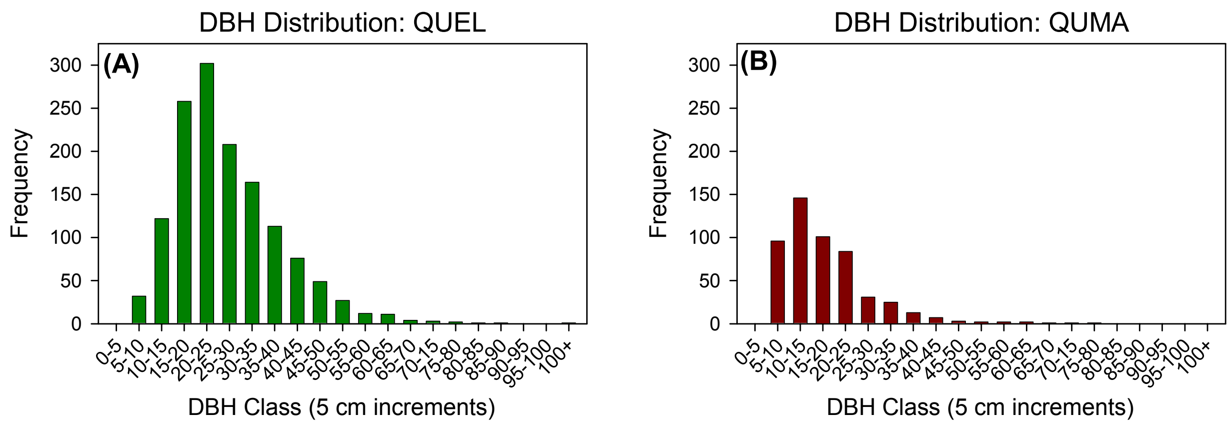


Figure 8—Diameter distribution of *Quercus ellipsoidalis* (A) and *Q. macrocarpa* (B) within the study area. Diameter at breast height is reported in 5-cm classes. Trees less than 5 cm in diameter were considered saplings and were recorded elsewhere.

Application of Ground-Based LIDAR for Fine-Scale Forest Fuel Modeling

E. Louise Loudermilk[1], Abhinav Singhania[2], Juan C. Fernandez[2], J. Kevin Hiers[3], Joseph J. O'Brien[4], Wendell P. Cropper Jr.[5], K. Clint Slatton[6], and Robert J. Mitchell[7]

***Abstract**—Frequent (1 to 5 year) low intensity fire regimes of longleaf pine (Pinus palustris) savannas of the Southeastern United States create a continuous fuelbed of understory grasses, forbs, flammable pine needle litter, with interstitial hardwood shrubs. Measuring the spatial heterogeneity of these fine-fuels can be difficult, requiring intensive field sampling. Ground-based LIDAR (LIght Detection and Ranging) may prove useful in this aspect, collecting accurate three-dimensional point-clouds of objects at the sub-centimeter level. Here we present the methods and discuss the applicability of using a ground-based LIDAR system, the Mobile Terrestrial Laser Scanner (MTLS), to measure variation in fuelbed structure. The MTLS consists of Optech's ILRIS 3_6D ground based laser scanner mounted on a lift atop a mobile platform, which increases its versatility in capturing details about the terrain at multiple angles, vertically and horizontally. We recorded sub-meter, spatially explicit fuel characteristics using the MTLS and manual point-intercept sampling techniques in multiple plots within a longleaf pine woodland. The LIDAR data required additional processing to make it comparable to the field data. This process involved merging individual scans of a plot taken at different angles and cropping out the areas of interest from the point clouds. Preliminary results illustrate that the fuelbeds can be classified into distinct categories with distinct characteristics, such as bulk density. The MTLS may be applicable for measuring spatially explicit plot-to-stand level fuel structure, continuity, and volume. Coupling MTLS derived fuel maps with fire behavior, through thermal imagery and modeling, combine to produce a promising strategy to connect fuels and fire at much finer scales than attempted before. This approach is particularly well suited to pine savannas with high frequency, low intensity fire regimes and other fuel types with fuel heights <10 m.*

Objectives

Our purpose was to introduce a new approach to measuring fine-scale fuelbed structure in forested ecosystems. Our first objective was to provide a detailed background of the technology used; the Mobile Terrestrial Laser Scanner (MTLS), a ground-based LIght Detection and Ranging (LIDAR) system. Our second objective was to present the field data collection procedures and beginning stages of the data processing methodology. Our third objective was to provide a brief discussion of the possible applicability of the MTLS in forest fuel, fire behavior, and fire effects modeling.

In: Butler, Bret W.; Cook, Wayne, comps. 2007. The fire environment—innovations, management, and policy; conference proceedings. 26-30 March 2007; Destin, FL. Proceedings RMRS-P-46CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 662 p. CD-ROM.

[1] Graduate Research Assistant, School of Natural Resources and Environment, University of Florida, Gainesville, FL. louisel@ufl.edu

[2] Graduate Research Assistants, Geosensing Engineering and Mapping Center, University of Florida, Gainesville, FL.

[3] Research Fellow in Fire Ecology, Joseph W. Jones Ecological Research Center, Ichauway, Newton, GA.

[4] Research Ecologist, U.S. Department of Agriculture, Forest Service, Athens, GA.

[5] Assistant Professor, School of Forest Resources and Conservation, University of Florida, Gainesville, FL.

[6] Assistant Professor, Department of Civil and Coastal Engineering and Department of Electrical and Computer Engineering, University of Florida, Gainesville, FL.

[7] Forest Ecology Scientist, Joseph W. Jones Ecological Research Center at Ichauway, Newton, GA.

Introduction

The frequent (1 to 5 year) low intensity fire regimes of longleaf pine (*Pinus palustris*) savannas of the Southeastern United States create a relatively continuous fuelbed of understory grasses, forbs, flammable pine needle litter, with scattered hardwood shrubs. Although this understory fuelbed is often considered homogenous within a stand, considerable heterogeneity exists at fine spatial scales (sub-meter; see table 1). Understanding the variation in these fine fuels is important for linking fuel, fire behavior, and fire effects modeling. Capturing the heterogeneity in fine-fuels can be difficult, requiring intensive field sampling. A LIDAR (LIght Detection and Ranging) system with three-dimensional (3D) capabilities and high accuracy information may provide critical spatial information needed to assess these fuel characteristics.

Table 1—Results from cluster analysis identifying discrete categories of 'fuel cells' at sub-meter scales. Heights are in centimeters.

Cluster no.	% of fuelbed	Mean fuelbed height	Mean litter height	Description of fuel cells
2	40	20	11	Wiregrass with perched pine litter
4	25	52	10	Shrub, wiregrass, and perched litter
3	13	11	6	Pine litter in interstitial space between wiregrass
5	10	29	5	Shrubs with oak litter
8	6	53	25	Other graminoids with perched pine
1	5	4	3	Oak and pine litter on mineral soil

Airborne LIDAR has been used extensively for measuring multidimensional forest metrics, namely tree canopy height, canopy density, tree volume/biomass (Hall and others 2005; Lefsky and others 1999; Nelson and others 1988) as well as understanding the spatial structure of a forest (Drake and Weishampel 2000) over large landscapes. Airborne LIDAR has not, however, been able to measure forest metrics related to understory vegetation at the sub-meter scale. Ground-based LIDAR could be used as a potential tool to address this problem.

Ground-based LIDAR is a new tool that brings the elements of airborne LIDAR to a finer-scale, collecting 3D point-clouds of objects at the sub-centimeter level. A complete description on the technology can be found in Lichti and others (2002) and Fröhlich and Mettenleiter (2004). In this study, we present the methods and discuss the applicability of using a ground-based LIDAR system, the Mobile Terrestrial Laser Scanner (MTLS), for measuring small-scale spatial variation in fuelbed structure. The MTLS consists of Optech's ILRIS 3_6D (Intelligent Laser Ranging and Imaging System) ground based laser scanner that is mounted on a lift atop a mobile platform (fig. 1), increasing its versatility in capturing details about the terrain at multiple angles. The ILRIS uses a 1,500 nm wavelength laser with a pulse frequency of 2,500 points per second, recording first or last returns of each laser pulse (user defined). The field of view is 40° in both horizontal as well as vertical plane. It has a range of 5 m to 1,500 m (at 80 percent reflectivity). The ILRIS has a pan-tilt base providing it a 360° rotation in the horizontal plane and about ± 40° in the vertical plane. The lift makes possible the vertical

Figure 1—A ground-based LIDAR system: The MTLS (Mobile Terrestrial Laser Scanner) is used to mobilize Optech's ILRIS 3_6D (yellow instrument) for collecting high-resolution 3D point-cloud laser data.

movement of the scanner up to a height of about 9 m. Mean point spacing of the laser data is user defined, typically ranging from 1 mm to a few cm. The ILRIS collects: (1) x, y, z values with respect to the position of the laser sensor; (2) intensity values of the return; (3) true color RGB values for each point obtained from an integrated and calibrated digital camera within the instrument.

The strength of the ground-based unit lies in its ability to produce accurate high-resolution data. This is not possible using airborne LIDAR, which covers large areas, while producing data at an average resolution of about 0.5 m horizontally. The MTLS, on the other hand, is a static, stop and scan laser scanner that covers limited area, but captures data at an average spot spacing at a sub-cm level. The MTLS, with its high-density point data, provides a useful tool for characterizing the fuelbed, particularly highly accurate fuel volumes.

As a newly developed instrument, there are few published examples of the application of ground-based LIDAR in forestry (but see Hopkinson and others 2004; Watt and Donoghue 2005). We know of no published work on the use of ground-based LIDAR to measure understory vegetation traits. This research provides a unique opportunity to develop an approach to accurately measure spatially explicit sub-meter vegetation characteristics.

Study Areas

Ichauway Preserve

A portion of the research was performed at Ichauway, an 11,000 ha reserve of the Jones Ecological Research Center in southwestern Georgia, USA. Ichauway is located within the Plains and Wiregrass Plains subsections of the Lower Coastal Plain and Flatwoods section (McNab and Avers 1994). Ichauway has an extensive tract of second-growth longleaf pine and has been managed with low intensity, dormant-season prescribed fires for at least 70 years, at a frequency of 1 to 3 years. The specific study site used had a 1 year rough.

Ordway-Swisher Biological Station

A portion of the research was also performed at the Ordway-Swisher Biological Station, a 3,800 ha reserve in north-central Florida, USA. It is managed by the University of Florida's Department of Wildlife Ecology and Conservation. Ordway has a large amount of second-growth longleaf pine as well and has been intensively managed for the past two decades with prescribed fire. The current fire frequency is 2 to 5 years, with some areas reaching more than 10 years. The specific study site used had a 2 year rough.

Field and Ground-LIDAR Data Collection

In early spring 2007, a total of 30 georeferenced 4 m x 4 m plots were set up throughout the forest matrix with a goal to capture fine-scale (< m) variation in fuelbed characteristics in relation to overstory structure (that is, within forest gaps, along gap edges, and so forth). The 4 m x 4 m area was chosen because it was a large enough area to capture heterogeneity at sub-meter scales, but small enough to support intensive sampling with minimal impact to the vegetation. Spatially explicit point-intercept sampling data were recorded for each plot using a graduated dowel rod. We used 0.33 m spacing between traditional point-intercept samples, including sampling along the edge of the plot, totaling 169 sample points within each plot (fig. 2). A ladder was suspended horizontally across each plot using make-shift saw-horses at each end to sample the interior of the plot, taking care not to disturb the vegetation. The spatially explicit arrangement and sampling intensity were performed to capture the spatial variation of the fuelbed found within this small (16 m^2) area and to relate to the cm-level 3D laser data collected from the ground-based LIDAR. At each sample point, fuelbed and litter depth (or height), as well as presence/absence of fuel and vegetation types, were recorded.

Within 2 weeks of field data collection, the MTLS collected ground-LIDAR data on all 30 plots. Prior to data collection, reference targets (consisting of a Styrofoam ball on top of a metal rod, fig. 3) were placed at all four corners of the plot. A double reference target (two Styrofoam balls on one metal rod) was used at the northwest corner of each plot to orient the plot for data processing. An additional one to four reference targets were placed just outside the 4 m plots to align lidar volume estimations with biomass clip plots. Biomass reference targets were placed in relatively homogeneous fuel types, with a circular area of 0.3 m^2. The MTLS was restricted to mapped roads

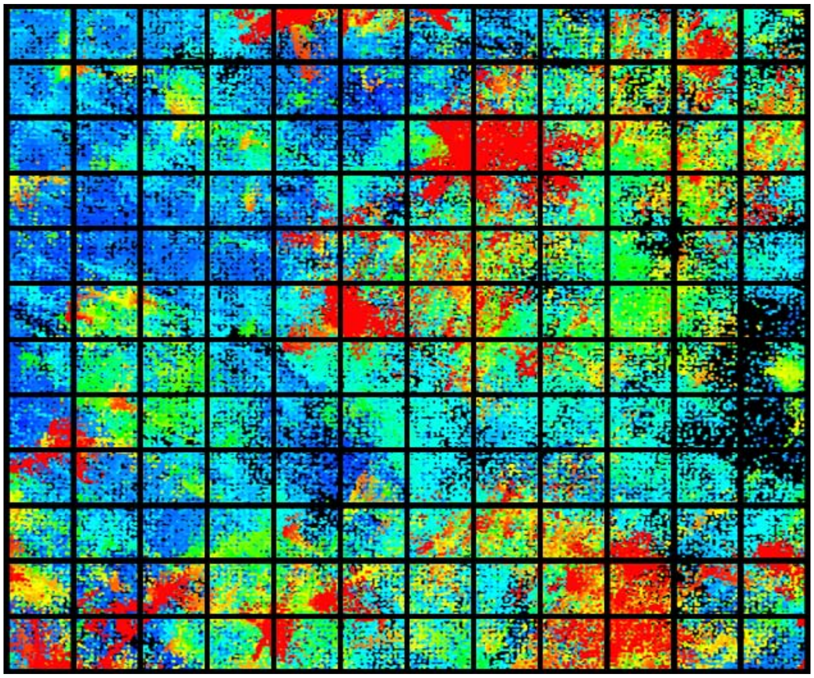


Figure 2—Example of the spatial grid pattern of field data points and corresponding LIDAR heights (color gradients) within the 4 m x 4 m plot (2D aerial view). Point-intercept data on fuel traits were collected every 0.33 m (cross sections of the grid) throughout the plot.

Figure 3—Example of a 4 m x 4 m plot, with reference targets set up for ground-LIDAR acquisition and subsequent data processing.

and trails, as well as a buffer of 6 to 10 m around each plot, to reduce site degradation and vegetation disturbance. The ILRIS was lifted to an appropriate height at each plot (6 to 7 m), with a goal to capture as much of an aerial view as possible, without bole or canopy obstruction. The ability to vary the height and angle of the ILRIS (hence, using the MTLS) allows significant reduction in shadowing effects within the fuelbed that may be found when using the ILRIS on a tripod. The ILRIS was set to a downward angle tilt of 25° (from horizontal). A true color digital photograph was taken by the ILRIS for each plot, and used in the field to delineate the focus area. This eliminates any unnecessary data collection, enhancing efficiency in the field and reducing file storage size. First-return laser pulses were recorded with 5 mm mean point spacing. One scan was taken on opposite sides of the plot to further reduce shadowing effects and ensure more accurate and complete sub-cm-scale data for both the 4 m and biomass plots. These two scans were merged in the processing stage to a single spatial coherent data set. Data collection with the MTLS took approximately 20 minutes per plot.

After laser data collection, the biomass plots were analyzed with traditional field methods. The biomass reference targets were used as the center of a 40 cm diameter circular area (area of 0.3 m^2). First, 20 random point-intercept samples were taken throughout the plot. The same fuelbed traits were measured as described above. All vegetation was removed from the plot, separated into perched litter, fine fuels (grasses, forbs, ground litter), woody vegetation, pine cones, and other woody debris, and subsequently dry weighed.

Data Processing

Initially, data processing involved converting the collected laser data from binary to ASCII format (that is, parsing). This raw data includes a four column text file containing x, y, z coordinates and laser return intensity values for each of the sampled laser points. Of the two scans taken per plot, the first was horizontally rectified by compensating for the original scanning geometry, where the instrument had a downward tilt of 25° with respect to horizontal. Then common points (reference targets) between the two scans were identified and their coordinates were used to compute the parameters of a 3D conformal transformation with a unit scale factor (Wolf and Ghilani 1997). The conformal transformation was then applied to the second scan to bring it to the same coordinate frame of the first scan, combining them into a single spatially coherent data set. The merged data set was then rotated about the z axis to orient the point cloud in cardinal space. A constant value offset was added to the height values in order to set the ground points to a value of zero. The digital image and the double reference target for the NW corner of the plot were especially helpful in this merging process and in orienting the plot in cardinal space. The 4 m x 4 m plot area (fig. 4) and biomass plot areas were clipped from the resulting merged scans using the reference targets. Roughly 600,000 to 700,000 sample laser points were found within each 4 m x 4 m plot. Point-densities, volume estimates, and height distributions were calculated for each biomass plot and each 4 m x 4 m plot.

Total volume (cm^3) was calculated in each plot by determining the presence/absence of laser points within each cm^3 space. The process involved using a 1 cm^3 3D window to move through each plot's point cloud in the x, y, and z direction, respectively. Every time a point (or points) was found in the 3D window, 1cm^3 of volume was added to the volume counter for that plot.

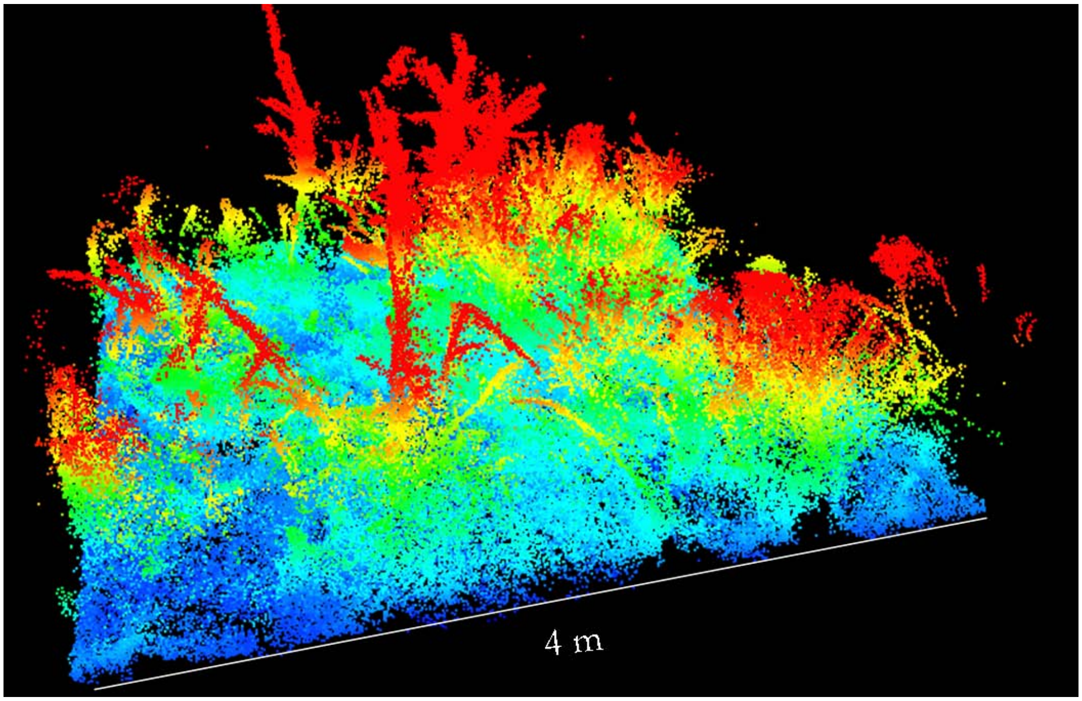


Figure 4—Example output 3D ground-LIDAR point-cloud of a 4 m x 4 m plot. (This is not the same plot as fig. 3.) Color gradients represent fuelbed height variation.

Applicability: Fuel Analysis and Modeling

We used cluster analysis to categorize variation across the fuelbed (table 1). These distinct clusters of fuels at these fine scales are termed 'fuel cells.' The distribution and arrangement of these fuel cells represent within-fuelbed variation, each with distinct bulk density, height, and composition. These categorized fuel cells may be used to classify the laser data into fuel types and then used to project fuel types across a similar dataset. Ultimately, these fuel cells may produce fine-scale burn heterogeneity, which may be important to managing prescribed fire effects.

With this new approach to measuring fine-scale fuels, future work will explore several aspects of fuelbed assessment that have been difficult to measure and understand thus far. We plan to use geostatistical techniques (for example, variogram analysis, model fitting, and so forth) to assess fuelbed variability across spatial scales, utilizing both the laser and field data. For instance, we can gain insight into how fuel depth varies with fuel type across the fuel bed. As fuel structure is apparent within the laser data outputs (fig. 4), it may be possible to run a pattern recognition analysis (with both field and laser data) to ultimately train the model to recognize certain fuel types across the fuelbed. With respect to fine-fuels, we are currently using ground-based LIDAR to accurately estimate fuel volumes, then relate this to field biomass, for more precise fuel volume measurements in bulk density calculations. We also hope to better understand bulk density estimates of particular fuels, such as common shrubs and grasses, utilizing the volumetric measurements (cm^3) extracted from the laser data. For instance, the volume estimates can be segregated in particular horizontal plains of data (such as every 10 cm) within the understory or for just one plant and related to leaf area. Such detailed information is critical for improving our understanding of the physical structure of fuelbeds that influence fire behavior, such as surface area to volume ratios, packing ratio, and fuel arrangement (such as horizontal continuity, patchiness). Furthermore, fine-scale variation in fuels, as measured by ground-based LIDAR, may provide insight to variation found within the plots that may be attributed to the forest structure (for example, forest gaps, edges), or spatial arrangement of the adult pines near the plot.

In a linked study, we are investigating how fine-scale variation in fuels may drive fire behavior and second order fire effects. We are using time-elapsed thermal imagery within these plots (as they burn) to assess fine-scale fire intensity, with a goal to relate the output thermal signatures to the fuel structure captured with both field and laser data. This imagery was recorded atop a custom telescoping lift above each plot. The results showed that fuel and fire behavior heterogeneity at this fine-scale varied together (spatial autocorrelation). Understanding fine-scale fuel heterogeneity and fire behavior will aid in better understanding the varying fire intensity effects on pine seedling and young oak demographics, which have been complex and difficult to study (Rebertus and others 1989).

Conclusions

Here, we introduce a novel approach to assessing fine-scale fuels and a preliminary description and assessment of some of the data collected and possible research applications. As this research progresses, we hope to learn more about the complexities of the fuelbed and its influence on fire behavior and secondary fire effects.

The variation in longleaf pine fuelbeds captured using this new technique is complex in physical structure. These structures (within fuelbed heterogeneity) may affect fine-scale fire behavior and subsequent plant response, especially related to pine seedling and young oak interactions. Ground-based LIDAR is a new tool that may be used to measure and analyze these vegetative features at multiple spatial scales and more accurately quantify important fuelbed properties, such as bulk density, packing ratios, and continuity.

References

Drake, J.B.; Weishampel, J.F. 2000. Multifractal analysis of canopy height measures in a longleaf pine savanna. Forest Ecology and Management 128: 121-127.

Fröhlich, C.; Mettenleiter, M. 2004. Terrestrial laser scanning – new perspectives in 3D surveying: conference proceedings. 3-6 October 2004; Freiburg, Germany. Proceedings ISSN 1682-1750: International Archives of Photogrammetry, Remote Sensing and Spatial Sensing: 7-13.

Hall, S.A.; Burke, I.C.; Box, D.O.; Kaufmann, M.R.; Stoker, J.M. 2005. Estimating stand structure using discrete-return lidar: an example from low density, fire prone ponderosa pine forests. Forest Ecology and Management 208: 189-209.

Hopkinson, C.; Chasmer, L.; Colin, Y.-P.; Treitz, P. 2004. Assessing forest metrics with a ground-based scanning lidar. Canadian Journal of Forest Research 34: 573-583.

Lefsky, M.A.; Harding, D.; Cohen, W.B.; Parker, G.; Shugart, H.H. 1999. Surface Lidar Remote Sensing of Basal Area and Biomass in Deciduous Forests of Eastern Maryland, USA. Remote Sensing of Environment 67: 83-98.

Lichti, D.D.; Gordon, S.J.; Stewart, M.P. 2002. Ground-based laser scanners: operation, systems and applications. Geomatica 56: 21–33.

McNab, H.; Avers, P.A. 1994. Ecological subregions of the United States. Section descriptions. Washington, DC: U.S. Department of Agriculture, Forest Service.

Nelson, R.; Krabill, W.; Tonelli, J. 1988. Estimating forest biomass and volume using airborne laser data. Remote Sensing of Environment 24: 247-267.

Rebertus, A.J.; Williamson, G.B.; Moser, E.B. 1989. Longleaf pine pyrogenicity and turkey oak mortality in Florida xeric sandhills. Ecology 70: 60-70.

Watt, P.J.; Donoghue, D.N.M. 2005. Measuring forest structure with terrestrial laser scanning. International Journal of Remote Sensing 26: 1427-1446.

Wolf, P.R.; Ghilani, C.D. 1997. Adjustment Computations: Statistics and Least Squares in Surveying GIS. New York, NY: John Wiley & Sons, Inc.584 p.

This page is blank on purpose

Innovations in Fuels Management: Demonstrating Success in Treating a Serious Threat of Wildfire in Northern Minnesota

Dennis Neitzke[1]

Abstract*—This case study illustrates the positive effects of strategic fuels treatments in continuous heavy fuels. In 1999, a severe windstorm blew down close to 1,000 square miles of forest land in northern Minnesota and Canada. As much as 400,000 acres of the blowdown occurred in the Boundary Waters Canoe Area Wilderness. Fire experts were invited to assess the hazardous fuels problem and to design and implement a treatment strategy that would effectively slow the spread of wildland fires and reduce the threat of a wildfire moving out of the Boundary Waters Canoe Area Wilderness (BWCAW) and into adjacent homes and businesses along a highly used area of the Superior National Forest. Treatment blocks were strategically placed in a brick/grid pattern across the blowdown landscape in order to slow a wildfire's progress while only treating 15 to 20 percent of the total area. Success of those treatments was demonstrated when a large fire threatened the area of businesses and homes along the Gunflint Trail in July 2006. While the brick/grid pattern treatments were not completely in place, the fuel treatments were effective in containing the 32,000 acre Cavity Lake Fire. The fire behavior dramatically dropped within the big treatment units, allowing firefighters to successfully implement control tactics and protect $31 million worth of structures in the direct path of the fire.*

Introduction

The setting for this case study is northeastern Minnesota, the home of the Superior National Forest (fig. 1). This part of the State is dominated by boreal forest, combining aspen, paper birch, balsam fir, white and black spruce, jack pine, red pine, and white pine. All of these species with the exception of red and white pine are short lived trees (60 to 100 years) and are adapted to large-scale disturbance, including wild fire. After heavy logging at the turn of the 19th century, the area was designated as a National Forest where reforestation

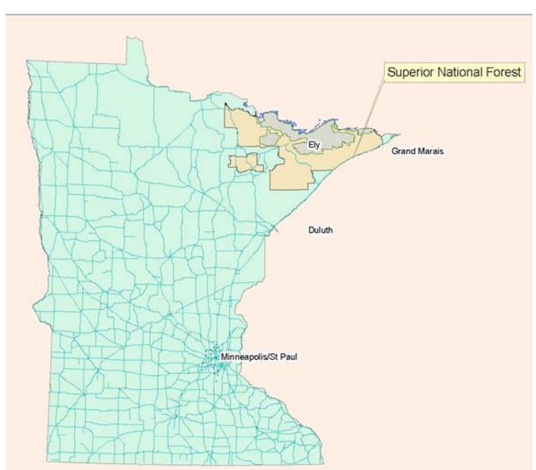


Figure 1—The Superior National Forest, in the northeastern part of Minnesota, borders Canada and shares a vast Wilderness resource with Canada, known as the Boundary Waters Canoe Area Wilderness.

In: Butler, Bret W.; Cook, Wayne, comps. 2007. The fire environment—innovations, management, and policy; conference proceedings. 26-30 March 2007; Destin, FL. Proceedings RMRS-P-46CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 662 p. CD-ROM.

[1] District Ranger, U.S. Department of Agriculture, Forest Service, Superior National Forest, Minnesota. ddneitzke@fs.fed.us

and protection became the primary objectives for decades. By the 1990s the Superior National Forest had abundant second growth forest. Although by this time forest management was common, a large part of the Forest had become mature to overmature and more than 1 million acres had been protected as the Boundary Waters Canoe Area Wilderness (BWCAW).

On July 4, 1999, a tremendous wind and rain storm caused substantial damage to the Superior and Chippewa National Forests as well as other public and private lands throughout northeastern Minnesota and Ontario, Canada. The storm, described as a Derecho, brought the jet stream to the surface of the forest, and winds of nearly 100 miles per hour flattened roughly 1,000 square miles of forest land. Approximately 477,000 acres of the Superior National Forest were damaged by the blowdown, concentrated in the BWCAW and in small, scattered areas on the remainder of the Forest. Fuel loadings in the damaged areas increased from an average of 10 tons per acre to more than110 tons per acre. A five county area in northeastern Minnesota was declared a Federal disaster by the President on July 28. The path of blowdown stretched over 125 miles and at times was 20 miles wide and as is typical for the Lake States lies in a direction from southwest to the northeast. Dozens of homes and businesses were damaged, hundreds of miles of roads were closed by tree fall, and more than 60 people camping in the BWCAW received injuries. The Superior National Forest recognized the immediate threats to life and property and initiated search and rescue efforts for those injured. Our second priority was to open roads and clean up property and businesses outside of the BWCAW.

Once the immediate health and safety of residents and visitors had been taken care of, the Forest set about to understand the long-term changes created by this new massive fuel bed. Obvious, at least to the Forest Service, was the increased risk of a major wildfire threatening everything in the path of the blowdown. Of particular concern were three narrow corridors of heavy private ownership that bisected the Wilderness; those corridors lie in the direct path of the blowdown. This case study involves one of those corridors, called the Gunflint Trail, basically a County Highway that bisected the BWCAW and dead ended near Canada. Directly in a downwind path was the urban interface of the upper Gunflint Trail where more than $31 million of homes and business exist. This area is also one of the most popular entry points for the Boundary Waters Canoe Area Wilderness (fig. 2).

Assessment

To fully understand the magnitude of the threat and to help develop alternative strategies, the Forest enlisted the help of a team of experts in fire behavior and fuels management analysis to provide an assessment of the Forest's situation. The team was lead by Dr. Mark Finney of the Rocky Mountain Research Station of the USDA Forest Service. Analysis was completed on several aspects of fire behavior to assist in planning necessary recovery measures. Modeling was done on fuel to estimate the risk of a fire spreading into the areas of homes and businesses within the Wilderness (fig. 3). This information was used to determine the breadth of fuels treatments necessary within the Wilderness in order to reduce the probability of a fire exiting the Wilderness. Other modeling was done to determine the intensity of behavior expected from a blowdown fire to allow us to determine appropriate suppression strategies and tools.

Figure 2—The nearly complete blowdown near the Seagull Lake area at the end of Gunflint Trail. Seagull Lake is a highly popular recreation site.

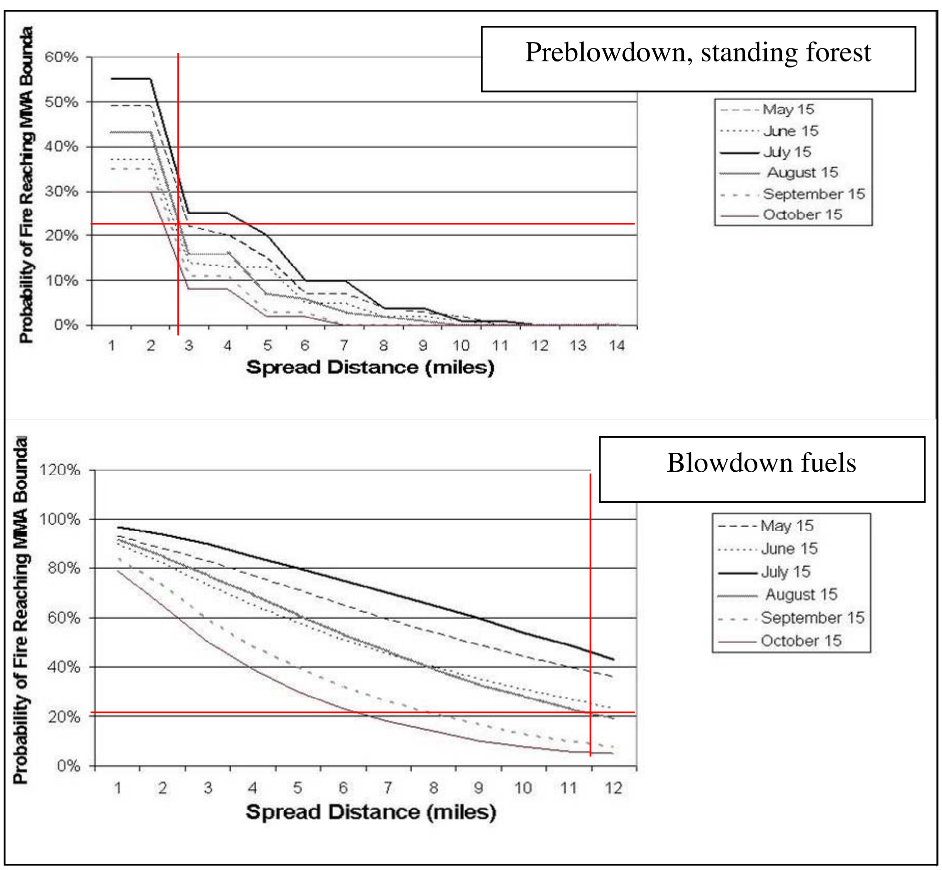


Figure 3—Comparison of probabilities that a wildfire might exit the BWCAW boundary and enter the urban interface. Top chart demonstrates that farther than 3 miles from the boundary, the probability drops well below 20 percent. Bottom chart demonstrates that even at 11 miles from the boundary, the probability is still greater than 20 percent.

Figure 4 demonstrates the dramatic increase in fire intensity in the low to moderate fire danger conditions. The yellow arrows indicate when fires under each set of conditions will exhibit such intensity that direct suppression tactics will have little impact. The two blue lines display the narrow window estimated to be available to implement prescribed fires in blowdown fuels.

Conclusions regarding fire behavior were presented to the Forest upon completion of the Fuels Risk Assessment that lead to a new strategy for managing fuels on the Forest. Those conclusions were:

- Fire will impact the BWCAW; it is not "if" a fire will happen, but "when."
- Blowdown will burn more intensely under a wider range of burning conditions.
- Blowdown will result in more consistent fire growth (less sensitive to weather variations).
- Blowdown fires will demonstrate faster growth, but not faster than crown fire.
- Blowdown fires will resist control, particularly using standard tactics.
- Treatments will slow, but not stop, fire growth.

Fuels from similar blowdown events in Canada demonstrated the ability to contribute to extreme fire behavior to beyond 30 years after the event. Further, the Superior National Forest has a history of at least 1 year each decade where weather conditions contribute to large fire growth. Adding those two factors together, we understood that there will be a significant wildfire in the blowdown if not treated. Therefore, a strategy for addressing blowdown fuels was necessary even though much of the blowdown occurred within the Wilderness.

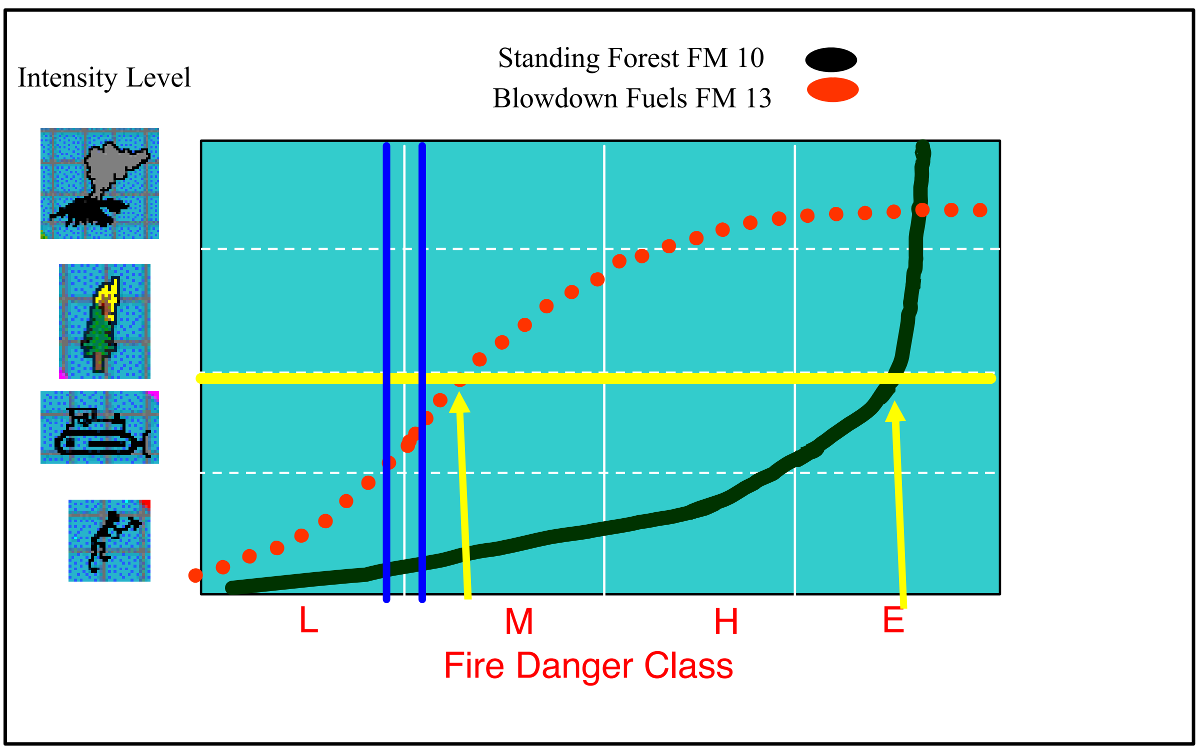


Figure 4—Hauling chart showing comparison of fuels related fire behavior.

Developing a Plan

Four critical focal points were emphasized in the Forest's response to the increased threat of a wildfire in the blowdown:

1. Intensify fire prevention.
2. Change fire suppression tactics and increase suppression capabilities.
3. Intensify emergency action planning, including evacuation planning.
4. Initiate fuel treatment techniques

Prevention

History tells us that prior to the blowdown, nearly 90 percent of the fires outside the Wilderness and 50 percent of the fires inside the Wilderness were human caused. Because of the volatility of the fuel bed left from the storm, time was necessary in order to implement all four prongs of the response strategy. It was critical to delay the impending wildfire long enough to complete the planning phases for our suppression tactics and evacuation planning, as well as time to employ the appropriate level of fuels treatment. Using the information gained from the Fuels Risk Assessment allowed all the levels of government to develop key messages and strategies to implement a prevention program. In 2006, the Superior National Forest experienced 128 fire starts of which only 10 were human caused, and none developed into a significant fire.

Emergency Action and Suppression Capability

Within the first year, county, State, and Federal governments had developed evacuation plans for each of the areas of urban interface. Each level of government brought a new set of fire resources to northeastern Minnesota including hand and engine crews, helicopters, and air tankers. Adding to our complement of available tools were the air tankers made available from Canada through border mutual aid agreements.

Fuel Treatment Techniques

With the information at hand, an overall strategy for treating the blowdown fuels was crafted: "start in close and work our way out." Fuels in and around homes, businesses, and areas where people congregate would be treated first. A two-pronged approach was used. First, fuels were completely removed from homeowner sites using either machinery or hand tools and transported to disposal sites. Second, homeowners took it upon themselves to install sprinkler systems on and around their buildings. With the abundant water in the vicinity of the Gunflint Trail, and given enough time, homeowners could create a blanket of wet fuels surrounding their homes.

Next in our strategy, we would treat areas adjacent to the previous points using both machinery and prescribed fire, creating a fuels treatment buffer. The final step would be to use prescribed fire to create spatially located treatments within the BWCAW to slow the spread of a wildfire (see fig. 5). The formal decision to carry out that strategy was done through three Environmental Impact Statements, two Environmental Assessments, Alternative Arrangements coordinated through CEQ, and some small Categorical Exclusions.

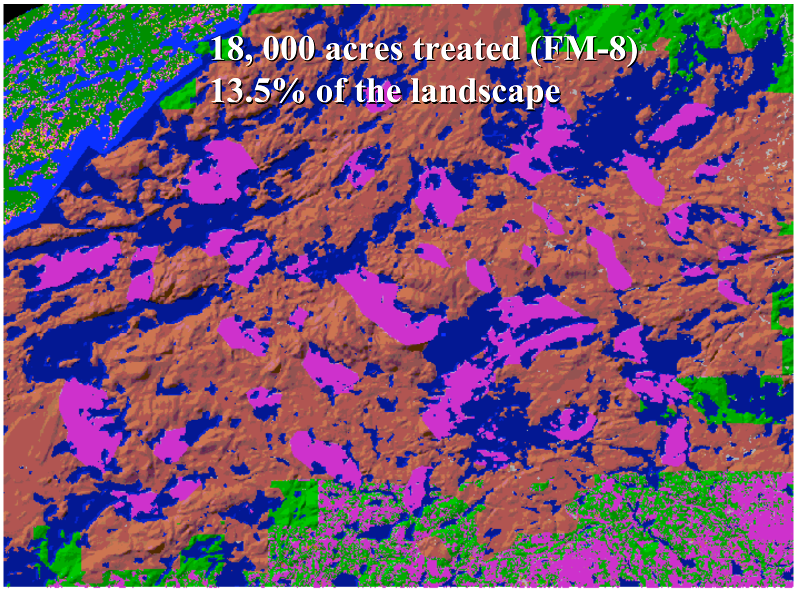


Figure 5—Strategic placement of treatments (SPOTS). Dr. Mark Finney (USDA Forest Service) developed a theory for treatment within the BWCAW where patches of prescribed fire land would connect to bodies of water. The concept is to interrupt the fuel bed to slow a fire and allow an opportunity for control measure to be used.

Implementing the Plan

Expediency was critical and the first two phases of the plan were completed by the end of 2001. To the greatest extent reasonable fuels treatments outside the BWCAW were completed using logging and other mechanical methods. However, Forest Service policy combined with limited, if any, access and steep, rugged terrain, precluded us from using mechanical tools to treat fuels inside the Wilderness. Prescribed fire with a heavy component of aerial resources was necessary to complete the fuels reduction within the BWCAW.

Inside the BWCAW, roughly 32,000 acres of complex blowdown burning to create the spatially located treatment units had been completed by the end of 2005. This included treating a band of the heaviest blowdown surrounding the upper end of the Gunflint Trail. We started slowly with smaller units that included better opportunities for control. We chose conditions where fuel and soil moistures were high enough so that the fire only consumed fuels generally 3 inches in diameter and smaller. The concept was to treat only those fuels that would contribute to high fire intensity and spread rates.

Following each year of burning we would conduct a formal review of operations, organization, cooperation, planning, fire behavior, and fuels consumption. Each year the lessons learned were rolled into the next year's burn plans to improve our knowledge, skills, abilities, and success. From the first fires, it was evident that the fuels Risk Assessment contained credible information and projections. Our ignitions efforts demonstrated that on the same day, same location, and same conditions, fire in standing timber would barely creep while fire in immediately adjacent blowdown displayed 50 to 60 ft flame lengths. As our experience grew, so did our confidence in burning larger units at one time, and eventually we were burning 3,000 to 4,000 acres in one unit.

Monitor, Learn, Adapt, and Tell the Story

Conducting complex prescribed fire, using a myriad of aircraft, experiencing fairly intense fire behavior, and generating copious amounts of smoke in the backyards of homeowners does not necessarily lead to great public relations.

One point we implemented from the beginning was to bring information back to the public in an open forum where questions could be asked and our progress could be discussed. We took the lessons from our after action review and presented those each year, along with a discussion on the changes we made as a result of lessons learned. Five years of success with fire, talking to people regularly, providing information, and inviting the public to observe our actions brought the comfort of most of our public to an acceptable level. However, those at that comfort level were not necessarily the vocal ones. It seemed that we could not convince everyone of the benefits of our actions. However, the positive relations we held with the majority proved to be a great asset in our interactions with critics.

Testing the Plan with Our First Significant Wildfire

The year 2005 brought dry conditions and in August a lightning strike pushed by strong winds brought about our first project size fire. Although the Alpine Lake fire was in the general blowdown area, the fire spread for the first day was in standing conifer. An early break in the weather allowed us to control the fire spread right at the trigger point we had outlined for evacuation. We took the time to compare fire behavior and fire effects between this fire and the blowdown burns we have implemented. One notable point was that a crown fire stops its major movement when the wind stops blowing, whereas a blowdown fire continues to spread until it runs out of blowdown fuels.

We conducted a BARC (burn area reflectance correlation) analysis to look at the effects between the fires. Because we implemented our prescribed fires with soil moistures at higher levels, we noticed the consumption of organic soil layers was much less with prescribed fire than with wildfire.

However, the real unanswered question was: Would our prescribed fire treatments withstand the test of a major wildfire?

With 6 years of preparation under our belts, 2006 once again proved to be dryer than normal. On July 14, the lightning storm moved across northeastern Minnesota and Ontario, Canada, igniting about 40 fires across northern Minnesota and several hundred in Ontario. The Cavity Lake Fire was reported by a patrol aircraft at 1533 and air tankers were ordered at 1537. The fire was 6 miles inside the BWCAW but was also in some of the heaviest blowdown fuels and upwind of several homes, businesses, a heavily used campground, and a youth camp located within the Gunflint Trail corridor. Although we had not fully implemented our fuels reduction plan, we did have a buffer of prescribed fire between Cavity Lake Fire and the values at risk.

Heavy action by water scooping air tankers had little effect on the blowdown fire and it grew to over 100 acres within 4 hours. Flame lengths were estimated to be 100 to 200 ft in blowdown causing spotting of up to 1,000 ft. The fire grew steadily through the night and each of the next 2 days so that by late afternoon of July 16 it covered about 3,000 acres.

We had a fire in the same general area 2 weeks earlier called the Rog Lake Fire. Our airtankers proved successful at halting the forward spread of that fire and provided enough control to allow firefighters to cut a path through the blowdown to actively suppress the fire. This particular fire was only 150 yards from the shore of Seagull Lake, but it took a crew of six firefighters, using chainsaws, 9 hours to cut a path to get to the fire. Cavity Lake Fire's origin was nearly 1.5 miles from the closest point of entry for firefighters. There was no safe method to approach the fire from the ground because the entire distance to the fire was through some of our heaviest blowdown.

The BWCAW is the heaviest used Wilderness in the National Forest System with nearly 12,000 persons per night camping somewhere in the Wilderness during the summer, the heaviest use time of year. The primary concern of our ground forces was to interact with the Wilderness visitors to ensure they were safely moving out of harm's way.

As the end of the third day approached, Cavity Lake Fire had not reached the prescribed fires treatments; however, the evening of July 16 brought a different story. A thunderstorm with winds from 40 to 50 miles per hour created a fire storm of significant size. Our meteorologists gave enough advanced warning to ensure all aircraft and firefighters were out of harm's way. However, the storm began late in the evening and continued past dusk and provided us no opportunity to assess the extent of fire growth or location. Reports persisted through the night that fire had spread into the forest surrounding the homes and youth camp that our prescribed fires were supposed to protect.

Years earlier the public had been vocal about our prescribed fire treatments in and around Seagull Lake, a major attraction for the end of the Gunflint Trail. The view and water quality were vital to the success of several businesses and were important to residents of the lake. We did treat the one major island that was about 3 miles long (oddly called 3-Mile Island), but we did consent to leave some smaller islands untreated by our prescribed burns. The public insisted these islands would not be affected in a fire advance, but we had some doubt; nevertheless, the islands remained with untreated blowdown.

The thunderstorm of the evening of July 16 lasted 2 to 3 hours, but it brought no rain. Our patrols through the night indicated no structures lost, but it was not known exactly how close the fire had advanced. As daylight came, we were able to put aircraft up and assess the situation and were stunned at what we saw. During the hours of the thunderstorm, the fire tripled in size to roughly 12,000 acres. Those small islands that we had agreed to leave untreated had in fact become involved in the advance of the fire (fig. 6) as it apparently island-hopped across nearly 4 miles of water and ignited the mainland in the vicinity of the homes. What we also saw was that the fire had

Figure 6— One of the small islands in Seagull Lake that was not supposed to carry fire. Several smaller islands were not treated with prescribed fire, and looking back, "No Treatment" proved to be a valuable teachable moment. (Photo by Carol DeSain)

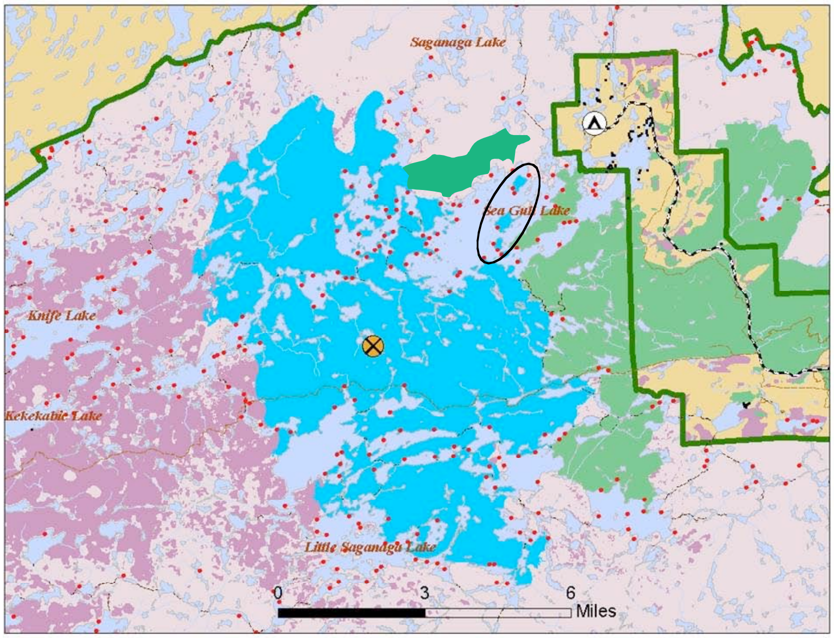


Figure 7—Final map of the Cavity Lake Fire. Origin of the fire is shown with the X while the blue shows the final extent of the fire. Prescribed fire treatments are shown in green on the eastern edge of the fire; further blowdown is shown in red to the west. Gunflint Trail corridor is shown within lines east of the fire. The area with many homes is near the symbol for the campground. The oval shows the islands that were not treated with prescribed fire but contributed to its spread.

spotted into the prescribed fires and was smoking at up to a half mile into the burns. However, the treatments had taken enough energy out of the fire to halt the spread toward the homes. A striking contrast existed between the black of the wildfire and the remaining green within the treated areas.

Over the next 2 weeks the fire continued to grow until it reached its final size of 32,400 acres (fig. 7). It challenged our suppression crews in other areas, but our fire specialists were able to use a combination of lakes and our prescribed fires to anchor control tactics that included burnout operations. Finally, 1.5 inches of rain stopped the spread and allowed more direct control measures, and though it smoldered into September, the fire made no further progress.

Results

During the course of the fire, we again brought fire behavior experts back to provide both a long-term assessment of fire growth potential and also to evaluate the Fuels Risk Assessment assumptions and our treatments as they related to Cavity Lake Fire (fig. 8). Our overhead team relied on the assessment to make decisions on control tactics including implementing the concepts of cost containment that are important to the Forest Service. Some of the major points from the evaluation:

- Fire in blown-down fuels behaved as predicted.
- The fuel treatment areas have functioned as designed.
- Prior analyses were based on "average" fire season climatology data.
- Probabilities for fires to exit the Wilderness as well as the projected fire sizes are greater than previously thought in a higher than normal fire danger year.
- It was a "Good Plan."

Looking back at the untreated islands that contributed to the fire spread across Seagull Lake, I conclude that it was not necessarily a bad decision. Although the fire was carried across the lake, enough energy was removed from the fire that movement on the mainland was minimal, and we easily controlled it there. The event fully demonstrated to the public that the conclusions from the Fuels Risk Assessment were not overstated.

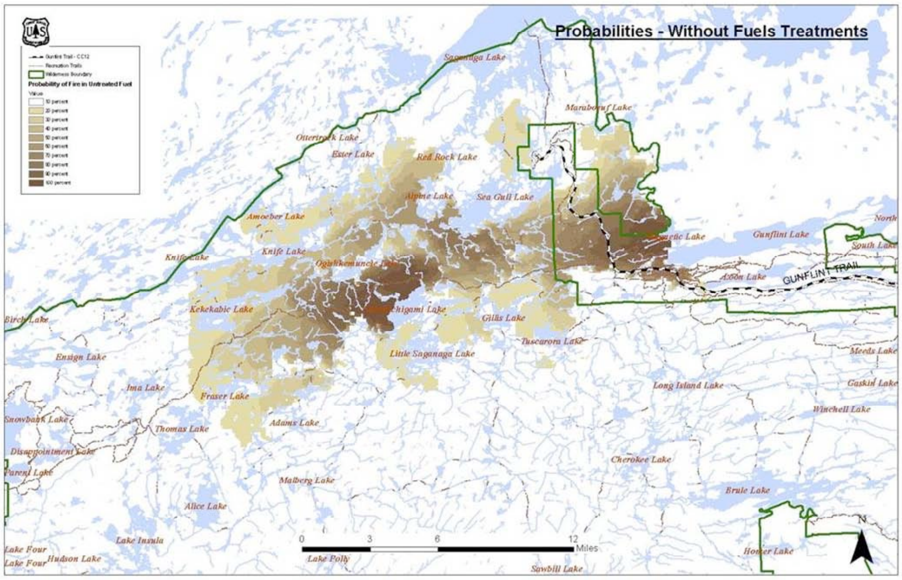


Figure 8—Fire behavior experts returned to help assess long-term fire behavior period, and to assess what the fire would have looked like without prior treatments. The darker the color equals higher probability of fire spread. The upper Gunflint Trail would have been inundated with fire.

Lessons Learned

As we do each year, we gathered in the fall and conducted a full after action review and looked for lessons learned. While there is always something to improve on, the positive factors and lessons learned from our review are as follows:

- Enlist outside expert analysis to aid your planning.
- Assess your fuels situation and develop strategies and tools to manage them.
- Fuels treatments are essential to reducing the threat of wildfire in an urban interface setting.
- Prescribed fire is effective as a method to take the energy out of a blowdown fire.
- You can never do too much public education or provide too much information on fires in the interface, and proper planning with practice pays off.
- Evacuation planning and practice (whether you use it or not) pays high dividends in terms of calming public response.
- The right decision is not always the popular decision.
- Using national resources to assist with long-term assessments provides critical information for decisionmaking on large events.
- Incident business advisors and buying teams help keep a District Ranger out of hot water during transition fires.

New Technology in Postfire Rehab

Joe Sabel[1]

Abstract*—PAM-12™ is a recycled office paper byproduct made into a spreadable mulch with added Water Soluble Polyacrylamide (WSPAM), a previously difficult polymer to apply. PAM-12 is extremely versatile and can be applied through several methods. In a field test, PAM-12 outperformed straw in every targeted performance area: erosion control, improving soil hydrophobicity, and plant establishment. ENCAP, LLC in Green Bay, WI, holds the patent to PAM-12.*

Introduction

A new technology, available for postfire rehabilitation and restoration work, stabilizes soil, improves native seed establishment, and reduces hydrophobicity in the soil. Government entities that need to rehab fire-decimated forests are effectively demonstrating it, testing it, using it more and more, and discovering the same thing: this innovation not only does a better job than traditional means, but it is more cost effective, allowing double the acreage on average to be restored for the same amount of money. The product revolves around the use of a highly researched Water Soluble Polyacrylamide (WSPAM). WSPAMs have been used in agriculture for decades; however, it has always been a difficult polymer to apply. ENCAP, LLC in Green Bay, WI, has patented an innovative carrier technology to make application of WSPAMs easy and cost effective.

The specific product is called PAM-12™ and with the help of Dr. Aicardo Roa, from the University of Wisconsin-Madison, it has been perfected as an extremely powerful yet cost effective tool that can be added to any erosion control program, especially postfire rehab. Specifically, PAM-12 is a recycled office paper byproduct made into a spreadable mulch impregnated with WSPAMs patented as Advanced Soil Technology™ (AST™). PAM-12 is extremely versatile in its application methods as it can be applied through traditional spreaders, drill-seeded, or hydro-seeded. Or uniquely, PAM-12 can be combined with any seed variety need and can be applied in one step saving even more time and money.

TRI, a reputable, independent testing agency, put PAM-12 to the test (as requested by Wisconsin Department of Transportation) by requiring it to pass the test that is required for erosion control blankets to pass. The passing grade is a C factor of 0.2 or below. The 0.2 is the amount of soil loss that 2,000 lb/acre of straw produces. At only 600 lb/acre, PAM-12 produced a C factor of 0.12. This paper reports the field trial results that show at only 600 lb/acre, PAM-12 outperformed straw (at 3,000 lb/acre) in every targeted performance area: erosion control, improving soil hydrophobicity, and plant establishment.

In: Butler, Bret W.; Cook, Wayne, comps. 2007. The fire environment—innovations, management, and policy; conference proceedings. 26-30 March 2007; Destin, FL. Proceedings RMRS-P-46CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 662 p. CD-ROM.

[1] Market Manager, ENCAP, LLC, Green Bay, WI. jsabel@encap.net

Methods

Uinta National Forest Red Bull Fire

The Red Bull Fire burned through the Uinta National Forest in the Spanish Fork Canyon near Provo, UT, in July/August 2004. The 1,836 acre fire burned for 6 days before being contained on August 3, 2004. Specialists with backgrounds in soil science, hydrology, ecology, archaeology, range management, and erosion control analyzed the burned area and proposed several treatments as part of the Burned Area Emergency Response (BAER) report/plan.

The rehabilitation treatments revegetated burned slopes through use of combining native seed species with use of straw mulch and PAM-12 to aid vegetative recover, reduce erosion, and prevent degradation of soil and water resources.

High severity burn areas experience higher rates of soil/vegetation loss from erosion due to high overland flow, decrease in infiltration (water repellency), and loss of vegetation coverage.

Objectives—Compare performance capabilities of PAM-12 to straw in the following targeted performance areas relating to revegetation:

- Soil hydrophobicity—scarred soil's tendency to resist water intake
- Erosion control
- Seed establishment and revegetation

Demonstration/evaluation method—In total, four demonstration sites were created (with seed): PAM-12, straw, Pam-12 plus straw, and a control

Participation/evaluation leadership team—Team members were:

- USDA Forest Service Soil Scientist Bob Davidson
- USDA Forest Service and BAER Leader: Ken Luckow
- USDA Forest Service Hydrologist Jeremy Jamecke
- Manufacturer: ENCAP, LLC, Mike Krysiak, President
- Distributor: UAP Timberland, Pat Thomas
- Pilot: Stephen West from Reeder Flying Service

Application—A helicopter aircraft was used for all aerial applications. A seeding bucket was used by the aircraft for application of the seed and PAM-12. Traditional aerial application methods were used for straw mulching and hay bale bombing. Application rates of products were as follows: seed = 46 lb/acre, PAM-12 = 600 lb/acre, straw =3,000 lb/acre.

Test protocol—Objective test protocols were established by the USDA Forest Service for each aforementioned Targeted Performance Area. Data were collected in triplicate per demonstration site for accurate representation.

Results and Discussion

After more than 9 months of field observation relating to revegetation, data conclusively demonstrate that PAM-12 outperformed straw in all three targeted performance areas: seed establishment, erosion control, and soil hydrophobicity.

Hydrophobic Soil Test Results

Both demonstration sites that utilized PAM-12 saw significant improvements in water infiltration of the treated soil. When directly comparing PAM-12 to straw, PAM-12 showed a 38 percent improvement in the hydrophobicity of soil, versus a 0 percent improvement shown in the straw plot (fig. 1).

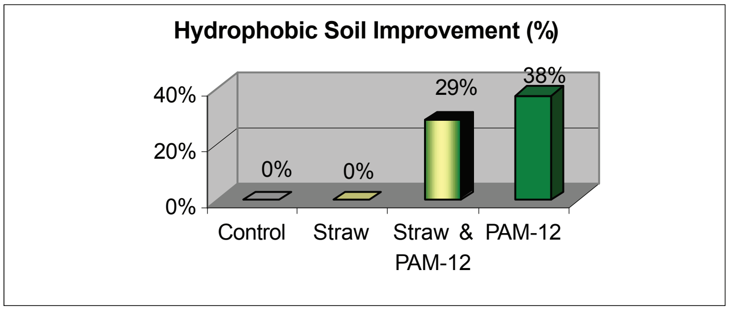


Figure 1—Comparison of four treatments and the hydrophobic soil improvement.

Erosion Control Test Results

PAM-12 outperformed straw in its ability to control erosion and reduce the total soil movement by over 60 percent. In addition, both demonstration plots treated with PAM-12 (strictly PAM-12 and PAM-12 with straw) did significantly better than plots not treated with PAM-12 (fig. 2).

Plant Establishment Test Results

Use of PAM-12 resulted in more plant life than straw by a ratio of more than 2:1. On the plot where PAM-12 was added with straw, the plot generated 78 percent more plant life than straw alone.

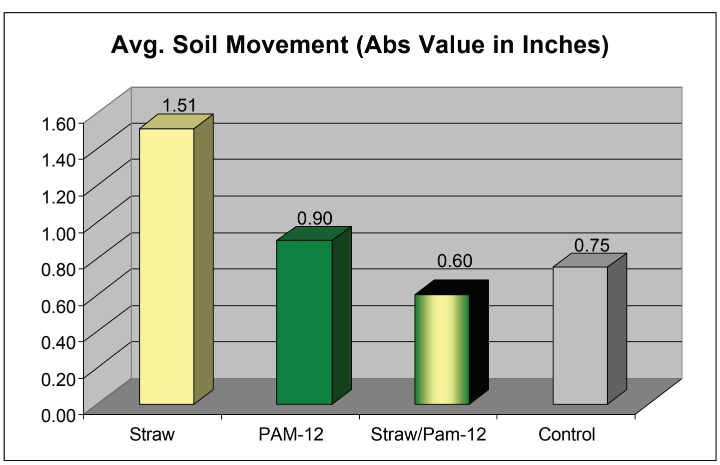


Figure 2—Erosion control test results on four treatments.

Observations

Successful germination and establishment of plant life is impacted by variables such as erosion, soil's hydrophobic nature, and soil type. PAM-12's performance in the other two targeted performance areas was certain to aid in helping to achieve better results in this third and final targeted performance area (fig. 3).

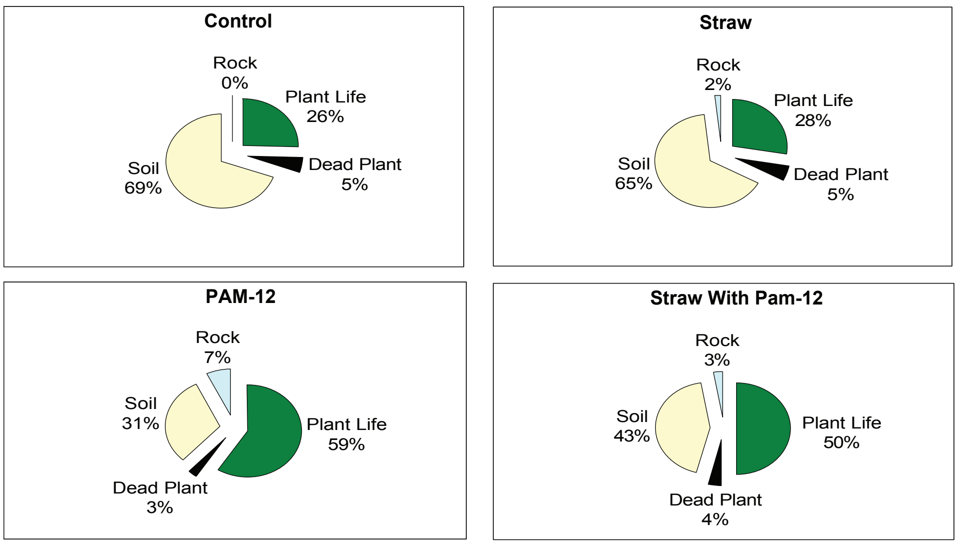


Figure 3—Plant establishment on four treatments.

Summary and Conclusions

In conclusion, PAM-12 is a proven product for forest fire rehabilitation and restoration. More and more government entities are adding PAM-12 to the list of tools in their toolbox. PAM-12 has the ability to not only control erosion, but to improve plant establishment and improve the hydrophobic layer formed in the soil after a burn. In addition, PAM-12 is effective in conjunction with other tools as the data above suggest. This gives one a "belts and suspenders" approach for those extreme cases where multiple means are needed to restore a mountainside.

In addition to all the aforementioned benefits PAM-12 brings, it is extremely cost effective as well. This is important as year after year, budgets get tighter and tighter. Utilizing PAM-12 in the rehab program allows an end user to rehab on average twice the amount of acreage than traditional methods (600 lb of PAM-12/acre versus 3,000 lb of straw per acre). Or instead of applying it by itself, PAM-12 has the unique ability to be combined with seed to do application of mulch and seed both at the same time saving time and money.

Verification of the WFAS Lightning Efficiency Map

Paul Sopko[1], Don Latham[2], and Isaac Grenfell[3]

Abstract*—A Lightning Ignition Efficiency map was added to the suite of daily maps offered by the Wildland Fire Assessment System (WFAS) in 1999. This map computes a lightning probability of ignition (POI) based on the estimated fuel type, fuel depth, and 100-hour fuel moisture interpolated from the Remote Automated Weather Station (RAWS) network. An attempt to verify the efficiency map was made using cloud-to-ground (CG) lightning discharge data acquired at the Missoula Fire Lab (through the Vaisala Corporation network), lightning fire location data from within USDA Forest Service (FS) Region 1 boundaries, and daily 100-hour fuel moisture values retrieved from historical National Fire Danger Rating System (NFDRS) archives for the 2003 fire season. Daily POI maps were recomputed for 153 days (May through September). Daily CG lightning density grids for the same timeframe were computed from lightning discharge data and were multiplied by the POI grid to yield a daily 1-km predicted number-of-fires or fire "possibility" grid. A daily lightning-caused fire density grid was produced using various agency fire occurrence databases from May through September. While preliminary spatial neighborhood analysis showed some predictive capability, the predicted number of lightning caused fires exceeded the actual reported fires. This overestimation could be due to the lack of differentiation between an ignition and reported fire and errors in fire occurrence databases. Being able to predict whether lightning resulted from a "wet" or "dry" storm could improve predictive ability. More refined and spatially accurate fuel maps have become available and are planned to be incorporated into future models.*

Introduction

Lightning is the primary cause of wildland fire ignitions in the Western United States. Networks to detect cloud-to-ground (CG) lightning strikes have covered this region in various forms since the 1970s. Presently, the network covering the continental United States, operated by Vaisala Corporation, advertises an 80 to 90 percent detection efficiency and a 500 m spatial accuracy. To date, we are not aware of any attempts to correlate individual CG discharges to actual lightning fires. This is due to a variety of reasons including the questionable quality of fire start data and the tendency of lightning ignitions to become "holdover" fires.

In 1999, a Lightning Ignition Efficiency map (USDA Forest Service 2002) was added to the Wildland Fire Assessment System (WFAS). This map computes a lightning probability of ignition (POI) based on the estimated fuel type, fuel depth, and 100-hour fuel moisture interpolated from the Remote Automated Weather Station (RAWS) network. The efficiency values are on a per-CG discharge basis, and the map is based on a 1-km^2 pixel. The values on the map are generated by an algorithm based on a laboratory research

In: Butler, Bret W.; Cook, Wayne, comps. 2007. The fire environment—innovations, management, and policy; conference proceedings. 26-30 March 2007; Destin, FL. Proceedings RMRS-P-46CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 662 p. CD-ROM.

[1] Physical Scientist, U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Missoula, MT. psopko@fs.fed.us

[2] Scientist, Emeritus, U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Missoula, MT.

[3] Statistician, Systems for Environmental Management, Missoula, MT.

study (Latham and Schlieter 1989). Verification of the algorithm was delayed by lack of a suitable data set covering a range of input variables and a large number of fires. We generated such a data set for the year 2003 spanning the months of May through September for an area covering approximately Region 1 of the USDA Forest Service.

This study is a "first cut" at analyzing the data. We wanted to become familiar with use of GIS-based data storage, presentation, and analysis techniques. In particular, we wanted to explore presentation of point data, such as lightning and fires, as gridded density data on the landscape, and examine the results both visually and statistically.

Data

Lightning flash and stroke data came from Vaisala Corporation (Cummings and others 1998). Each flash in the data set has a date, time, latitude, and longitude. Values needed for calculating environmental variables came from the National Fire Danger Rating System (NFDRS) through operational RAWS stations. The base fuel map used to decipher fuel type and depth for the POI calculation came from Schmidt and others (2002). During May through September 2003, a total of 709,879 flashes were recorded and used in this study. One day's data are shown in figure 1, comprising 21,192 flashes. Flashes are shown here regardless of the polarity of the flash, because the WFAS algorithm was generated to be polarity-free.

Fire locations were obtained from the USDA Forest Service, Montana Department of Natural Resources and Conservation (DNRC), Idaho Department of Lands (IDL), Bureau of Indian Affairs (BIA), Bureau of Land Management (BLM), National Park Service (NPS), and Fish and Wildlife Service (FWS). In all, the recorded latitude and longitude of 1,948 fires attributed to lightning along with the discovery dates were entered into the set. The results for 1 day's data are shown in figure 2.

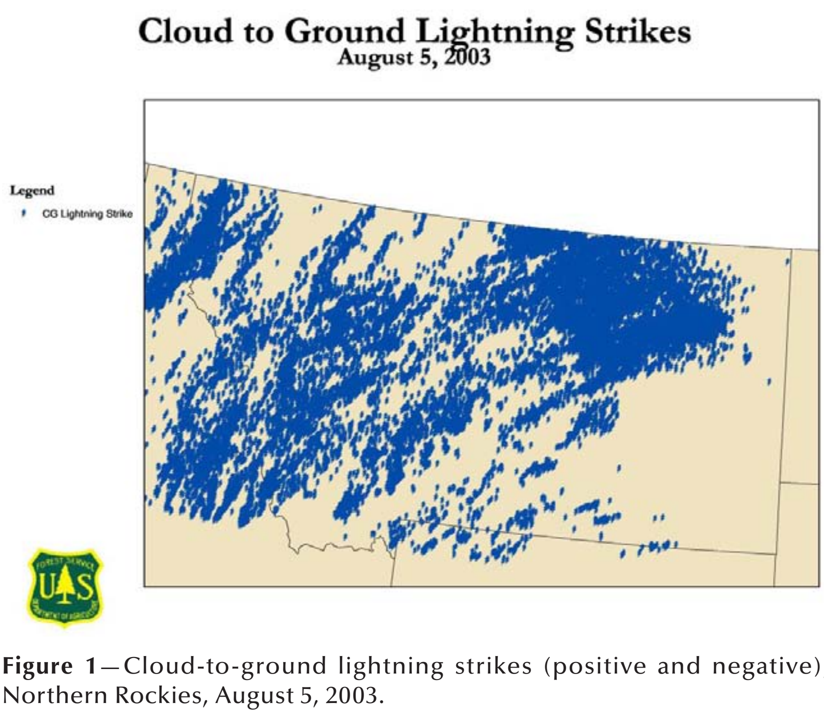


Figure 1—Cloud-to-ground lightning strikes (positive and negative), Northern Rockies, August 5, 2003.

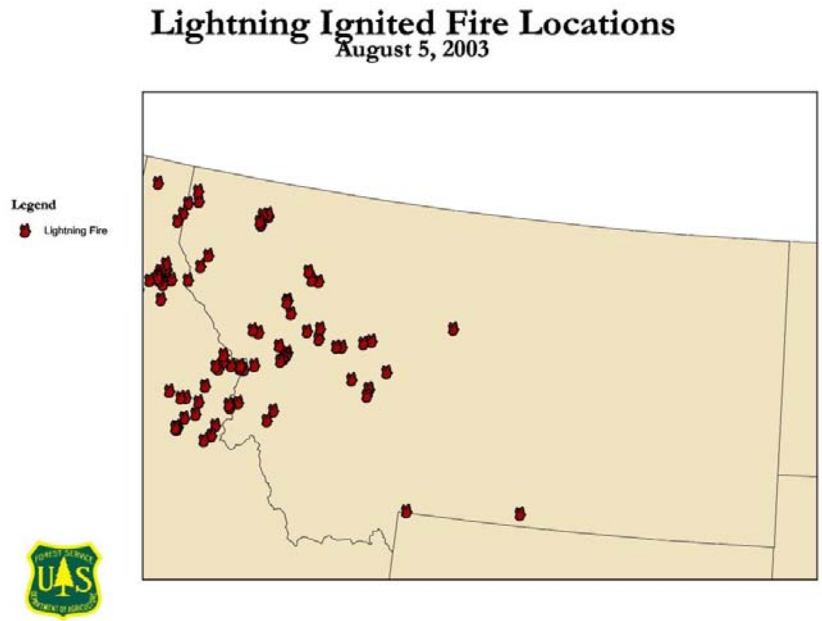


Figure 2—Lightning-caused fires, August 5, 2003.

For our analysis, we needed to calculate the WFAS daily lightning probability (efficiency). The algorithm requires a fuel type, depth, and the 100-hour NFDRS fuel moisture. Ignition probability in most fuels depends on fuel moisture. Short needled fuels depend more on duff depth (USDA Forest Service 2002). The ignition probabilities that depend on fuel moisture are not really in the 1-hour fuel moisture class but are closer to 25 to 50 hour. Because we are estimating the probability in the morning for the day, we chose the 100-hour class as the best representation. The 100-hour moistures were obtained from RAWS stations through the NFDRS data warehouse using FireFamily Plus (Bradshaw and McCormick 2000). The 100-hour fuel moisture values were converted to 1-km^2 grids using the weighted inverse distance-squared interpolation method (Burgan and others 1997). The moisture field for a sample day is shown in figure 3.

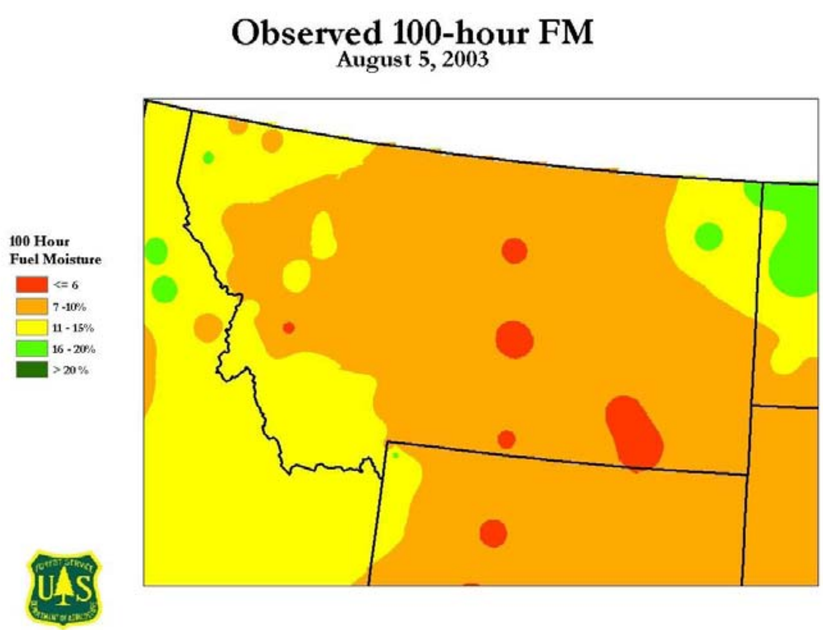


Figure 3—Interpolated 100-hour fuel moisture map, Northern Rockies, August 5, 2003.

The lightning probability algorithm has six fuel types: long-needled species such as ponderosa pine (*Pinus ponderosa*), short-needled species such as Douglas-Fir (*Pseudtsuga menziesii*), intermediate needle such as lodgepole pine (*Pinus contorta*), mixed high-altitude such as Englemann spruce (*Picea engelmannii*), grasses and hardwoods, and other nonconsidered such as water, farmland, cities, and barren land. The map of lightning fuel types, derived from Schmidt and others (2002), is static and applied here on a 1-km^2 pixel basis (fig. 4).

A typical WFAS ignition probability product is shown as figure 5. The probability of ignition for the Northern Rockies on August 5, 2003, is shown in figure 6.

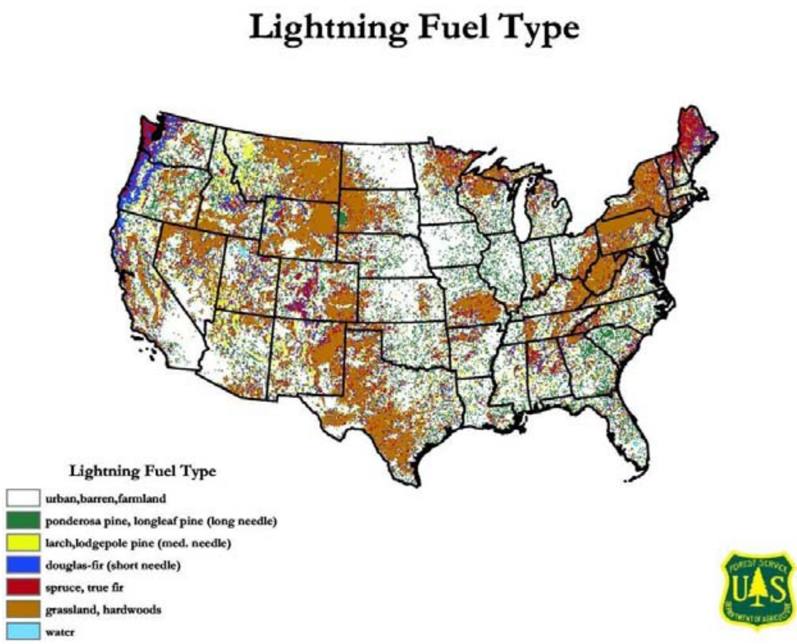


Figure 4—Lightning fuel types.

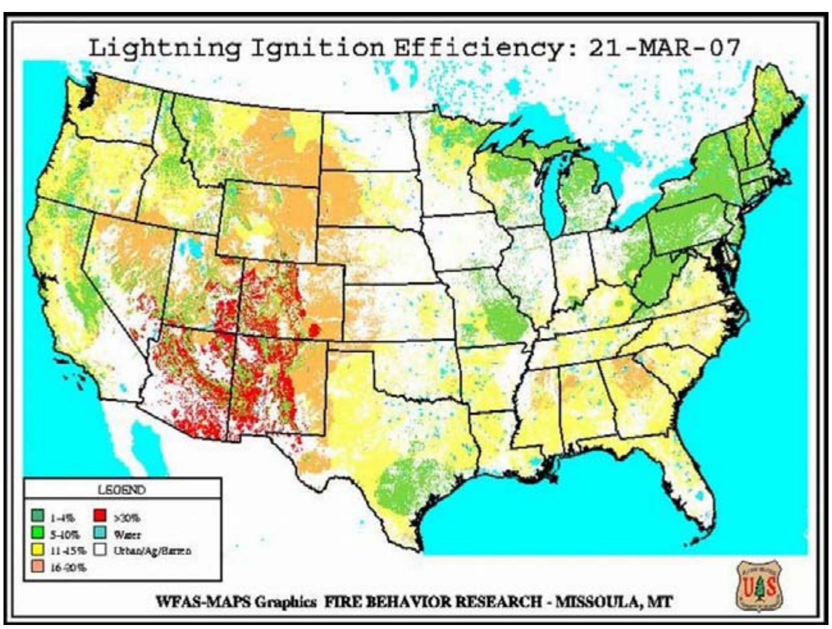


Figure 5—WFAS lightning probability of ignition, March 21, 2007.

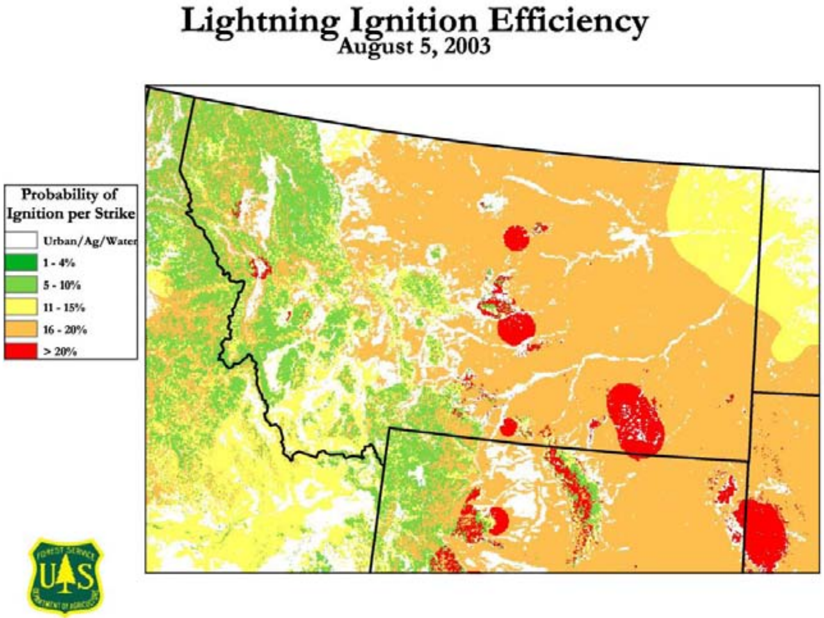


Figure 6—Probability of ignition, Northern Rockies, August 5, 2003.

Analysis

Because we are exploring GIS techniques for the data analysis, we need to convert the point values for the lightning flashes and fire locations into densities; that is, the lightning flash and fire locations need to be converted into flashes or fires per square kilometer per day. In this way, we can apply the ignition probability on a daily basis to the daily flash density and compare to the daily fire density. In order to account for spatial error and to smooth the coarse edges, the density grids were refined using the ArcInfo spatial low pass filter "focalmedian" function. The focalmedian is a local neighborhood function and, in this instance, returned the median of the nine pixel values in the surrounding 3 X 3 matrix. Flash density for August 5 is shown in figure 7 and fire density in figure 8.

The lightning flash density can be directly combined with the probability of ignition data by a simple pixel-by-pixel multiplication. The results are presented here as an ignition "possibility" map (an invented name for this paper only) (fig. 9). For example, if a given pixel has a 20 percent probability of ignition, five flashes would be needed within that pixel to generate a fire possibility of one. Note that at this stage the fires are treated as a continuous variable. To improve interpretation the continuous data are grouped into eight classes in figure 9. Obviously there cannot be 0.06 fires, but a possible ignition/fire density map does convey information of possible use to wildland fire organizations.

Figures 10 and 11 show actual fires superimposed on the fire possibility map for August 5, 2003. The fire locations are shown as point data. We formulated the fires as a density, or fires per square kilometer per day, for the preliminary statistical examination described later. For now though, we wanted to have a visual representation of how accurate the prediction could be. Figure 11, a "blowup" of the outlined section of figure 10, shows an example of how well we succeeded.

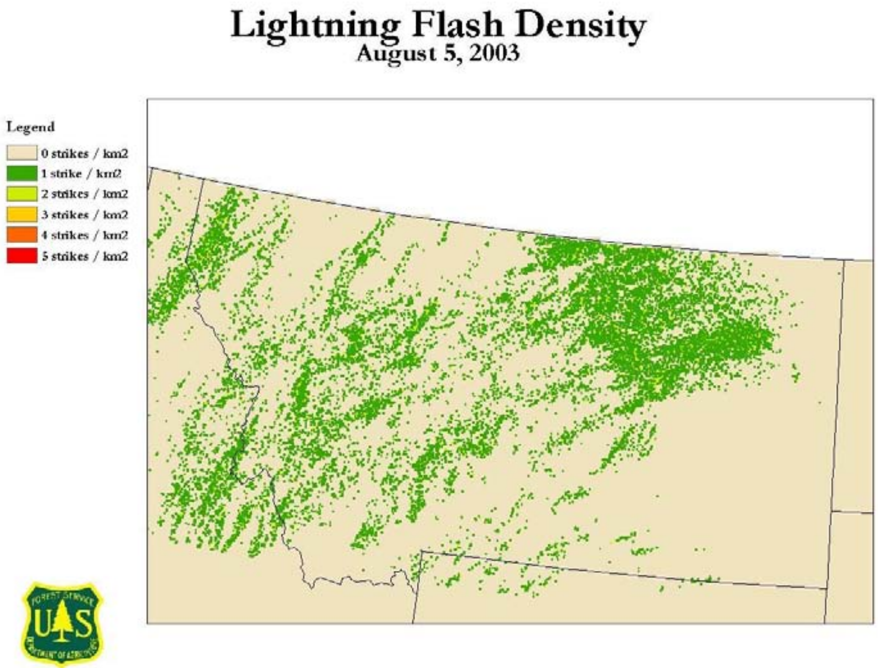


Figure 7—Lightning flash density, Northern Rockies, August 5, 2003.

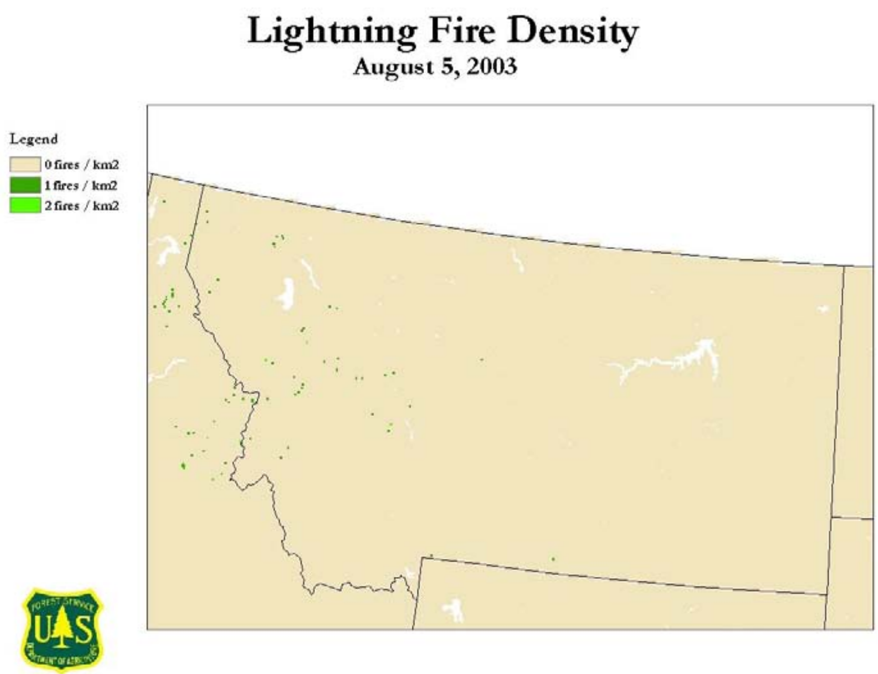


Figure 8—Lightning fire density, Northern Rockies, August 5, 2003.

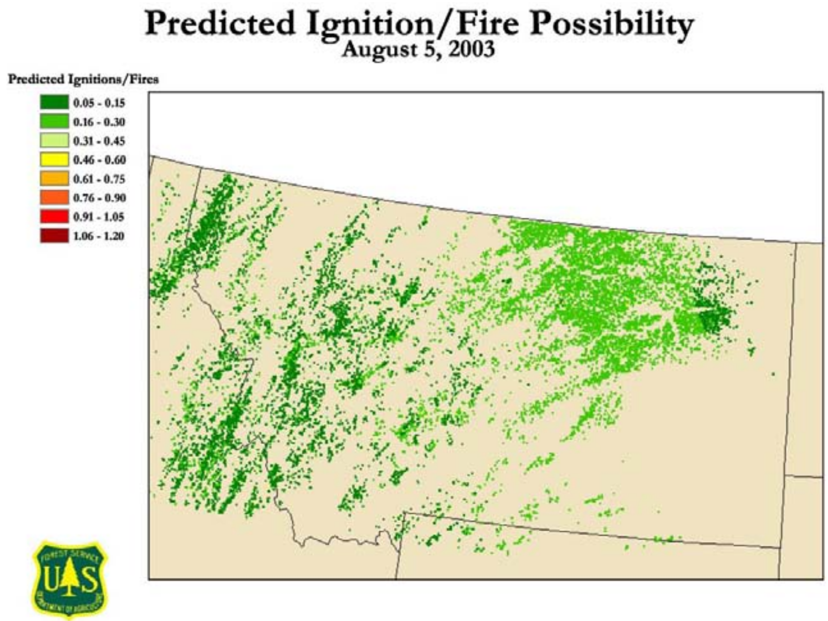


Figure 9—Predicted ignition possibility, Northern Rockies, August 5, 2003.

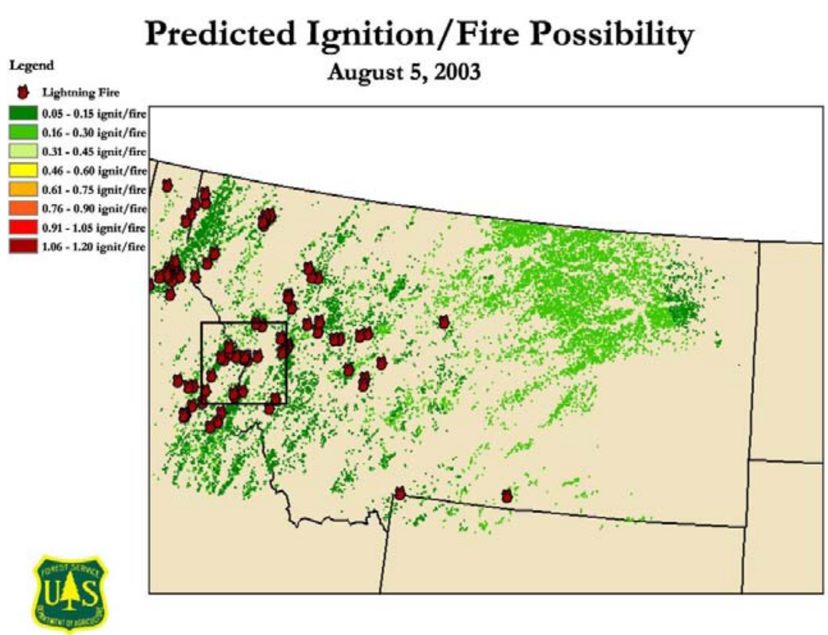


Figure 10—Predicted ignition possibility with lightning-caused fires, Northern Rockies August 5, 2003.

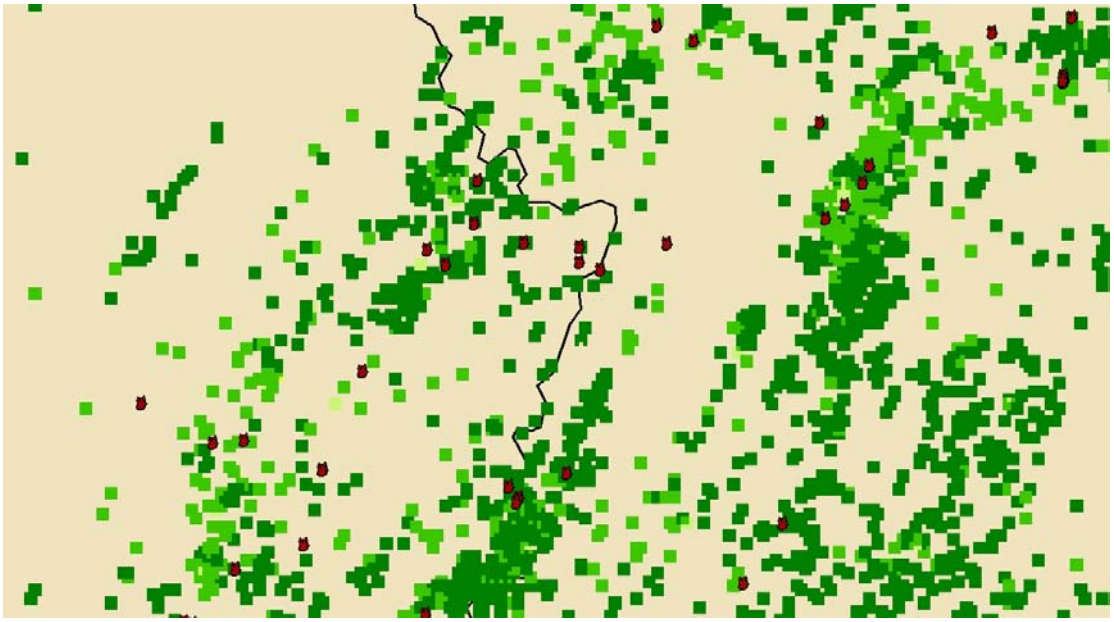


Figure 11—Closeup of outlined portion of figure 10.

On the whole, the visual picture is adequate. There are, of course, some fires ostensibly produced by lightning that are in places where there should not be any fires (fire possibility of zero). In general, however, the fires do seem to occur more often in the pale green patches rather than in the dark green ones; that is, fires are appearing in places where the expected density is higher as the legend in figure 8 shows. For comparison, figure 12 shows actual fires superimposed on the POI map for August 5, 2003.

For this preliminary examination we looked at the total data set in a more conventional manner. For the whole study period, the fires were "binned" by the probability of ignition categories they fell in for that day. Figure 13 presents a breakdown of the number of pixels of lightning ignition probability having fires in them. There are 168 fires in locations with a zero probability that they could be in unclassified places such as farmland or the like, or the fire locations are off slightly. Most fires fall in ignition probability classes up to about 0.25 and the remainder in classes greater than that.

Next, for each day in the study period, we multiplied the lightning strike density grid by the probability of ignition grid yielding a fire possibility grid. In other words, we only included pixels that had one or more lightning strikes in them. This analysis was done on a per day basis; that is, if a fire occurred, we looked to see what the corresponding fire possibility value was for the corresponding pixel on the same day. The results are shown in figures 14 and 15. Looking at the number of fires in the fire possibility classes in this more restricted way presents a different picture. According to figure 14, almost all of the fires occurred in 1 km^2 pixels having no flashes. Figure 15 shows that the remainders are distributed as one might expect because the flash density seldom exceeds more than one flash per pixel.

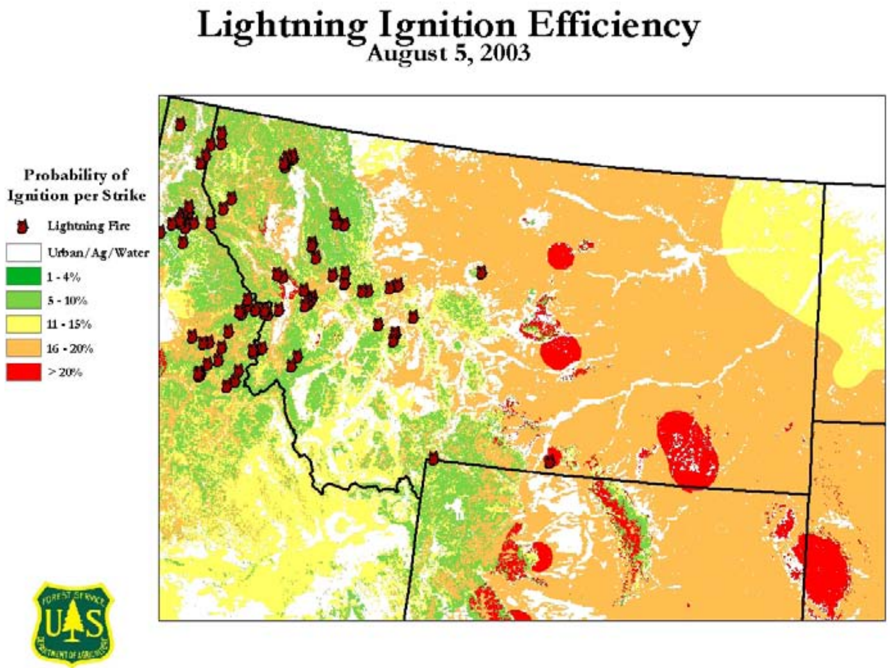


Figure 12—Lightning caused fires and probability of ignition, Northern Rockies, August 5, 2003.

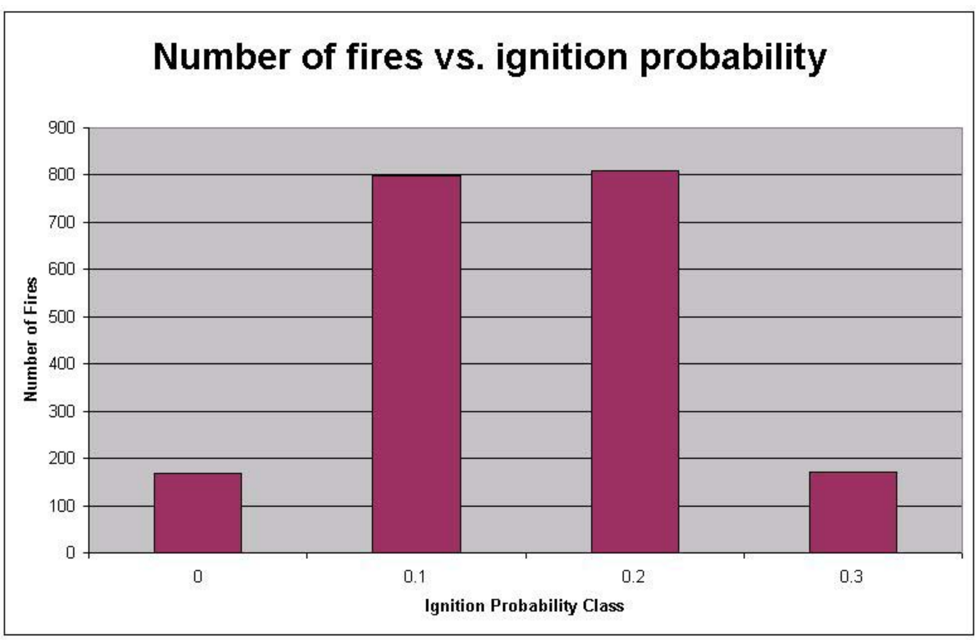


Figure 13—Number of fires in ignition probability categories.

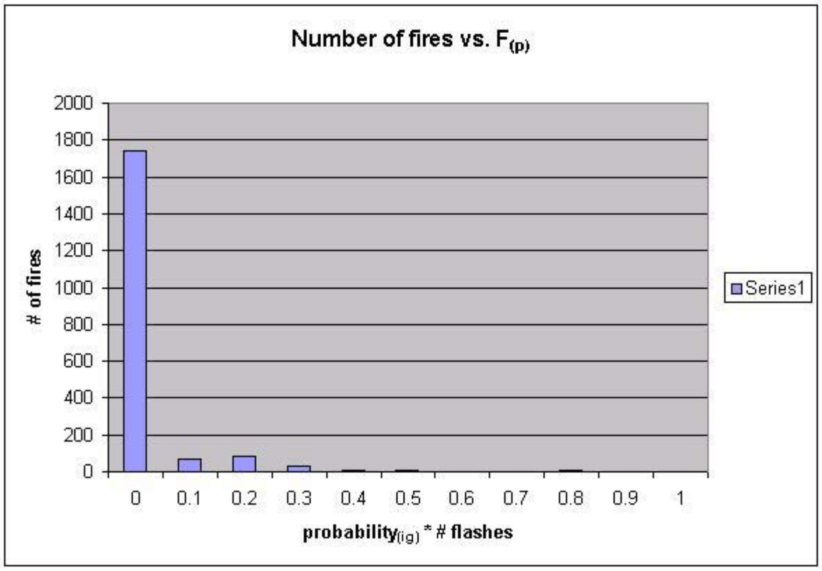


Figure 14—Total fires in fire possibility (F_p) categories.

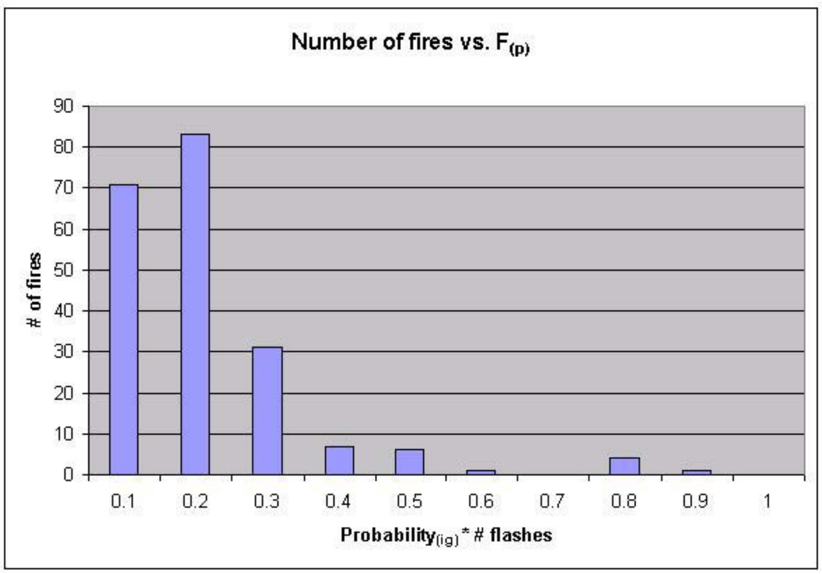


Figure 15—Total fires in fire possibility (F_p) categories—zero Fp excluded.

Discussion

We need to further consider the results from the data set. Presently, the POI map is calculated using a 1-km^2 grid size. Perhaps this grid size is too small given the errors inherent in the lightning and fire point data. In particular, the error in the lightning flash data is known to be on the order of 500 m in radius around the flash location and can be larger. Because the fire location data came from multiple agencies using different fire reporting protocol, the spatial and temporal error of the combined fire dataset is unknown. Across the study area, we assumed locations were determined with various techniques including Global Positioning System (GPS) receivers, maps, memory, best guess, and so forth. We need to get an idea of the size of the potential fire location error by asking some questions of the agencies supplying the data. For example, DNRC warned that the fire location data from the multiagency jurisdictional area of eastern Montana was of poor quality. There appears to be a need for a multiagency standard protocol for determining fire ignition locations. Given the low cost and ready availability of GPS devices, we think they should be a standard tool provided to all initial attack crews.

The number of reporting RAWS stations affects the accuracy of the POI calculation. Figures 3 and 6 show the relationship between the 100-hour fuel moisture value and the probability of ignition. The “bull’s eye” pattern observed for some areas in figure 3 is an artifact of the interpolation algorithm caused by low RAWS station densities. Figure 6 shows how the bull’s eye effect caused by the 100-hour moisture calculation manifests itself in the POI map. The number of operational RAWS stations typically waxes and wanes through the fire season. For example, we had 64 operational RAWS stations on May 1, the first day of the study period. On August 5, our example day, there were 81 operational RAWS stations and 78 on September 30. The station density is highest in the western part of Region 1 and lowest in the east.

The 1-day example shown in figures 10 and 11 highlights the model’s tendency to overpredict the potential number of ignitions/fires. Each colored pixel (brown represents zero probability) represents a probability of a predicted ignition or fire “possibility” greater than zero. The values of these pixels are derived from a simple multiplication of the probability of ignition and number of lightning strikes falling within that pixel.

There appears to be a need to distinguish between a potential ignition and an actual reportable fire. A certain percentage of lightning ignitions never become reportable fires. Ignitions can decay, grow and decay before being detected, or grow and become detected as fires (Latham 1979). “Holdover” fires are another subset that needs further study. The current POI map predicts potential ignitions. We attempted to verify the map using reported fires. Because no dataset of all lightning ignitions, including those that decay, exists, we were forced to use the reported fire database for verification.

We need to identify all of the potential factors that influence lightning ignition/fire growth. Variables accounted for in the POI/fire possibility calculation include fuel moisture (before the storm), fuel type, duff depth, and number of lightning strikes. Other factors that determine whether an ignition grows and becomes a reportable fire include fuel and duff moisture after the storm (“wet” versus “dry” lightning storm), available fuel for fire spread and for holdover prediction, temperature, relative humidity, and wind speed in the days following a lightning strike. The National Weather Service provides a Doppler radar estimate of accumulated rainfall (Storm Total Precipitation). This product can be used to estimate daily accumulated precipitation. Rorig and Ferguson (1999) developed a discriminant rule using the dewpoint depression at 85kPa and temperature difference between 85 and 50 kPa to classify convective days as either “wet” or “dry”. We plan to retrieve the appropriate upper air and daily estimated rainfall data for our study period and see if it proves to be a significant factor in predicting fires.

The NFDRS index Energy Release Component (ERC) is an indicator of potential heat release in the flaming zone at the head of a fire. The ERC can be considered an indicator of available fuel since it represents the contribution of all live and dead fuel to fire spread. It is also considered one of the best fire danger components for indicating the effects of intermediate to long-term drying (Hall and others 2003). Using the same techniques we employed to recreate the daily 100-hour fuel moisture values and POI index, we plan to calculate the daily ERC values, combine with the POI model, and see if any correlation with fire prediction exists.

LANDFIRE (Rollins and Frame 2006) will soon have a more refined and spatially accurate fuel map available for the Western United States. We would like to use these data to update our lightning fuel type map used for fuel type and depth inputs in the POI calculation.

Our goal is to produce a fire probability model that provides managers with immediate information on where lightning caused fires are likely to occur. What has the best potential for success is a daily grid or contour map that incorporates lightning strike data, probability of ignition with other variables that prove significant such as the NFDRS index Energy Release Component (ERC), Doppler radar estimated precipitation, and upper air soundings.

What other questions can we attempt to answer with the 2003 data set?

- How are fires distributed by lightning probability fuel type? This can be easily accomplished by statistically comparing the fire database with the lightning fuel type map.
- How do we account for holdover fires? This will be tricky. There are large variances and random factors that drive some of the hidden processes that influence holdover fires. In the present verification effort, we only consider the lightning and probability of ignition values for the fire's reported ignition date. We could, for example, expand the scope of analysis of fire possibility out 7 days after the fire ignition date. Initial attempts to do this have proven problematic. By increasing the number of days in the analysis searching for a predicted fire, large numbers of predicted fire pixels with values of zero increase the statistical noise and resultant binary correlation values.
- What is the relative error between the lightning location and a possible resulting fire? Each lightning strike has an associated error ellipse. The fire locations do not. The relative error of each strike can be quantified using the error ellipse data. The lack of a cross-agency location reporting protocol along with other variables makes the errors in fire location point data hard to measure. We hope to use the error ellipse data to measure the lightning location error.
- Does the ignition probability actually predict fire probability? Given our preliminary verification analysis, the answer to this question is no. Increasing the pixel size is an obvious first step. We think that the incorporation of other predictors such as ERC (fire season drought or available fuel), radar rainfall estimates (Storm Total Precipitation), upper air sounding grids, or a spread variable into the fire probability model will significantly improve its predictive ability.
- Will stroke data rather than flash data improve the analysis? Each lightning strike is made up of multiple "strokes." This is referred to as the strikes' multiplicity. We have the stroke data for the study period and plan to substitute them for the strike data to see if they improve the analysis.

Acknowledgments

Dr. Latham thanks the Fire Behavior Project at the Missoula Fire Lab for their support. We thank Matt Jolly and Charles McHugh for their assistance with GIS analysis and Larry Bradshaw for his extensive knowledge and assistance with FireFamily Plus and WFAS algorithms. The detailed comments of Miriam Rorig and Jim Reardon are greatly appreciated.

References

Bradshaw, L.S.; McCormick, E. 2000. FireFamily Plus User's Guide, Version 2.0., General Tech. Rep. RMRS-GTR-67. Fort Collins, CO. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 124 p.

Burgan, R.E.; Andrews, P.L.; Bradshaw, L.S.; Chase, C.H.; Hartford, R.A.; Latham, D.J. 1997. WFAS: wildland fire assessment system. Fire Management Notes 57:14-17.

Cummins, K.L.; Murphy, M.J.; Bardo, E.A.; Hiscox, W.L.; Pyle, R.B.; Pifer, A.E. 1998. A combined TOA/MDF technology upgrade of the U.S. National Lightning Detection Network. J. Geophys. Res. 103: 9035-9044.

Hall, B.L.; Brown, T.J.; Bradshaw, L.S.; Jolly, W.M.; Nemani, R. 2003. National standardized energy release component (ERC) forecasts. Proc. 5th Symposium on Fire and Forest Meteorology and the 2nd International Wildland Fire Ecology and Fire Management Congress, Orlando, FL. J11.10

Latham, D.J. 1979. Progress Toward Locating Lightning Fires. Research Note INT-269. Ogden, UT: U.S. Department of Agriculture Forest Service, Intermountain Forest and Range Experiment Station. 6 p.

Latham, D.J.; Schlieter, J.A. 1989. Ignition probabilities of wildland fuels based on simulated lightning discharges. Research Paper INT-411. Ogden, UT: U.S. Department of Agriculture Forest Service, Intermountain Research Station. 16 p.

Rollins, M.G.; Frame, C.K. tech. eds. 2006. The Landfire Prototype Project: nationally consistent and locally relevant geospatial data for wildland fire management. General Tech. Rep. RMRS-GTR-175. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 416 p.

Rorig, M.L.; Ferguson, S.E. 1999. Characteristics of Lightning and Wildland Fire Ignition in the Pacific Northwest. Journal of Applied Meteorology 38: 1565-1575

Schmidt, K.M.; Menakis, J.P.; Hardy, C.C.; Hann, W.J.; Bunnell, D.L. 2002. Development of coarse-scale spatial data for wildland fire and fuel management. General Tech. Rep. RMRS-GTR-87. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 41 p +CD.

U.S. Department of Agriculture, Forest Service. 2002. WFAS Lightning Ignition Efficiency webpage. 30 April 2007. < http://www.wfas.net/content/view/18/33/>

This page is blank on purpose

Communication and Collaboration

This
page is
blank
on purpose

Integrating Climatic and Fuels Information into National Fire Risk Decision Support Tools

W. Cooke[1], V. Anantharaj[2], C. Wax[1], J. Choi[1], K. Grala[1], M. Jolly[3], G.P. Dixon[1], J. Dyer[1], D.L. Evans[4], and G.B. Goodrich[5]

Abstract—*The Wildland Fire Assessment System (WFAS) is a component of the U.S. Department of Agriculture, Forest Service Decision Support Systems (DSS) that support fire potential modeling. Fire potential models for Mississippi and for Eastern fire environments have been developed as part of a National Aeronautic and Space Agency-funded study aimed at demonstrating the utility of NASA assets in fire potential decision support systems. Climate, fuels, topography and ignition are recognized as important components for modeling fire potential in Eastern forests and grasslands. We produced temporal and spatial water budget estimates using daily assessments of precipitation and evaporation (P-E) in a Geographic Information System. Precipitation values are derived from Doppler radar-based estimates of hourly rainfall accumulation, published on the Hydrologic Rainfall Analysis Project (HRAP) grid. Precipitation data are routinely available, but evaporation data are not. Regional estimates of evaporation have been produced to fill this void. Regression models that estimate daily evaporation in the Southern region of the United States were developed from readily available weather station observations. Evaporation estimates were combined with precipitation to compute the cumulative water budget. Improvement of these estimates when compared to Keetch-Byrum Drought Index (KBDI) was demonstrated using fire location data in Mississippi. Evapotranspiration (ET) from the NASA Land Information System (LIS), is currently being evaluated as a landscape moisture variable. We have implemented a hierarchical modeling methodology that combines information derived from ICESat (GLAS) data and MODIS Enhanced Vegetation Indices (EVI) to describe fuels structure. A graphical user interface (GUI) has been developed using Visual Basic (VB) that accesses an ESRI geospatial database that integrates water budget and fuels. The ignition component is derived from gravity models that assess the interaction of population density and forest areal size.*

In: Butler, Bret W.; Cook, Wayne, comps. 2007. The fire environment—innovations, management, and policy; conference proceedings. 26-30 March 2007; Destin, FL. Proceedings RMRS-P-46CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 662 p. CD-ROM.

[1] Department of Geosciences, Mississippi State University, Mississippi State, MS. Lead author whc5@geosci.msstate.edu

[2] GeoResources Institute, Mississippi State University, Mississippi State, MS.

[3] U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Missoula, MT.

[4] Department of Forestry, Mississippi State University, Mississippi State, MS.

[5] Department of Geography, Western Kentucky University, Bowling Green, KY.

Introduction

The Mississippi State University Departments of Forestry, Geosciences, and the GeoResources Institute have received National Aeronautical and Space Agency (NASA) funding to develop linear additive Geographic Information System (GIS) models designed to determine fire potential in Eastern forest regimes. Modeling concepts have been developed in cooperation with the USDA Forest Service Fire Sciences Laboratory (Missoula, MT), the Forest Inventory and Analysis (FIA) unit (Knoxville, TN), and the Mississippi Forestry Commission (MFC).

Much of the existing literature on fire potential modeling in the United States is oriented toward Western U.S. fire regimes. Fire is also of ecological and economic importance in the Southeastern United States. In Mississippi, fire frequency data obtained from the MFC indicates that on average, for a

15-year period beginning in 1990, fire personnel were dispatched to more 4,000 fires per year. Decisions regarding fire response and suppression, personnel and equipment staging, prescribe burning for fuel reduction, and implementation of burn bans could benefit from spatial and temporal depictions of fire potential. GIS-based fire potential models can be a valuable aid for describing the temporal and spatial conditions that are favorable (or unfavorable) for fire ignition and spread.

Morgan and others (2001) compared several approaches for mapping fire regimes including two rule-based approaches, a vegetation succession modeling approach, and a statistical modeling approach for the Interior Columbia River Basin. Results of these comparisons show that fire frequency is related to four factors: climate, vegetation (fuels), anthropogenic influences (ignition), and topography (Morgan and others 2001). Topography is an important fire variable in the Western United States where changes in elevation and aspect are determinants of vegetation and climate. However, topography has less influence on fire potential in the Eastern United States where topography is characterized by much gentler slopes (Zhai and others 2003).

Results of modeling efforts designed to assess the importance of climate, fuels, and ignition are presented. The climate component is discussed in terms of the usefulness of water-budget indices and global climate processes in predicting fire potential. Topography is treated as a modifier of total precipitation in our models. The fuels variable is examined in more detail, particularly in light of damage to forests due to hurricane Katrina. The ignition component is presented as a comparison between road density and gravity models and their application in predicting fire potential. Finally, development of the data acquisition interface for fire potential modeling is described.

Discussion

The modeling flowchart (fig. 1) illustrates the conceptual approach used for modeling fire potential. Models are being developed and validated for Mississippi with the ultimate goal of expanding the modeling concepts regionally. GIS-based linear algebra approaches using raster (cell) data were developed to characterize fire potential in Mississippi. Climate, fuels, and ignition are the primary (weighted) variables, and topography is implemented as a modifier of precipitation. Different types of base data have been tested for usefulness for each variable. Initially, each variable's correlation to historic fire occurrence in Mississippi was tested. The results of these tests ultimately guide decisions about the importance of each variable and variable weights for the full model.

Climate

KBDI evaluation—The importance of climate for fire potential models in Mississippi is not clear. Figure 2 illustrates a 14-year history of the relationship between climate and fire frequency in Mississippi. Drought conditions generally occur in the late summer and fall in Mississippi and are associated with increased fire frequency, but the temporal period with highest fire frequency is associated with periods of luxury rainfall (spring). Indices like the Keetch-Byram Drought Index (KBDI) are often used (Texas Forest Service, WFAS, and others) to estimate fire potential. The usefulness of KBDI alone for determining fire potential in Mississippi has not been documented in

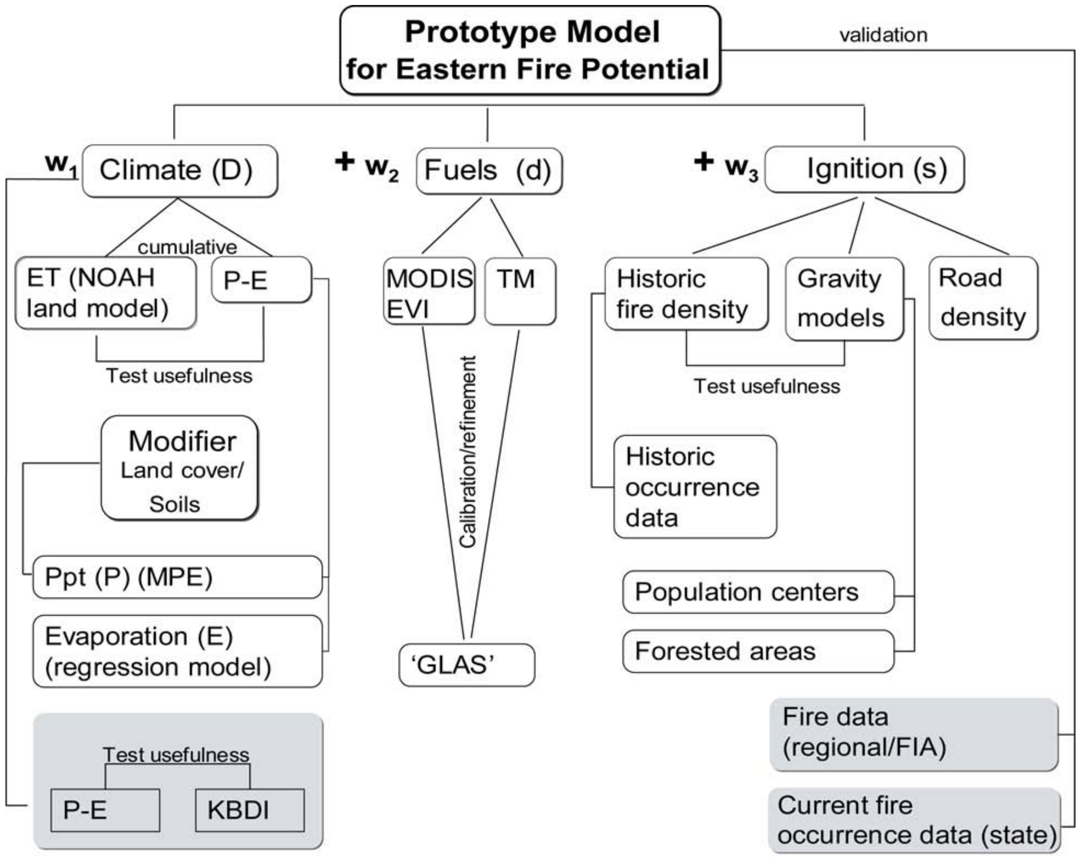


Figure 1—Modeling flowchart.

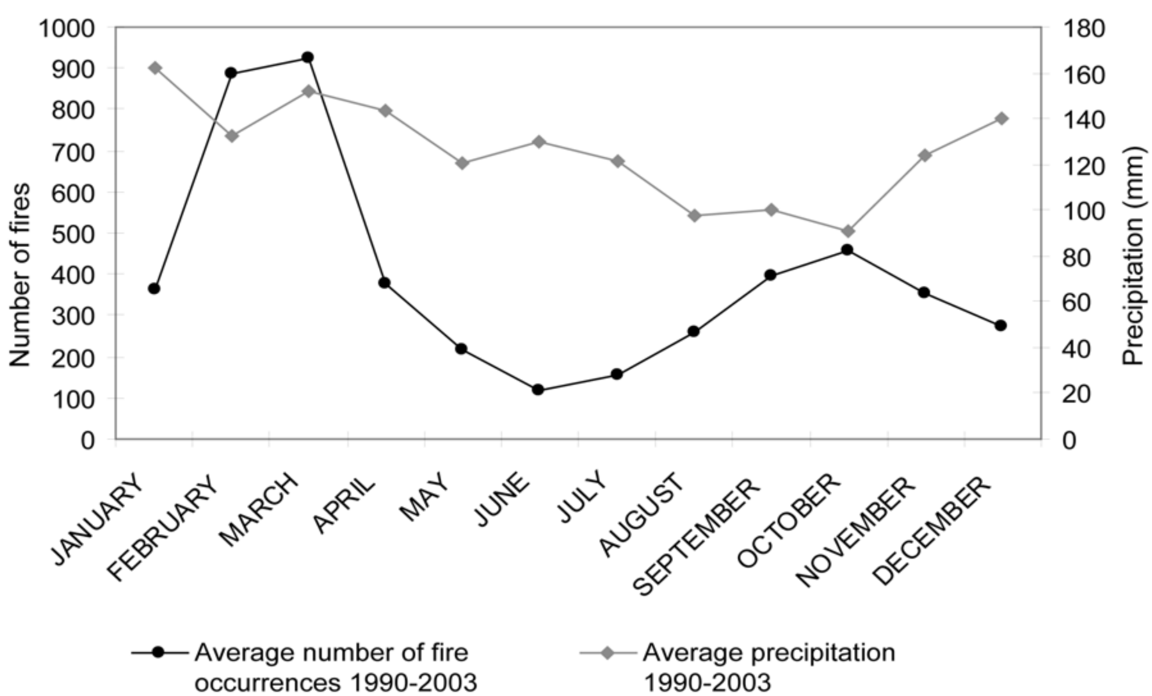


Figure 2—Relationship between climate and fire.

the literature. We tested the usefulness of KBDI alone as a measure of fire potential. KBDI was a poor predictor of forest fire potential in southern Mississippi. Results are presented in table 1 and figure 3. Pearson's r = 0.220 (May through August) and r = 0.257 (September through December) are significant, but regression results indicate poor model fit and little of the variance in fire frequency or fire size is explained by KBDI (r-square = 0.048 and r-square = 0.066 respectively). Based on these results, other measures of climate were considered.

Table 1— KBDI as a measure of fire potential analysis results.

January – April 1989-2003					
X	**Y**	**Pearson's *r***	**R^2**	**Adjusted R^2**	***p*-value for *r***
KBDI	Fire total	.035	.001	.001	.166
May – August 1989-2003					
X	**Y**	**Pearson's *r***	**R^2**	**Adjusted R^2**	***p*-value for *r***
KBDI	Fire total	.220	.048	.048	.000
September – December 1989-2003					
X	**Y**	**Pearson's *r***	**R^2**	**Adjusted R^2**	***p*-value for *r***
KBDI	Fire total	.257	.066	.065	.000

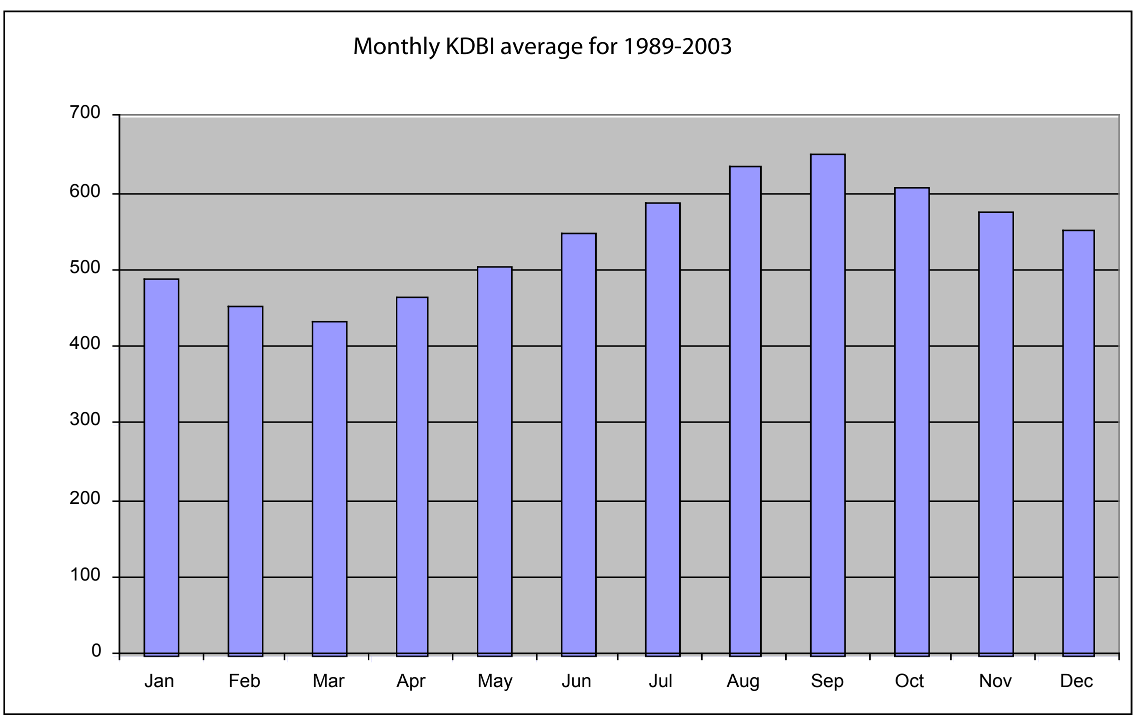


Figure 3—Monthly KBDI averages for 1989 through 2003.

Comparison of multisensor precipitation estimate (MPE) and weather station estimates—KBDI is calculated from data obtained from weather stations' data. We tested whether increased sample density of MPE is superior to weather station-based precipitation. Interpolated Doppler (NEXRAD) radar estimates of daily precipitation recorded at 4 km intervals on the Hydrologic Rainfall Analysis Project (HRAP) point grid were tested against precipitation estimates interpolated at more widely distributed weather stations. Estimated precipitation at high spatial densities (HRAP grid) offers increased spatial precision necessary for recording the relatively small convective weather events that are characteristic of summer weather conditions.

Continuous surface raster grids of precipitation estimates derived from weather station data were compared with precipitation estimates from MPE data (Gilreath 2006). For each day, MPE and weather station data were interpolated to a continuous raster surface grid. All days in a month were added for a summary of the district's cumulative monthly precipitation. To compare monthly cumulative precipitation between different months the MPE and weather station data value ranges were normalized using a z-score transformation. The normalized MPE and weather station grids were then standardized to five fire potential classes via histogram slicing using Jenk's Natural Breaks. A value of 5 represented highest fire potential and 1 represented lowest fire potential. The standardized fire potential values for both the MPE and weather station surface grids were extracted at each known fire location using a 'zonal' function in a GIS. The extracted fire potential estimates for summer 2003 and summer 2004 are compared in bar graphs in figures 4 and 5. In general, monthly mean fire potential at known fire locations is higher when precipitation is derived from MPE although exceptions are noted for September and October 2003.

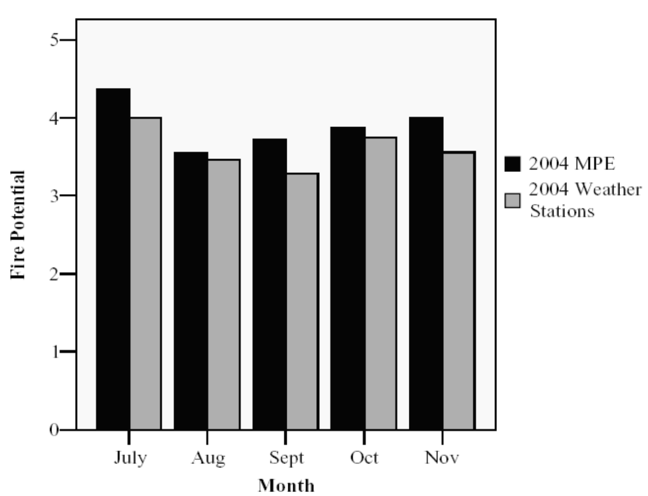


Figure 4—Comparison of the 2004 monthly fire potential estimates of the MPE and weather station layers

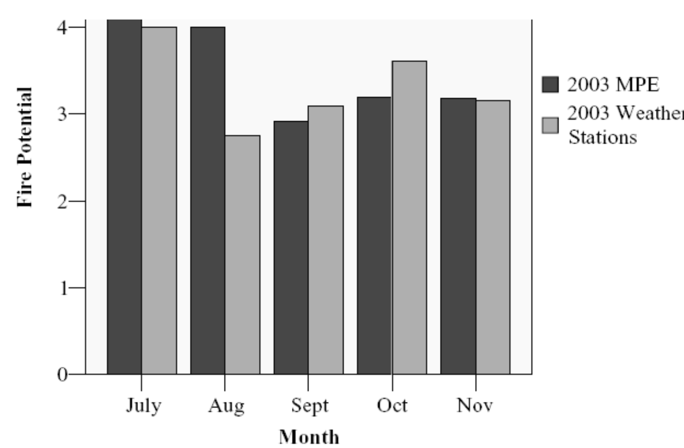


Figure 5—Comparison of the 2003 monthly mean fire potential estimates of the MPE and weather station layers.

P-E estimate—Precipitation (P) is a critical fuel moisture component, but high temperatures in Mississippi are associated with high rates of evaporation (E). Including evaporation in water budget calculations is important when determining available moisture in the environment. Pan evaporation was compared to regression-based predictions of evaporation developed in association with the Mississippi State Climatologist (Charles Wax). Pan evaporation stations that provide evaporation data exist but are sparsely distributed across the Southeastern United States. Therefore, regression models for inland and coastal locations have been developed that characterize the lower and higher humidity environments of the landscape respectively. Regression models were constructed using minimum daily relative humidity, maximum daily temperature, and total daily solar radiation data acquired at several pan evaporation locations. Evaporation predictions can now be made at any weather station that records daily minimum relative humidity and maximum temperature. These regression models enable interpolations of evaporation at a much denser point pattern than previously available at pan evaporation locations.

Daily water budget estimates were calculated by accumulating (summing) each day's precipitation minus evaporation (P-E) estimates and comparing these to long-term daily averages. Therefore, the water budget variable is an index that is calculated by measuring the daily departure of P-E from the historic P-E averages. While not a direct measure of fuel moisture, this index is representative of landscape moisture conditions critical for assessing fuel moisture in the various 'hour' fuels that exist in Mississippi and the Southeastern United States. The spatial depiction of cumulative wet or dry landscape conditions, used in conjunction with vegetation, ignition, soil, and topography, provide both a spatial and temporal view of patterns of fire potential.

Climate (P-E) modifier—A constructed variable similar to the soil textural pyramid is being developed by combining slope, vegetation, and soil texture. Slope was derived from the USGS National Elevation Data (NED) 30m Digital Elevation Model (DEM) data. Vegetation is characterized using summer 16-day MOderate Resolution Imaging Spectrometer (MODIS) Normalized Difference Vegetation Index (NDVI) data. Soil permeability from the State Soil Geographic (STATSGO) database was used as a surrogate for soil texture. This variable was designed to estimate the amount of runoff expected under various states of vegetation, slope, and soil texture and will act as a modifier of daily precipitation estimates.

Teleconnections—potential for fire potential predictions—In addition to traditional climate variables we examined the effects of global climate processes on regional weather of the Southeastern United States to better understand the impacts of climate variability on forest fires in Mississippi. Results of these analyses have the potential to support prediction of fire size and frequency in the region. Teleconection indices that were analyzed included: El Niño - Southern Oscillation (ENSO), Pacific-Decadal Oscillation (PDO), Atlantic Multidecadal Oscillation (AMO), North Atlantic Oscillation (NAO), and Pacific-North America Oscillation (PNA).

The literature documents that the El Niño – La Niña climate cycle has an effect on fuel load buildup and fire potential in the Western United States. During wet El Niño years, vegetation tend to thrive and expand. Big fire years in the West tend to occur when wet El Niño years are followed by dry La Niña conditions (Kitzberger and others 2001; Simard and others 1985).

Unfortunately, assessing fire potential is not as simple as identifying the phase of ENSO. Norman and Taylor (2003) also found that fires are more widespread during warm, dry years that followed cool, wet years. However, the effect of ENSO appears to be mediated by the PDO, such that fires are more widespread when the PDO is in a warm or normal phase (Norman and Taylor 2003). Further, it seems that the AMO may be the most dominant teleconnection index with respect to forest fire probability in the Western United States (Sibold and Veblen 2006). Nevertheless, no single climate variable appears sufficient for assessing and/or predicting fire risk. Rather, a combination of negative ENSO (La Niña), negative PDO, and positive AMO seems to be the most reliable method for predicting wildfires in the Western United States (Sibold and Veblen 2006).

Monthly fire data for each month during the study period (July 1990 to June 2006; 192 months) were aggregated into three categories: total fire events, average acres per fire event, and total acres burned. These categories are treated as dependent variables for this study. Squared bivariate correlation coefficients (r2) were then calculated for the relationships between each teleconnection index and each fire variable for each month of the year. It is possible that variations in the teleconnection indices may not affect Mississippi fires until a few months later, and/or the effects may last several months. Therefore, fire variables were also correlated with teleconnection index values from each of the 6 previous months in order to identify any lagging relationships.

Best results for analyzed lagging relationships between teleconnection indices and fire events organized monthly are shown in figure 6. More specific correlations are outlined below:

- Niño 3.4: Late summer (August, September) is the only time of year that consistently displays strong statistical relationships ($\alpha = 0.05$) between fire variables and Niño 3.4. August fire variables display the strongest relationships with Niño 3.4 values.
- NAO: The relationships between fire variables and the NAO appear to be driven by NAO values in early spring and fall. NAO values during February and March display notable correlations with the average fire size during the months of March, June, and July. In addition, April NAO values appear to affect the number of fires in September and October. Finally, NAO values during September and October display consistent correlations with fire variables in October, November, and December.
- PDO: The number of fire events in February show consistent correlations with PDO values during the months of December, January, and February, but the average fire size shows essentially no relationship to antecedent PDO values. All three fire variables for the month of August display impressive correlations with August PDO values. Of course, such a relationship provides little in the way of predictive ability. Nevertheless, despite no statistically significant relationships ($\alpha = 0.05$), PDO values during the previous 5 months appear to have some effects on fires in August, and PDO values in the previous February (6-month lag) have strong relationships with fire variables in August. Similarly, March PDO values display strong correlations with fire events in July.
- PNA: PNA values during the month of July illustrate the most impressive relationships with fire variables, as at least two of the three fire variables in each of the months July through October display statistically significant correlations with July PNA values. In addition, fire totals in January show some correlation with PNA values in the previous September, February fires are related to PNA values in January and February, and March fires appear to be affected by previous November PNA values.

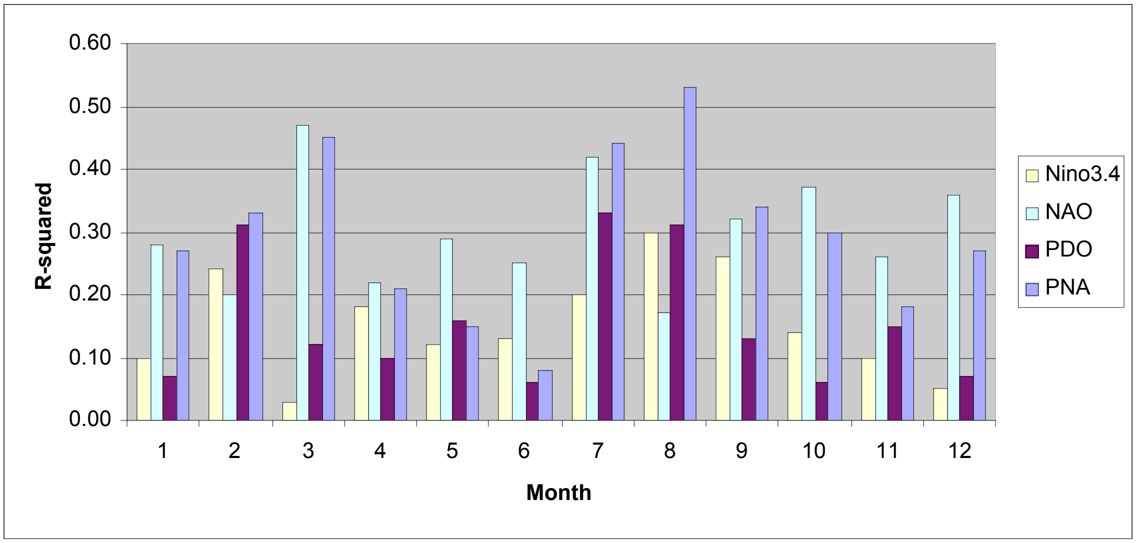


Figure 6—Best results for analyzed lagging relationships between teleconnection indices and fire events organized monthly.

Our analyses point out some correlations between indices and soil moisture. For example, all of the ENSO-fire relationships are negative (that is, positive Niño 3.4 anomalies lead to decreased fire potential). This is most likely due to the annual minimum in precipitation that typically occurs in late summer. During these dry conditions, antecedent soil moisture becomes a primary factor controlling the fire occurrence and extent. Since positive Niño 3.4 anomalies (El Niño) usually result in increased precipitation across the Southeast, soil moisture remains high. There is also a negative relationship between PDO and fire events in Mississippi. Again, positive PDO periods are accompanied by increased precipitation across the Southeastern United States., so soil moisture is likely to remain above normal. Finally, most months display a negative PNA-fire relationship, but positive PNA values during and around the month of September seem to result in increased fires throughout the fall and winter. Usually, positive PNA leads to lower temperatures across the Southeast, which should yield fewer fires. However, fewer fires in August may mean more residual fuels available for fires in fall and winter, which could explain the reversal in sign of the correlation.

Fuels

Typically, fuel load is a relatively static or slowly changing variable; however, sudden changes in moisture conditions and substantial vegetation damage can contribute to rapid changes in fire potential. Development of GIS layers that enable rapid characterization of changes in forest fuel conditions is important for determining how fire potential can change due to natural disasters such as hurricanes. For that reason, in response to damage caused by Katrina, we developed GIS fuel-based models that assessed fire potential in areas of Mississippi that were most severely impacted by the hurricane.

Long time-series of Landsat imagery, pre- and post-Katrina satellite imagery, and aerial imagery were integrated into the fuel-based model. Pre- and post-Katrina fire potential was compared for six counties in southern Mississippi using information on forest age classes, forest type and damage categories. Information on forest age classes and types were derived from

Landsat satellite data (Collins and others 2005). Hurricane damage information was derived from AWIFS imagery in form of binary damage mask, while aerial imagery interpretation of forest stand conditions was used to classify the damage categories and assess the accuracy of the satellite damage mask.

Pre-Katrina fire potential was derived a-priori from fire occurrence data. Forest type/age groups of similar fire frequency characteristics were determined by summarizing 20 months of pre-Katrina fire occurrence data. Number of fires, average fire size, and percentage of area burned in each class were evaluated and used as criteria for the assignment of fire potential for each group. This resulted in the several unique age/type group combinations that were assigned fire potential ranks ranging from 0 (no fire potential) to 5 (very high fire potential). Post-Katrina fire potential was determined by assigning the same ranks as pre-Katrina fire potential for undamaged areas and assigning an increased fire potential rank to areas classified as damaged by the satellite damage mask. A unique number was assigned to each unique combination of forest type, age, and damage layers to ensure that all combinations were assigned with appropriate fire potential rank. This is an important consideration in GIS modeling that enables the analyst to assess the exact conditions at a given cell location that give rise to a fire potential rank value.

The analysis resulted in spatial depictions (fig. 7) and statistical summaries of pre- and post-Katrina fire potential. Overall accuracy of the remotely sensed damage assessment was 72 percent. Based on the modeling results, validated with actual 2006 fire data, the fire potential in the region increased after the hurricane. The post-Katrina landscape is characterized by reduction in the contiguity of areas classified as very low fire potential, and increases in the amount and contiguity of areas classified as very high fire potential (fig. 7). Due to the hurricane, areas of very low potential decreased from 19 to 3 percent, while areas of very high potential increased from 3 to 13 percent.

Overall, the proportion of the landscape that was classified as very high fire potential after Katrina is greatest in the western counties (Hancock and Pearl River), somewhat lower in the central counties (Harrison and Stone), and lowest in the eastern counties (Jackson and George). This west-to-east fire potential gradient corresponds closely with the strongest wind speeds and highest amount of rainfall that occurred in Hancock, Harrison, Stone, and Pearl River counties.

The modeling results were validated with actual fire occurrence data. The greatest increase in post-Katrina fire potential was observed in the very low potential class (mixed and broadleaf stands), which may indicate that areas traditionally considered fire resistant change dramatically in terms of fire potential following hurricanes. Overall modeling results point out that increased numbers of fire suppression personnel may be needed for coming fire seasons in the impacted region.

Ideally, the fuels variable should characterize the amount of 1-hour, 10-hour, and other fuels (Anderson 1982). We are currently testing the usefulness of space-borne waveform Light Detection and Ranging (LiDAR) data for measuring vertical structure and fuel loads. Similar to the Fire Potential Index (FPI) described by (Burgan and others 1998), we use NDVI derived from Advanced Very High Resolution Radiometer (AVHRR) and MODIS data for regional fuels analyses. We have tested regression approaches for describing the sub-pixel components relevant to fuel loads using Landsat Thematic Mapper (TM) data (Berryman 2004), 'QuickBird' high resolution multispectral imagery, and airborne pulse LiDAR data.

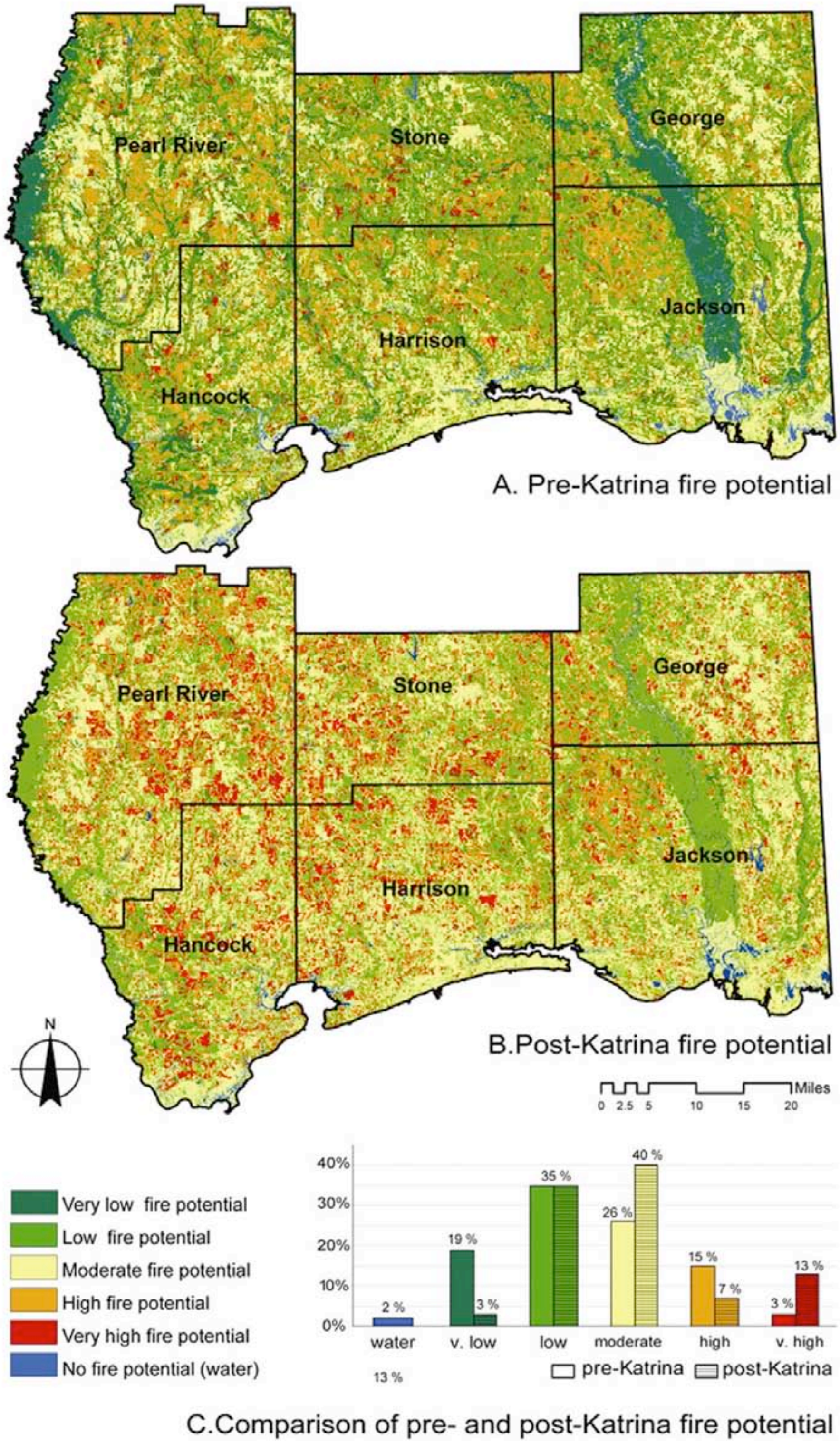


Figure 7—Pre- and post-Katrina fire potential comparison for six southern Mississippi counties.

Field work was recently begun designed to calibrate ICESAT GLAS data waveform LiDAR with fuel characteristics in a study area on the MSU 'Starr' Forest in Mississippi. Data were acquired over a variety of forest and some nonforest conditions. The ground data collection includes understory and overstory measurements for 60 field plots that are coincident with the elliptical footprint of the GLAS data. Figure 8 contrasts waveform differences between Anderson's fuel model 9 (pine plantation with little understory and downed woody debris) and fuel model 10 (mature pine plantation with hardwood understory and downed woody debris). Note that the earliest waveform returns are from the canopy, the next waveform returns are from the midstory and understory, and the last (and highest intensity) returns are from the ground. Our goal is to characterize fuel models from LiDAR samples for a variety of conditions, then extrapolate those conditions to larger (regional) landscapes via coarse resolution MODIS data using a subpixel prediction algorithm under development.

Ignition

Anthropogenic factors play a major role in fire ignition in Mississippi. Humans affect wildfire ignition by altering the vegetative fuel load characteristics and by providing an ignition source (Petrakis and others 2005; Pye and others 2003). Pye and others (2003) demonstrated that proximity to roads and certain levels of road density are significantly correlated with increased fire risk. Gilreath (2006) showed that in Mississippi, road density calculated using the gaussian kernel for all primary, secondary and county roads is a good predictor of fire frequency. Findings indicate that areas of very high and very low road density are at very low fire potential. Conversely, areas of moderate road density are at significantly higher risk. Sadasivuni (2007) tested the application of gravity models that measure the interaction among cities and medium-age large contiguous pine forests for fire frequency

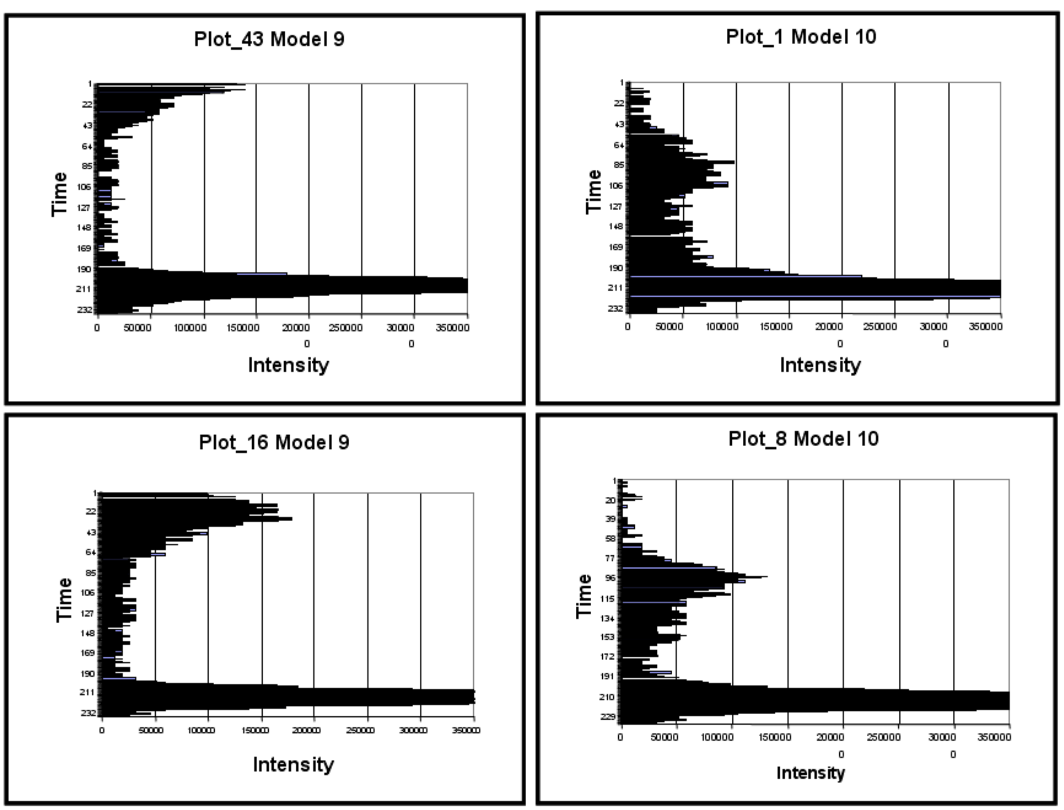


Figure 8—Contrasting waveforms for Anderson's fuel model 9 and 10.

relationships. Independent t-tests were used to test for significant differences among levels (ranks) of gravity models and road density models for all fires, winter fires and summer fires. Finally, t-tests for significant differences between levels (ranks) of gravity models versus road density models were made to test the hypothesis that no differences exist between the two methods for predicting fire frequency. Results of the tests for no differences between the two methods are shown in table 2. The gravity model proved to be better overall for estimating fire potential at the very low fire potential level for all seasons. It was also better at estimating fire potential in the medium level during the winter and for low and medium levels in the summer. For all other comparisons, there was no significant difference between road density and gravity models as predictors of fire potential.

Fire Potential Modeling Tool (FTMT)

Our geospatial database integrates water budget and fuels for wild fire potential modeling for the Eastern United States. A fire potential modeling tool (FPMT) has been developed to manage the geospatial database and to extract water budget (P-E) for the fire potential model. Development of an extension is underway for tools that will incorporate data from the Noah land model.

The database adopts the ESRI Geodatabase structure (fig. 9). Feature classes include radar sample points and weather station location. Two object classes store radar data and weather station data that are connected to the corresponding feature table based on measurement time in the time table. Time table is the third object class. Precipitation and evaporation are accumulated based on the period chosen as user's input. Individual accumulation data are stored as object tables, which are connected to the corresponding feature tables. To populate climatic data in the database, the automated procedures were developed in FPMT.

Table 2—Results of t-tests for gravity models and road density models (*indicates statistically significant results).

Gravity and road density	Annual critical	Annual p-value	Winter critical	Winter p-value	Summer critical	Summer p-value
Very low gravity and very low road density	3.51*	0.0085	3.64*	0.0058	3.58*	0.007
Low gravity and low road density	1.6	0.11	1.56	0.13	2.0*	0.05
Medium gravity and medium road density	3.09*	0.003	2.82*	0.0064	2.78*	0.007
High gravity and high road density	0.62	0.534	0.67	0.5	0.29	0.77
Very high gravity and very high road density	0.44	0.664	0.08	0.58	0.42	0.68

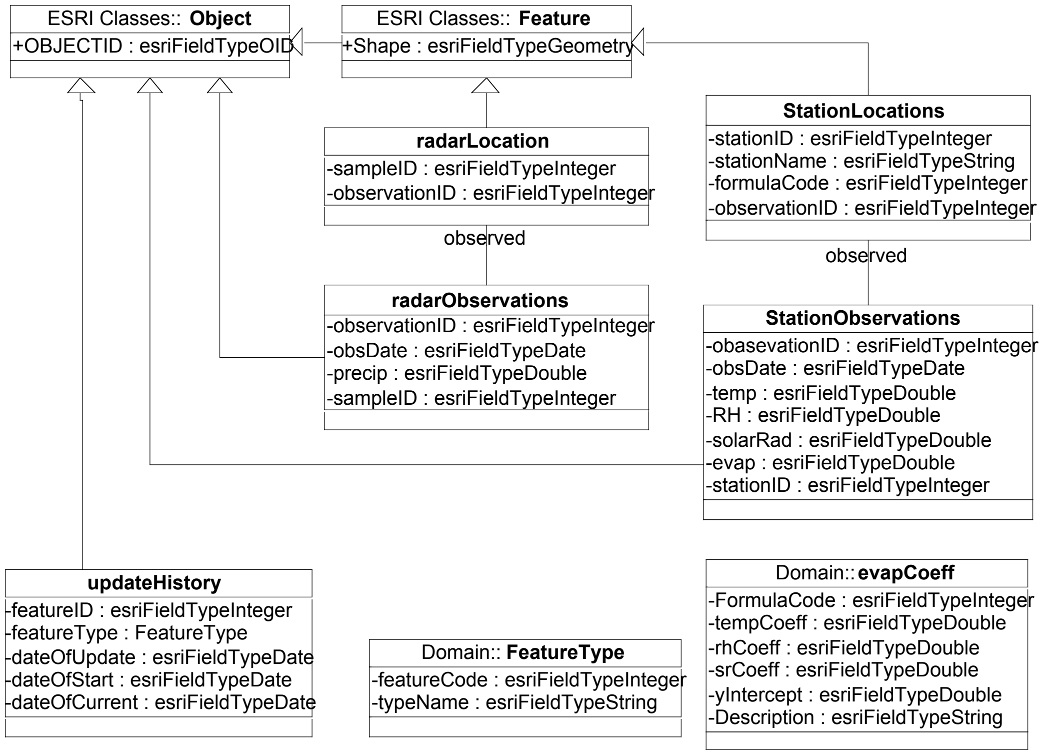


Figure 9—Geodatabase structure.

FPMT is an application designed to facilitate data management, spatial modeling, and map generation. Therefore, FPMT consists of three sub modules: data management, fire fuel modeling, and mapping modules. Current FPMT includes the data management module that includes data input, formatting, coordinate transformation, and accumulation procedures. Fire fuel modeling and mapping modules are under way, which include interpolation, fire fuel model, and creating map documents.

Conclusions and Plans

Each variable that has the potential of being included in the Mississippi fire potential models has been tested with historic fire occurrence data. Once the model variables and weights have been calibrated for Mississippi landscapes, we will extend the models to the southern region to test the usefulness of these modeling concepts over a larger landscape area.

We believe that measures of climate should include the effects of precipitation and evaporation (P-E) and that calculation of environmental moisture is cumulative and compared through time against the long-term P-E average. Although KBDI is a cumulative (soil) moisture index, our studies show that KBDI is a poor predictor of fire frequency and fire size for southern Mississippi. Precipitation and evaporation are important components for water budget calculations. Our goal was to interpolate precipitation and evaporation from the densest available source. Local measurements of precipitation and evaporation for our models result in descriptive products that are designed to estimate relative fire potential on the basis of comparisons of current climatic conditions with long-term averages. The ability to forecast future fire potential depends on understanding how global climatic processes influence fire occurrence (teleconnections). We are testing historic information derived from Pacific and Atlantic oscillation indices against historic fire occurrence in Mississippi, particularly concentrating on the temporal lag between index values and fire frequency and size.

This project demonstrated the utility of combing GIS raster modeling and remote sensing change analysis in assessing fire potential following hurricane Katrina. In this study actual change in fire threat was demonstrated empirically by validating fire potential predictions with actual fire occurrence data. This study demonstrates the capability of GIS-based analysis to provide rapid assessment of landscape conditions that favor fire ignition in coastal regions following destructive hurricane events. Such information is essential for emergency and wood recovery personnel to allocate their resources within areas of elevated fire hazard.

Understanding the anthropogenic factors that affect fire ignition is important in the Southeastern United States. We examined two methods of determining ignition from a spatial perspective. We found that city/fuels interaction (gravity) models are better than road density for characterizing fire potential in very low and low fire potential strata.

We have recently acquired 18 years of AVHRR NDVI bi-monthly composites for the United States. We calculated the 18-year average greenness for physiographic regions in Mississippi. We plan to test correlations between fire variables and NDVI (greenness) as a departure from the 18-year average.

We are designing a Web-based graphical interface for our fire potential modeling tools (FPMT) to display results. Initially, fire potential estimates will be summarized on a bi-monthly basis. The data acquisition interface is user-friendly and can adapt to a variety of precipitation input data. We hope to have the fire models calibrated, functional and available on the Web in the near future.

References

Anderson, H.E. 1982. Aids to determining fuel models for estimating fire behavior. INT-GTR-122. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station.

Berryman, B.N. 2004. Investigating of relationships between Landsat ETM+ data and ground-adjusted LIDAR measurements in southern pine stands. Thesis. Mississippi State, MS: Mississippi State University.

Burgan, R.E.; Klaver, R.W.; Klaver, J.M. 1998. Fuel Models and Fire Potential from Satellite and Surface Observations. Int J Wildland Fire 8:159-170.

Collins, C.A.; Wilkinson, D.W.; Evans, D.L. 2005. Multi-temporal Analysis of Landsat Data to Determine Forest Age Classes for the Mississippi Statewide Forest Inventory –Preliminary Results. In: Proceedings of the Third International Workshop on the Analysis of Multi-Temporal Remote Sensing Images. Biloxi, MS. CD-ROM.

Gilreath, J.M. 2006. Validation of variables for the creation of a descriptive fire potential model for the Southeastern Fire District of Mississippi. Thesis. Mississippi State, MS: Mississippi State University.

Kitzberger, T.; Swetnam, T.W.; Veblen, T.T. 2001. Inter-hemispheric synchrony of forest fires and the El Nino-Southern Oscillation. Global Ecol Biogeogr 10: 315-326.

Morgan, P.; Hardy, C.C.; Swetnam, T.W.; Rollins, M.G.; Long, D.G. 2001. Mapping fire regimes across time and space: Understanding coarse and fine-scale fire patterns. Int J Wildland Fire 10: 329-342.

Morris J.A. 2007. An Analysis of the Keetch-Byram drought index as a predictor of forest fire potential. Thesis in preparation. Mississippi State, MS: Mississippi State University.

Norman, S.P.; Taylor, A.H. 2003. Tropical and north Pacific teleconnections influence fire regimes in pine-dominated forests of north-eastern California, USA. J Biogeogr 30: 1081-1092.

Petrakis, M.; Psiloglou, B.; Lianou, M.; Keramitsoglou, I.; Cartalis, C. 2005. Evaluation of forest fire risk and fire extinction difficulty at the mountainous park of Vikos-Aoos, Northern Greece: use of remote sensing and GIS techniques. International Journal of Risk Assessment and Management 5: 50-65.

Pye, J.M.; Prestemon, J.P.; Butry, D.T.; Abt, K.L. 2003. Prescribed Burning and Wildfire Risk in the 1998 Fire Season in Florida. In: Fire, fuel treatments, and ecological restoration. 2002 April 16-18; Fort Collins, CO. Proceedings RMRS-P-29. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Sadasivuni R. 2007. Gravity model to detect forest fire prone areas in the southeast fire district of Mississippi. Thesis. Mississippi State, MS: Mississippi State University.

Sibold, J.S.; Veblen, T.T. 2006. Relationships of subalpine forest fires in the Colorado Front Range with interannual and multidecadal-scale climatic variation. J Biogeogr 33: 833-842.

Simard, A.J.; Haines, D.A.; Main, W.A. 1985. Relations between El Niño/Southern oscillation Anomalies and wildland fire activity in the United States. Agric. Forest Meteorology 36; 93-104.

Zhai, Y.S.; Munn, I.A.; Evans, D.L. 2003. Modeling forest fire probabilities in the South Central United States using FIA data. South J Appl For 27; 11-17.

This
page is
blank
on purpose

Educating and Engaging the Business Sector in Reducing Wildfire Property Losses

Anne S. Fege[1] and Christopher Blaylock[1]

Abstract—*Most wildfire education programs have relied overwhelmingly on homeowner information and education, limiting the role of such business professionals as architects, builders, insurance agents, landscape architects and contractors, planners, media, and realtors. This project was undertaken to engage and educate professionals who design landscapes and homes, work for home and property owners, and make decisions that affect homeowners and communities—and in the long run, to change best management practices in these industries. Market surveys for the target professions were conducted at the outset, reaching 58 individuals and organizations and gathering information on continuing education requirements, subject relevance, training format, pricing, and marketing. About 30 business professionals were involved in the selection of existing materials and development of curriculum for four modules: industry issues, fire environment, building materials and design, and site planning and maintenance. Four seminars were held in March 2007 at sites that provided geographic and time-of-day distribution, and 100 business professionals attended from the target audiences. Ongoing project evaluation incorporated the market scoping, interaction with business groups, and classes. The project team identified new business practices and cooperative efforts that contribute to property-loss prevention, are economically viable, are likely to be adopted, and extend the reach of the traditional fire and land management professionals.*

Introduction

The challenges of reducing wildfire property losses, while sustaining healthy natural environments, grow with the increase in homes built at the wildland-urban interface and intermix. Substantial gains have been made in the past half-century on the technology of building ignition-resistant homes; selecting and maintaining landscapes that minimizes radiation exposure of the house; and siting structures and developments. Yet many individuals, businesses, and agencies are still unaware of, or are unwilling to apply, these measures. Furthermore, most wildfire education programs have relied overwhelmingly on homeowner information and education, limiting the contributions of such business professionals as architects, builders, insurance agents, landscape architects and contractors, planners, media, and realtors.

The planning profession produced and published "Planning for Wildfires" in their professional series (Schwab and Meck 2005). Schwab and Meck emphasize wildfire planning in a comprehensive context, regulation and enforcement that stresses property owner responsibility, and education and outreach to affected residents and property owners. Whereas the "Planning for Wildfires" manual exemplifies the application of wildfire risk reduction

In: Butler, Bret W.; Cook, Wayne, comps. 2007. The fire environment—innovations, management, and policy; conference proceedings. 26-30 March 2007; Destin, FL. Proceedings RMRS-P-46CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 662 p. CD-ROM.

[1] Botany Research Associate and Wildfire Education Project Manager, respectively, San Diego Natural History Museum, San Diego, CA. Lead author afege@sdnhm.org

principles and practices by planning professionals, the authors do not address the importance of accurate and effective advice to homeowners from architects, landscape designers, realtors, and other business professionals. The extensive information published by the National Fire Protection Association (2002) on planning, construction, maintenance, education, and management elements for reducing wildfire losses is written for fire officials and is likely referenced by few business professionals.

Various studies underscore the value of specific information applied to local community settings. Although these studies do not mention business professionals, who advise and do work for homeowners, it is their expertise and individual advice that could contribute to decisions by homeowners to reduce their wildfire risks. Kumagai and others (2004) reported that people are more likely to believe wildfire hazard risk information if it is specific, consistent, certain, and disseminated repeatedly. Brenkert and others (2005) conducted interviews with residents in Larimer County, Colorado, regarding wildfire mitigation actions, and found that the most common motivating factors were the informal social processes by which homeowners learn about and form opinions about wildfire risk; their perceptions about the biophysical setting of their property, community, and nearby public lands; and their knowledge about the effectiveness of various mitigation measures. The authors noted that one-on-one information tailored to a particular property, from a credible source, was associated with homeowners taking mitigation action.

The sessions at a national wildfire education conference (FireWise Communities 2006) highlighted public education, community involvement, and government partnerships. Only three of the 75 presentations focused on the role of business professionals: how forestry and arborists can communicate with potential homeowner clients and provide quality services; how landscape architects can balance safety, aesthetics, and ecology in their designs; and how insurance agents work cooperatively with homeowners and fire agencies.

Social science and marketing research are now being applied to better understand the attitudes and behaviors of homeowners about fire prevention investments in the wildland-urban interface. Social marketing builds on social exchange theory wherein people adopt behaviors that they believe have a positive benefit for them or their community, and that results in both individual and societal gains. Social marketing principles suggest that information should be tailored to the cultural, political, and economic conditions of the community that is expected to invest in survivable space (Absher and others 2006; Andreasen 1995; Kotler and others 2002; Hoban and others 2003). Similar gains could be made with the business sector, as objectives can be adapted to fit their physical, social, economic, and political environment.

With the support of the Joint Fire Sciences program and the U.S. Fish and Wildlife Service, San Diego Wildlife Refuge Complex, this project was undertaken to engage and educate business professionals who design landscapes and homes, work for home and property owners, and make decisions that affect homeowners and communities. The San Diego Natural History Museum developed, marketed, and conducted seminars entitled, "Wildfire Education for Business Professionals," cooperating with local professional associations to promote and provide certification or sponsorship. Curriculum for these interdisciplinary seminars was developed with local professionals, emphasizing property risk reduction while minimizing the impact to the native environment.

San Diego Setting

San Diego is a large urban area with a rapid rate of development; the scientific, business, educational, and professional resources are extensive; the October 2003 wildfires affected virtually every community, business, and individual, at least indirectly. The biodiversity, fire-adapted landscapes, low rainfall, and rapid rate of development in San Diego are unique and unequaled—and San Diego is always "between wildfires." In late October 2003, three wildfires in San Diego County burned 152,000 ha, almost 15 percent of the land area of the county—including the Cedar Fire, the largest in California since historical records were first kept in 1910. Sixteen lives and more than 3,200 structures were lost.

A Damage Assessment Team was assigned to document damaged structures and property after the Cedar Fire, and the findings were included in a report about wildfire losses in California (Fire Cause Analysis 2004). Destruction and damage were attributed to poor accessibility, inadequate clearance of vegetation, wooden landscape improvements, wood or composition shingles, flammable exterior siding, and uncovered vents to attics and crawlspaces.

Absher and Kyle (2006) surveyed homes in the wildland-urban interface zone in San Diego County, near the Cleveland National Forest. Of the 770 returning surveys (35 percent), 98 percent of the households saw smoke in 2003; 97 percent saw flames; 40 percent were evacuated; 42 percent had their work or livelihood disrupted; and 30 percent had property damage. They found high compliance for some behaviors (such as cleaning roof and gutters, stacking firewood away from the house); moderate compliance for others (such as reducing vegetation density); and low to moderate levels of community participation (49 percent received information, 22 percent attended meetings, 12 percent volunteered time, 26 percent willing to get involved with a FireSafe Council).

In the county of San Diego, local building and brush reduction codes have been passed in virtually all jurisdictions and are fairly similar though not identical. There is abundant, if somewhat scattered, technical information for homeowners and business professionals on how to reduce wildfire risks. Numerous forums and workshops have been held by groups such as the San Diego Fire Recovery Network in cooperation with the Museum, the San Diego Horticultural Society, the Fire and Rescue and the Water Departments in the city of San Diego, National Fire Protection Association, local chapters of the American Society of Landscape Architects and the California Native Plant Society, and the University of California Cooperative Extension program.

Methods

Market Surveys

Because business professionals have generally not been targeted in wildfire education and prevention activities, market research was needed to understand their vested interests in wildfire risk reduction and continuing education. The audience was defined as businesses and professionals who work in and around home sites and community developments, and included architects, builders, insurance agents, landscape architects and contractors, planners, media, and real estate professionals. Market surveys for the target professions were conducted at the outset, reaching 58 individuals and organizations and gathering information on continuing education requirements, subject relevance, training format, pricing, and marketing.

Market research into these business sectors was focused initially on national professional organizations that are membership-based, provide services that range from continuing education to advocacy and lobbying, and have unique insights into their industry trends and needs. Information was gathered in phone calls to officers and staff within each organization, asking questions regarding how to best accommodate the learning style of professionals in that industry; how to provide value to the professionals to motivate them to attend and utilize the concepts once taught; and how to address budget and time constraints to accommodate the greatest number of potential students.

A second phase of market research focused on the local chapters of those organizations and/or companies unique to southern California. This outreach gathered information on the curriculum and training products that address local business practices in wildfire loss prevention, market forces behind changes in business practices, ways to market seminars to local professionals and companies, and how to develop partnerships and involvement with local organizations and businesses.

Curriculum Development

The project "Wildfire Education for the Business Sector" assumed that existing wildfire education materials were adequate and could be adapted by local professionals and experienced national and regional experts for the seminars. Wildfire education materials applicable to the southern California setting had already been gathered and used in local wildfire education grants after the 2003 wildfires (McElhinney and Younkman 2005), and more recently gathered by the University of California Extension Service (Janis Gonzales, personal communication, March 2007).

Resource professionals have for decades known most of the principles and practices for reducing wildfire-related property and resources losses in southern California. A homeowners' guide—Radtke (1982)—was produced from earlier research, and this guide was more recently slightly modified and reprinted (Radtke 2004). These publications describe chaparral ecology and fire regimes, the effect of topography on fire behavior, risk reduction through planning and site design, modification of existing structures to reduce risks, and more. Compared with contemporary wildfire education publications, Radtke (1982) placed greater emphasis on watershed values, erosion reduction, rooting depth and drought tolerance, slope engineering, hillside landscaping, and postfire rehabilitation.

An advisory committee provided guidance throughout the development of the project, helped with curriculum development, and helped train and evaluate the instructors in the material to be presented. Originally a group of about 10, it was informally expanded to include 29 local professionals involved in curriculum development from various fields (table 1). Whereas involvement by national experts was originally planned, it was discovered that several local experts were on the "leading edge" of various subject areas, and consultation with national experts was done occasionally and informally.

The local experts assisted with the selection of existing materials, development of curriculum objectives, and PowerPoint presentations for four modules:

1. Industry issues. Representatives from the various target industries were asked to prepare a 3 to 5 minute presentation about the issues they face in the field with regard to wildfire. A conference call was held with all participants to provide an opportunity for practice and feedback.

Table 1—Professional affiliations of participants in wildfire education project.

Participants	Curriculum development	Seminar attendance
Architects	1	5
Consultants (environmental, wildfire prevention planning)	10	14
FireSafe council and homeowners' association members	1	9
Insurance agents, brokers and underwriters	1	8
Landscape architects, landscape designers, and contractors	6	17
Property managers, real estate agents, and appraisers	1	16
Public employees (planning, wildfire, land management)	18	26
Total	**38**	**98**

2. Fire environment (including fire basics, local habitats, and local fire ecology). The fire basics objectives and illustrations were drawn from basic wildland firefighting training materials. The local habitats section was developed by RECON Environmental, Inc., a consulting firm based in San Diego, CA, as a partnership and donation to the project. The fire ecology section was developed by California Chaparral Institute, based in Escondido, CA.
3. Building materials and design. Information from damage assessments after the 2003 Cedar and Paradise Fires, as well as Statewide deliberations about local building codes, had been incorporated into a PowerPoint presentation by Rancho Santa Fe Fire Protection District (2006). This was shortened and otherwise unaltered for this module.
4. Site planning and maintenance. A task force of about a dozen landscape architects, arborists, and planners met four times to outline, discuss extensively, and develop the objectives and the presentation for site design, defensible space, and fuels management. Two landscape architects provided most of the photos and review, one in private practice and one working for a local agency planning review department.

Drafts of the written outlines and corresponding PowerPoint presentations were distributed electronically for review by all of those who contributed to the curriculum development, as well as local fire officials and professionals willing to support the review process. Finally, two dry-run presentations were held with an open invitation to attend. This provided instructors with the opportunity to practice, the team with an opportunity to refine the curriculum, and local stakeholders an opportunity to review the materials.

Seminar Marketing Efforts

The Museum's marketing department assisted with media outreach, sending three press releases in the 6 months prior to the seminars. Contacts were made with local professional organizations and associations, to request that they include the wildfire seminar information in scheduled e-mail messages and newsletters. Announcements were sent directly to about 500 real estate professionals and were distributed as "e-mail blasts" to such other organizations as local chambers of commerce, Rotary Club and other service clubs, Sierra Club, and California Native Plant Society.

Results

Market Surveys

Respondents generally recommended a training format of about 4 to 6 hours, and indicated that a cross-training (interdisciplinary) format would be beneficial to most industries. Most organizations indicated that there are few wildfire education opportunities targeted toward their respective industry, either currently or in the past. Education programs commonly are in the form of offsite seminars with presentations and handouts.

Education is generally pursued by individual professionals, with companies reimbursing them when it is applicable to their jobs and benefits their performance. When continuing education credits are required to maintain licensure, the course provided must be approved by the regulatory agency or organization, and professionals expect to pay for the courses that they attend. Courses can be comarketed with professional associations, and information provided in e-mail announcements and newsletters.

There are clear differences between the five business sectors that were the focus of this project (table 2). These differences underscore the importance of adapting seminar offerings and marketing to various business sectors, to enhance participation and educational value.

Table 2—Summary of market survey of business sectors.

Architecture, building, and design industries	Formal wildfire information is limited and generally is obtained inefficiently as professionals deal with codes and enforcement in each jurisdiction. Architects in California have annual CE requirements for maintaining their licenses, and few courses are offered to meet the hours required in health, safety, and welfare.
Insurance agents, brokers, and underwriters	These professionals are required to complete some CE-certified training annually and are most interested in how to gain local site-specific information and make onsite assessments. Most contacts indicated that existing programs charged a nominal fee, and one contact from the Insurance Education Association recommended a $199 fee for a half-day class.
Landscape architects, landscape designers, and contractors	Landscape professionals' interests include the effectiveness of various mitigation techniques to meet local codes, and how to plan for clients in the back country. Most have no CE requirements and are accustomed to attending offsite programs, workshops, and seminars that are free or have only a nominal charge.
City planners, environmental consultants	Planning professionals attend both luncheon meetings and workshops and are particularly interested in knowing county fire protection plan requirements, different jurisdictional standards, and ways to address community fire planning early in the development decision process.
Real estate agents, brokers, and appraisers	Real estate professionals are looking for courses on either "how to make money or how to stay out of trouble (risk management)."

Curriculum

Protecting property from wildfire requires a systems approach. That is, no one aspect of mitigation protects the structure entirely but instead works within a larger system of mitigations and preparation to save the home. It is important then for landscapers not only to have a deeper understanding of how their work contributes to a fire-safe landscape, but that they also have an understanding of how it fits into the larger system that includes structural design and fire physics. It is therefore useful for them to learn about "Building materials and design" and other subject areas in order to understand the larger system. It is also likely that larger system information has not been presented to landscape architects in their traditional education, whereas they may already be familiar with fire-safe landscaping principles.

Therefore, it was decided that all sections would be presented to all professionals, reinforcing the comprehensive systems approach that underlies the concepts of wildfire risk reduction and protection of natural environments. By giving different industries the full curriculum, better interaction and partnership were facilitated among professionals and industries. Landscapers can theoretically work better with building contractors or insurance professionals, for example, now that they both have a better understanding of the full scope of what is involved, not just the aspects that relate to their narrow scope of work.

Concerns about wildfire risk mitigation practices, when accomplished initially by excessive fuel reduction, have been expressed repeatedly by biologists and other environmental professionals in southern California (Halsey 2004). This curriculum was developed to teach the principles of wildfire mitigation while minimizing the impact to the native environment. The wildfire education seminars focus on appropriate vegetation reduction practices that reduce water use, plant maintenance, erosion, slope instability, invasion by highly flammable nonnative plants, and therefore also costs to the homeowner. When ignition-resistant structures are considered the first "line of defense," and when the landscape practices minimize the width of defensible space necessary to protect structures, the acreage of natural habitat loss will be minimized.

Reports, brochures, State codes, county and city of San Diego codes, contacts for smaller jurisdictions, sample fire management plans, and Web site links were provided on a CD to seminar participants. For example, copies of materials produced by the Center for Fire Research and Outreach at the University of California in Berkeley (2006) were included, from their Web-based "Fire Information Engine Toolkit" that has extensive information on mitigating home-related fire hazards based on observations of wildfire damage, data from fire tests, and input from firefighters. The "Homeowner's Wildfire Mitigation Guide" has descriptions and illustrations of problems and solutions for roofs and gutters, vents, siding, windows, garages, decks, fences, plants, and trees. The CD also included copies of the fire performance tests of roofs, decks, walls, and windows that provide detail suitable for architects and construction professionals (Quarles 2006).

The core curriculum consisted of PowerPoint presentations with written outlines and slide printouts distributed to each participant, for the four modules: industry issues, the fire environment, building materials and design, and site planning and maintenance (San Diego Natural History Museum 2007). PowerPoint presentations were included, and attendees were encouraged to use and adapt them in their work with clients, employees, and other contacts. The Museum synchronized audio from the live presentations with their corresponding PowerPoint slides, suitable for Web-casts or for training new instructors. Attention was given to the exact wording of the outlines, as they are the principles that seminar participants will apply and share with their clients. An excerpt from the "fire environment" module is provided in table 3.

Following the development of curriculum objectives and outlines, professional associations were approached for their willingness to assign continuing education units (CEUs) for these classes, ostensibly as an attractive motive for professionals to attend. By partnering with local organizations, CEUs were secured for the following:

1. Certified arborists, through the Western Chapter International Society of Arboriculture
2. Certified urban foresters, through the California Urban Forests Council

Table 3—Excerpts from wildfire education curriculum.

a. Local fire ecology – Why Sunshine, Shrubs and Wildfire?
    - i. Survival in a Mediterranean climate
        1. Mediterranean climate exists in only five places in the world, representing only 2% of the world's land area. This unique climate helps makes Southern California's flora and fauna some of the most unique and diverse in the world.
        2. Seasons dictated by rainfall that is distributed differently than other climates.
            - a. Spring: After first rains, usually in November/December
            - b. Fall: Very brief, usually in June (or August at higher elevations)
            - c. Summer drought
    - ii. Adaptation: An adaptation is a pre-existing behavioral or physical trait of a group of organisms that allows it to survive an environmental condition.
        1. Drought adaptations
            - a. Leaf adaptations
            - b. Avoiders: Usually have deep tap roots that find water
            - c. Persisters: Shallow roots but hang on through conservation
            - d. Retreaters: Annuals
            - e. Chameleons: Hang out but leaves change; semi-deciduous
        2. Fire adaptations
            - a. Obligate resprouters: Don't completely die, resprout after fire
            - b. Obligate seeders: Adults die, seeds can't germinate unless scarified by fire in some way
            - c. Facultative seeders: respond both by resprouting and germination
            - d. Annuals and short-live perennial "fire followers"
            - e. Geophytes: bulbs that bloom after until fire removes the canopy and allows sunlight on these sites
    - iii. Fire regimes
        1. Difference between "fire" and fire regimes with distinct frequency, intensity and seasonality of fire
        2. Chaparral not dependent on fire for regeneration, but has survived certain fire regimes in Mediterranean climate and human occupation
        3. Fire ignitions have increased linearly with population increases
        4. Fire suppression has not led to bigger fires in Southern California
    - iv. So what do we do about it?
        1. Create sustainable, fire-safe environments for our homes by starting from the house out, rather than from the wildland in.
        2. Systems approaches
            - a. Community design
            - b. Building design
            - c. Landscape design
            - d. Personal responsibility

3. Community managers, through the California Association of Community Managers
4. Architects, through the American Institute of Architects (self-reporting)
5. Planners, through the American Planning Association (self-reporting)

Seminar Marketing Efforts

Through periodic press releases and contacts with local media, the Museum was able to secure media coverage in four publications. Two local newspaper articles were written from the press release information, and two articles in national insurance and real estate trade publications were written from interviews with the project manager and local professionals referred by the project manager.

Professional associations provided a major outlet for distribution of seminar information. Different organizations took different levels of interest in the project and promoted them accordingly. Some simply forwarded the seminar invitations in their e-mail blasts. Others, such as the local chapter American Society of Landscape Architects (ASLA) and California Association of Community Managers (CACM), were far more aggressive with their promotion and, as a result, landscape and property professionals constituted 13 and 17 percent of the participants, respectively.

Class registration fees played a role in marketing. Market research indicated that some industries were used to paying over $100 for similar classes, and other industries commonly pay no registration fees or only nominal fees for similar offerings. When the seminars were initially announced with $100 tuition, some industry representatives indicated they would register multiple employees if fees were lower, and some in the government and nonprofit sector advised us that the fee was too high. A “scholarship” was originally envisioned, but that become awkward to administer. In order to promote the classes for this initial offering, the seminar fee was reduced to $25, and no one commented further about the fee.

Seminar Offerings

Four seminars (classes) were held in March 2007 at sites that provided geographic and time-of-day distribution in order to attract the widest possible audience. They were held on Friday morning, Thursday afternoon, Friday afternoon, and Saturday morning, each for five hours (including 10 minute breaks after every 50 minutes of instruction). Professional affiliations of attendees are listed in table 2.

One class was cohosted by the San Miguel Fire Protection District, at a location convenient for professionals in eastern San Diego County, where there is extensive wildland-urban interface. Another class was hosted by the San Diego chapter of the American Society of Landscape Architects. Although it was expected that the class would be heavily slanted toward landscape professionals, a diverse range of professionals attended and it was one of the more dynamic classes. The Rancho Santa Fe Fire Protection District cosponsored a class at their facilities, and this drew professionals from northern San Diego County.

The insurance industry was an active, enthusiastic participant in the curriculum development, marketing, and attendance at the seminars. Chubb Group of Insurance provided extensive perspectives and suggestions, and an industry panelist for three seminars. Chubb Group of Insurance and the Museum cohosted an introductory 1.5-hour wildfire course in February 2007 with an out-of-town instructor and CEUs through the California Department of Insurance. The class reached 22 insurance professionals and likely contributed to insurance sector participation in the wildfire education seminars in March 2007. It is expected that this course will continue to be available to insurance professionals in southern California, though it is cost-effective for insurance offices to attend the local Wildfire Education for the Business Sector seminars, rather than bringing out-of-town instructors.

A fire prevention course was initiated about 3 years ago by the FireSafe Council of San Diego County and was accredited by the California Department of Real Estate in March 2007, "Rural Home Fire Safety for Real Estate Professionals Course." This 6-hour course includes an overview of the wildfire problem in California, factors that increase the fire danger to a home, features that make a structure more fire-resistant, and how to assist their clients in selling and selecting homes located and built with fire safety in mind. Course instructors will be qualified professionals approved by the FireSafe Council of San Diego County, and six Consumer Service CEUs will be given to real estate professionals who complete the course. Because of the many common elements, it is expected that it will be comarketed with the Wildfire Education Seminars in the future.

Evaluation

Feedback forms were provided to each participant in order to gather information about the effectiveness of the training; 39 feedback forms were returned. The feedback indicated that participants understood the fundamental points. Many professionals indicated a new understanding of the need to look at fire-wise building and landscape design within the context of the natural environment. Professionals who are in a position to advise homeowners indicated they would use this information to better educate their clients. Design professionals indicated that they received ideas that would help them early in the planning process. Some design professionals indicated a desire for greater detail and potentially a more advanced course. Selected comments are provided in table 4.

Project evaluation elements also included the market scoping, interaction with business groups, and feedback from professionals developing the curriculum. From these insights, new business practices and cooperative efforts are already being identified that will contribute to property-loss prevention, are economically viable, are likely to be adopted, and extend the reach of the traditional fire and land management professionals.

Future Seminars

Businesses and professionals gained greater understanding of fire-safe principles and codes, an understanding that will benefit their clientele in the form of knowledgeable homeowners and fire-resistant homes or communities. As the wildfire knowledge base in southern California expands through such wildfire education efforts, property protection will likely increase and losses in the next wildfire will likely decline.

Discussions are ongoing, about whether and how to shorten the seminars from 5 to 3 hours. Some possible scenarios for continuing the wildfire education seminars have been explored and include:

1. Offer seminars regularly by local organizations with ongoing educational programs on related topics, including the Museum, the Water Conservation Garden (which is sponsored by water companies), Quail Botanical Gardens, and the Burn Institute.

Table 4—Comments from participant feedback forms.

"How very naïve we are, regarding our native environment" *
"Homeowners must understand where they live and accept the responsibility through a fire-safe lifestyle that includes house, landscape, and evacuation (or staying to defend the house)."
"Industry panel was very insightful; include city code enforcement and planning department as panelists." "Include local land use regulation perspective on panel—I volunteer!"
"Suggest alternatives for building materials during architectural review." Property manager.
"Great to have real examples of building ignitions, alternative materials, landscaping techniques, and local ecology."
"Printing brush management codes on landscape architects' plans (City of San Diego) provide ongoing reminders."
"Establish demonstration gardens around a typical home to show 'fire-safer' gardens, perhaps a garden at the local fire station or a Sunset 'idea home' that goes on tour periodically to demonstrate the latest designs and products."
"Suggest more information on how to combine defensible space with aesthetic appeal, annual calendar for maintenance, considerations for wildlife plantings, and more time for questions." Property manager.
"As a land conservancy, we've had illegal brush management clearing adjacent to our preserves; we need to work with insurance agents, developers and homeowners to address this problem." Biologist.
"Talk about how local communities and organized neighbors could organize to review their needs and take corrective actions to help the fire department prevent disasters." Real estate professional.
*Professional identity listed, if provided on feedback form.

2. Package the seminars and arrange for local organizations and companies to undertake marketing, registration, and logistics. To retain the valuable cross-training aspects of the seminars, it would be advisable for two or more professional organizations to cohost a seminar and market to their professional base. Examples include American Society of Landscape Architects and American Institute of Architects, or a real estate office and a nearby homeowner's association, or a fire marshal and local Fire-Safe council.
3. Package the seminars and market them to other regions of southern California. If this approach is taken, it would be advisable for the hosts to arrange a short review process involving local regulators and professionals and to arrange for a local industry panel.
4. Incorporate any related courses, targeted to the insurance and real estate industries, into the marketing efforts.

Conclusions and Recommendations

The businesses and individuals who advise and interact with homeowners are in a unique position to affect the physical properties of homes, communities, and landscapes. This project successfully developed and held seminars for business professionals to impart the fundamentals of mitigating for wildfire with minimal impact to the surrounding environment.

The wildfire knowledge base in southern California has been enhanced by engaging professionals in wildfire education efforts. If these efforts continue, property protection will likely increase and, potentially, losses from the next fire would decrease. Businesses and professionals gained greater understanding of fire-safe principles and codes, an understanding that will benefit their clientele (homeowners, property owners, and communities). By participating in this project, businesses and professionals gained information that can be applied as greater understanding of local codes, better business practices with respect to mitigation investments and maintenance, and perhaps greater accountability for wildfire risk reduction without constant compliance checks by fire marshals and other officials.

The development of this project revealed that engaging professionals in the development of seminars or similar programs may be just as valuable as getting students into the wildfire education seminars. Education in this instance is not a one-way street with information flowing from the fire knowledge base to professionals, but instead a two-way street of information to address complex wildfire issues. Application of this information can shift "best management practices" and reduce wildfire property losses through better design, construction, maintenance, and advice. As professionals are engaged, they add their own field expertise to the larger fire knowledge base, and develop new business practices and cooperative efforts that are economically viable and will increase investments in property-loss prevention. Such discussions also revealed the need for further adaptation of some practices, notably the use of targeted goat grazing, width of defensible space approved in new developments, irrigation demands in light of future water shortages, and investments in existing, nonconforming structures.

The collaboration that developed around this project is a priceless product of the wildfire education efforts. The development of the project both required and provided the ideal conditions for stakeholders of every bias and background to come together and bring their respective specialized knowledge to the table. In that respect many individuals and organizations played several roles throughout the project: providing written materials, developing the outlines and PowerPoint presentations, instructing class sessions, marketing the seminars through their business and professional contacts, and providing feedback and other valuable assistance. This project succeeded only with these invaluable investments from business and government partners.

By engaging business professionals, the fire agencies gain a larger "militia" in the effort to reach homeowners and help protect homes and communities in wildfire prone areas. When they understand the potential of improving their services to homeowners and the principles of wildfire-resilient homes in harmony with natural lands, business professionals can be a large, effective asset that complements the traditional fire prevention programs of fire and land management agencies.

References

Absher, J.D.; Kyle, G.T. 2006. Perceptions of wildfire management issues by San Diego County wildland-urban interface residents. Presentation to Third International Fire Ecology and Management Congress; San Diego, CA; November 13-17. [available from first author]

Absher, J.D.; Vaske, J.J.; Bright, A.D.; Don Carlos, A. 2006. Effective communication about wildfire management along the Colorado Front Range. Proceedings of the Third International Fire Ecology and Management Congress; 2006 November 13-17; San Diego, CA. [on DVD, track 2, community wildfire management] 6 p.

Andreasen, A.R. 1995. Marketing social change: Changing behavior to promote health, social development, and the environment. San Francisco, CA: Jossey-Bass.

Brenkert, H.; Champ, P.; Flores, N. 2005. Mitigation of wildfire risk by homeowners. Gen. Tech. Rep. RMRS-RN-25WWW. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. Available at http://www.fs.fed.us/rm/pubs/rmrs_rn025.pdf. Accessed on 4/10/07.

Fire Cause Analysis. 2004. Fire at the urban wildland interface: Performance of California homes and buildings. Report prepared for California Department of Forestry and Fire Protection. 103 p. Available at http://osfm.fire.ca.gov/pdf/regulations/UWIRpt1-ALL091004.pdf. Accessed 4/15/07.

FireWise Communities. 2006. National Wildland/Urban Interface Fire Education Conference, "Backyards and Beyond." November 2-4, 2006, Denver, CO. Available at http://www.firewise.org/fw_youcanuse/conference/. Accessed on 4/10/07.

Halsey, R. 2004. Fire, chaparral, and survival in southern California. El Cajon, CA: Sunbelt Publications. 224 p.

Hoban, V.; Leary, P.; Rivaldi, M.; Weis, J. 2004. Give yourself a fighting chance: How to protect homes from destructive wildfires through education and action. San Diego, CA: San Diego State University, Graduate School of Business Administration (unpublished)

Kotler, P.; Roberto, N.; Lee, N. 2002. Social marketing: Improving the quality of life (2 ed.) Sage Publications.

Kumagai, Y.; Carroll, M.S.; Cohn, P. 2004. Coping with interface wildfire as a human event: Lessons from the disaster/hazards literature. J. For. 102(6):38-32.

McElhinney, M.; Younkman, D. 2005. Final report on wildfire education programs. Report provided to San Diego Women's Foundation and San Diego Foundation "After the Fires" Fund.

National Fire Protection Association. 2002. NFPA 1144: Standard for Protection of Life and Property from Wildfire, 2002 edition. Quincy, MA.

Quarles, S. 2006. Fire performance testing: Roofs. [Also for decks, walls, and windows.] Available at http://firecenter.berkeley.edu/quarles/roof_kit-SQ.pdf. Accessed on 4/16/07.

Radtke, K.W.H. 2004. A homeowners' guide to fire and watershed management at the chaparral/urban interface. City of San Diego Water Department. 47 p. Also available at http://www.sandiego.gov/water/pdf/firewatershed.pdf

Radtke, K.W.H. 1982. A homeowners' guide to fire and watershed management at the chaparral/urban interface. Gen. Tech. Rep. 67. Berkeley, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station.

Rancho Santa Fe Fire Protection District. 2006. Rancho Santa Fe shelter-in-place resource guide. Elements available at http://www.rsf-fire.org/. Accessed on 4/15/07.

San Diego Natural History Museum. 2007. Wildfire education for the business sector: Course materials. Unpublished documents on CD, available from afege@sdnhm.org.

Schwab, J. and S. Meck. 2005. Planning for wildfires. Chicago, IL: American Planning Association. 124 p.

University of California, Center for Fire Research and Outreach. 2006. Homeowners' wildfire mitigation guide. Available at http://groups.ucanr.org/HWMG/. Accessed on 4/16/07.

This page is blank on purpose

Efficacy of the California Bureau of Land Management Community Assistance and Hazardous Fuels Programs

David J. Ganz[1], David S. Saah[2], Matthew A. Wilson[2], and Austin Troy[2]

***Abstract**—This study provides a framework for assessing the social and environmental benefits and public education outcomes associated with the U.S. Department of the Interior, Bureau of Land Management's Community Assistance and Hazardous Fuel Programs in California. Evaluations of fire hazard mitigation programs tend to focus primarily on the number of acres treated and treatment costs associated with mitigation without adequately assessing the benefits of these treatments. While some evaluations account for the value of protected structures or the avoided costs of suppression, few account for the ecosystem service value of protected natural capital. Examples include the water purification and flood abatement functions of wetlands, the hydrologic regulation functions of forests, and the recreational value of various natural landscapes. The total economic value approach to environmental assessment used in this study includes both the market-based and nonmarket values that are at risk from wildfire, particularly ecosystem goods and services. Using a decision support methodology, the data allows the BLM to more effectively quantify and account for the social and environmental benefits derived from fire mitigation treatments. Suggestions are provided for how this approach could effectively be scaled up and used at a national, regional, or Statewide level to analyze the efficacy of all BLM programs. Although this approach is currently compatible with BLM current reporting system, the assessment provides recommendations on how to augment the evaluation system so that future program elements or "system" elements that enable (or prevent) communities to take part in raising awareness and taking action for themselves are evaluated at the broader BLM program level for the Community Assistance and Hazardous Fuel Programs in California.*

Introduction

Not all fire is harmful, and it is important to differentiate between harmful and beneficial fires (Ganz and Moore 2002). Federal fire policy has been significantly modified since 1995 to recognize and embrace the role of fire as an essential ecological process (USDA 1995; USDI–USDA 1995; NWCG 2001). The value of ecosystem goods and services should be recognized when considering the positive and negative effects of fire on a landscape. Traditionally, economic assessment methodologies such as Cost-Benefit Analysis have not accounted for the value of many ecosystem services because the tools and techniques to evaluate ecological goods and services in a cost-effective manner were not widely available (EPA 2000; National Research Council 2004). When tradeoffs are made between alternative land use and fire management decisions, the best available information is needed to avoid systematic biases in the resulting decision.

In: Butler, Bret W.; Cook, Wayne, comps. 2007. The fire environment—innovations, management, and policy; conference proceedings. 26-30 March 2007; Destin, FL. Proceedings RMRS-P-46CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 662 p. CD-ROM.

[1] Fire Scientist, TSS Consultants, Oakland, CA. Dganz@tssconsultants.com.

[2] Landscape Ecologist, Economist, and GIS Analyst, respectively, Spatial Informatics Group, LLC, San Leandro, CA.

If hidden costs or benefits are not fully accounted for, people will tend to make uninformed choices leading to inefficient outcomes. For example, as witnessed in the Katrina hurricane, the valuation literature has long shown that offshore barrier islands and near shore saltwater wetlands in the Gulf Coast region do tend to provide significant benefits to coastal communities in the form of alleviating flooding and hurricane storm surge (Farber 1987). Yet, when these ecological benefits are not adequately quantified and incorporated into short-term land use development decisions, critical information is left outside of the market calculus and inefficiencies arise with sometimes disastrous results. The same quantification needs to be applied when evaluating the significant benefits to communities living in a fire adapted ecosystem. While this assessment focuses on the avoided costs of losing these benefits to an unwanted fire, we recognize that some ecological goods and services may benefit from periodic low intensity fires. To assist the U.S. Department of the Interior, Bureau of Land Management (BLM) in California gather such knowledge, we have developed a conservative, baseline ecological-economic assessment of the ecosystem goods and services for three selected counties in that State. Counties were selected based upon the frequency of BLM projects, the availability of land cover data, and the landscape heterogeneity and transferability. Our goal has been to use the best available methods, data sources, and spatial analysis techniques to generate defensible value estimates that can then be integrated into better land use planning and environmental decisionmaking throughout the region.

Study Objectives

This study provides the basis for a quantified assessment of the benefits, cost effectiveness as related to National Fire Plan (NFP) funded projects administered by the California BLM. The projects evaluated cover those implemented during the 2002 through 2004 study period. Primary objectives of the study are:

- Quantification of the economic values associated with the Community Assistance and Hazardous Fuels Programs (HFP) in three counties that are representative of California's heterogeneous landscapes.
- Providing a framework and analysis of which BLM fuel reduction projects offer the highest return on the investment when considering the ecosystem goods and services included as part of the HFP.

The assessment differs from previous ones in that it takes into consideration *both* the market-based and nonmarket values likely to be impacted by a catastrophic fire. Specifically, it provides a first-order baseline estimate of the ecosystem goods and services provide by California's natural landscapes that might be threatened by catastrophic fire. Using a decision support methodology developed by Spatial Informatics Group LLC, the NaturalAssets™ Information System, the study presents data that will allow the BLM to more effectively quantify and account for the social and environmental benefits derived from fire mitigation treatments.

Study Site Selection

Study sites were chosen by first generating a query map of the concentrations of community assistance grants, and fuels projects funded by the BLM and the Rural Fire Assistance Program (RFA) from 2002 through 2004.

A density analysis map (fig. 1) was created by the BLM with data generated from the National Fire Plan Operations and Reporting System (NFPORS). The purpose of this first level of analysis was to determine those locations in California that have been targeted for receiving the most funding through these Federal programs; three counties were chosen that had high concentrations of grant recipients. The three counties selected for performing the NaturalAssets™ Information System evaluation were Napa, Humboldt, and San Bernardino. They were selected because:

- These counties represent a good cross section of vegetative communities, latitude, and development patterns.
- All three have significant BLM lands within their boundaries.
- All three counties have a diverse number of land cover types and hazardous fuel treatments.
- All three counties are covered by the 1997 to 2001 California Land Cover Mapping and Monitoring Program.

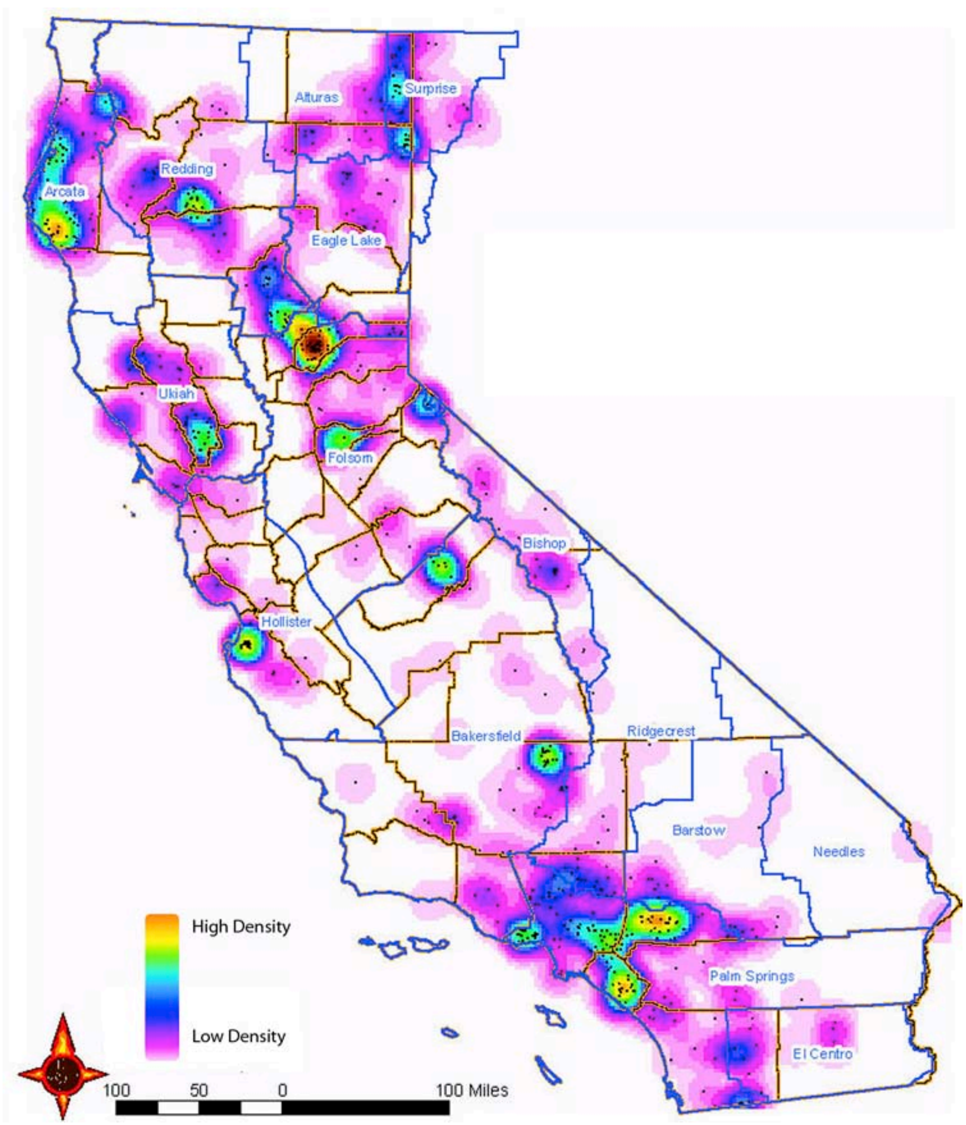


Figure 1—Density analysis of BLM funded projects in California (adapted from BLM 2004). The density analysis was conducted by BLM using the following data (in a point format): 2002 to 2004 Fuels Treatments (NRPORS), 2002 to 2004 Rural Fire Assistance Grants, 2002 to 2004 Community Assistance Activities only from the following counties: Humboldt, Butte, Nevada, Napa, Madera, Kern, Los Angeles, San Bernardino, and Orange.

We also provided the BLM with two case studies: the town of Petrolia in Humboldt County and Morongo Valley in San Bernardino County (fig. 2). These two case studies are used to compare the costs of treatment to the estimated benefits from those treatments, including both protected structures and Ecosystem Service Valuations (ESVs). Morongo Valley is a highly developed part of San Bernardino County while Petrolia is in a rural part of Humboldt County. Both of these communities are in the wildland urban interface with Petrolia listed as a Community at Risk and Morongo Valley listed as a Community of Interest.

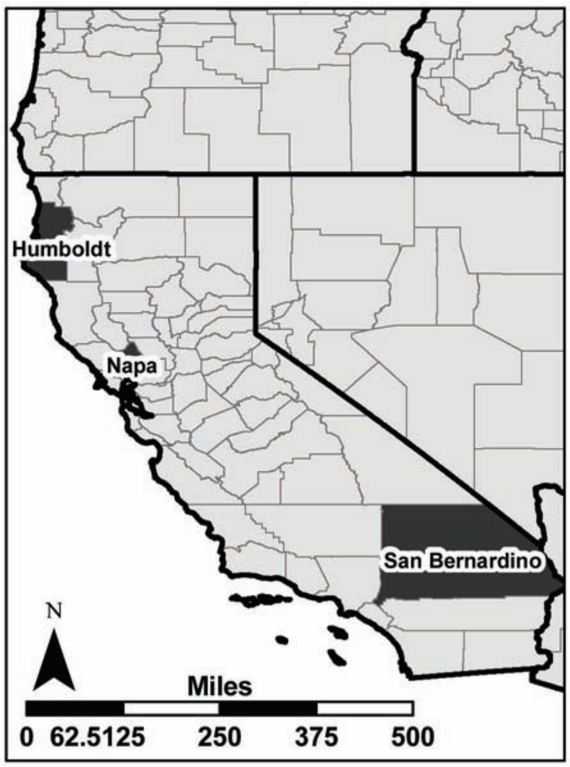


Figure 2—Case study locations include Napa, Humboldt, and San Bernardino Counties.

Methods

Economic valuation can help to ensure that ecosystem services that are not traded in markets and do not have market prices receive explicit treatment in economic assessments. Our goal is not to "create" values for ecosystems. Rather, our purpose is to generate a conservative baseline estimate of the values that people already hold with respect to these ecosystems through an assessment of the best available literature. Such information will in turn assist in our assessments of the benefits provided by community assistance and hazardous fuels programs in California. This approach is consistent with that being taken in the international Millennium Ecosystem Assessment, which focuses international policymakers' attention on the contributions of ecosystems to human wellbeing (Millennium Ecosystem Assessment 2003;

Argady and others 2005). Due to the lack of credible metrics for evaluating the effectiveness of the BLM projects, we have made a series of assumptions for this study including:

- Hazardous fuel treatments, irrespective of size, will have an impact on reducing the fire hazard on a landscape scale. Although the focus of this assessment is not to model (spatially or temporally) how much of an impact these treatments might have on fire behavior, there is credible research to indicate that strategically placed treatments can change fire behavior (Finney 2001; Knapp and others 2004). We assume that all BLM funded hazardous fuels projects have a beneficial impact on protecting market and nonmarket assets regardless of the probability of burning or the level of changes to fire behavior.
- Communities value their structures more than any other market asset. The research to date on community perceptions of fire support this assumption (Hodgson 1994; Winter and Fried 2000; Everett 2002). As far as generating monetary values for marketable assets, this assessment focuses on parcels and the improvement values (generated from the Grand list) and not other market assets. While the market value of standing timber is clearly high in Humboldt County, we chose not to attempt to quantify it due to the lack of data on forest accessibility, size, and age structure.
- Environmental aesthetics and recreational opportunities are important services provided by forests in the urban/wildland interface. The natural landscape in and around communities has amenity and recreational values that tend to be quite high in California. In California's Sierran foothills, for example, Hodgson (1994) did a survey of residences and found that one in five respondents considered protection of the landscape more important than the protection of structures. Californians value their natural landscape and are willing to pay for the costs associated with living in a fire-prone area for the other natural amenities that these surroundings provide.
- There are additional ecosystem goods and services from which local California residents benefit even though they may not be as aware of them. These include flood avoidance, wildlife habitat refugia, and clean water provision, all of which provide real benefits to society. This assessment includes value estimates for those ecosystem goods and services that have been quantified in the peer-reviewed literature.
- If hazardous fuel treatments are going to be effective in California, they need to be coordinated with an outreach effort to raise awareness of why landscape scale treatments are needed. This is especially important in California where the environmental assessments (performed under the National Environmental Protection Act and/or the California Environmental Quality Act) require public input and often turn into legal battles over whether fuel treatments are appropriate in certain ecological and socio-political systems. Although it is not within this assessment's scope to address or resolve these conflicts, we should be aware that they exist in the State and contribute to the costs of implementing a hazardous fuel treatment program.

Building on these assumptions, we recognize that the protection of forests from fire damage can generate real benefits to society—benefits that go beyond the protection of market goods and structural assets. Scenic views, recreational opportunities, flood control, wildlife habitat protection, sediment retention, and water supply all contribute to the wellbeing of people and the communities they live in. The challenge is that currently many of the economic values associated with fire mitigation efforts remain unaccounted for because they are not easily quantified in conventional policy assessments or cost-benefit analyses.

Value Transfer of Nonmarket, Nonuse Estimates

One of the primary goals in this the study is to shed light on the nonmarket economic benefits of ecosystem goods and services associated with the landscapes that are affected by fire hazard mitigation efforts. While a fair amount of research has been done on the economic value of ecosystem services globally (Costanza and others 1997; Millennium Ecosystem Assessment 2003), relatively limited peer-reviewed work has been done to estimate the specific economic values of ecosystem services located in San Bernardino, Napa, and Humboldt Counties. Because limited empirical ecosystem service valuation research has been done at the study sites, we were required to "transfer" values from other sites.

Measuring the use values associated with marketed goods and services simply requires monitoring market data for observable trades; but the nonmarket values of goods and services are much more difficult to measure (Bingham and others 1995). When there are no explicit markets for ecosystem goods and services, more indirect means of assessing economic values must therefore be used. A subset of economic valuation techniques commonly used to establish values when market values do not exist are identified in table 1. (This list of nonmarket valuation techniques is not intended to be all-inclusive. Rather, it is intended to reveal the breadth of available empirical techniques that have been and are currently being explored in the field of ecosystem service valuation.)

Table 1—Conventional nonmarket valuation techniques.

Avoided Cost (AC): services allow society to avoid costs that would have been incurred in the absence of those services; flood control (barrier islands) avoids property damages, and waste treatment by wetlands avoids incurred health costs.
Marginal Product Estimation (MP): Service demand is generated in a dynamic modeling environment using production function (that is, Cobb-Douglas) to estimate value of output in response to corresponding material input.
Factor Income (FI): services provide for the enhancement of incomes; water quality improvements increase commercial fisheries harvest and, thus, incomes of fishermen.
Travel Cost (TC): service demand may require travel, whose costs can reflect the implied value of the service; recreation areas attract distant visitors whose value placed on that area must be at least what they were willing to pay to travel to it.
Hedonic Pricing (HP): service demand may be reflected in the prices people will pay for associated goods: For example, housing prices along the shore of pristine freshwater lakes tend to exceed the prices of inland homes.
Contingent Valuation (CV): service demand may be elicited by posing hypothetical scenarios that involve some valuation of alternatives; people would be willing to pay for increased water quality in freshwater lakes and streams.

As the descriptions in table 1 suggest, each nonmarket valuation methodology represented in the NaturalAssets™ information system (NAIS) has its own strengths and limitations, often limiting its use to a select range of ecosystem goods and services within a given landscape. For example, the economic value generated by a naturally functioning ecological system can be estimated using avoided cost (AC), based on the estimated cost of damages due to lost services. However, because these estimates are highly sensitive to market conditions used to estimate costs, they must be used with great caution. While rigorous and well established in the field, travel cost (TC) is primarily limited to estimating recreation values, while hedonic pricing (HP) is used for estimating property values associated with aesthetic qualities of natural ecosystems. On the other hand, contingent valuation (CV) surveys are often widely used to estimate the economic value of less tangible services such as critical wildlife habitat or biodiversity. The challenge with CV and related methods such as choice modeling is that estimated values are highly sensitive to the survey format and context of valuation (Heberlein and others 2005).

In this study, the full suite of ecosystem valuation techniques is used to account for the economic value of goods and services provided by natural landscapes in San Bernardino, Napa, and Humboldt Counties.

Value transfer by definition involves the adaptation of existing valuation information or data to new policy contexts with little or no data. (Following Desvouges and others [1998], the term "value transfer" is used instead of the more commonly used term "benefit transfer" to reflect the fact that the transfer method is not restricted to economic benefits, but can also be extended to include the analysis of potential economic costs, as well as welfare functions more generally.) The transfer involves obtaining an estimate for the economic value of nonmarket goods or services through the analysis of a single study, or group of studies, that have been previously carried out to value similar goods or services. The transfer itself refers to the application of estimated point values, derived utility functions, and other information from the original "study site" to a "policy site" (Loomis 1992; Desvousges and others 1998).

While we accept the fundamental premise that primary valuation research will always be a "first-best" strategy for gathering information about the value of ecosystem goods and services (Smith 1992; Downing and Ozuna 1996; Kirchhoff and others 1997), we also recognize that value transfer has become an increasingly practical way to inform policy decisions when primary data collection is not feasible due to budget and time constraints, or when expected payoffs are small (EPA 2000; National Research Council 2004).

In other words, value transfers will always represent a policy-relevant compromise solution. When primary valuation research is not possible or plausible, then value transfer, as a "second-best" strategy, is important to consider as a source of meaningful baselines for the evaluation of management and policy impacts on ecosystem goods and services. However, the real-world alternative is to treat the economic values of ecosystem services as zero; a status quo solution that, based on the weight of the empirical evidence, will often be more error prone than value transfer itself.

Ecosystem Service Valuation (ESV) Data

The raw material for the value transfer exercise comes from previously published studies that empirically measured the economic value of environmental goods and services. Three types of valuation research exist in the literature today:

- Peer-reviewed journal articles, books and book chapters, proceedings, and technical reports that use conventional environmental economic valuation techniques and that are restricted to an analysis of social and economic values.
- Non peer-reviewed publications that include PhD dissertations, non peer-reviewed technical reports and proceedings, as well as raw data available on the Internet.
- Secondary analysis (for example, meta analysis) of peer-reviewed and/or non peer-reviewed studies that use both conventional and nonconventional valuation methods.

The critical underlying assumption of NAIS is that the ESVs for ecosystem goods or services can be inferred with sufficient accuracy from the analysis of existing nonmarket valuation studies. Clearly, as the level of information increases within the source literature (in other words, more studies are done), the accuracy of the value transfer likewise improves. The research team developed a set of explicit decision rules for querying economic results from the raw data contained in NAIS that would allow us to estimate with sufficient accuracy the economic value of ecosystem services in San Bernardino, Napa, and Humboldt Counties. The research team selected valuation studies that were:

- Peer reviewed and published in recognized journals
- Focused on temperate regions in either North America, Canada, or Europe
- Focused primarily on nonconsumptive use

Using these search criteria, we were able to obtain data from a set of viable studies (n=84) whose results were then standardized to 2004 U.S. dollar equivalents per acre to provide a consistent basis for comparison. (All dollar values are standardized to 2004 using Consumer Price Index tables published by the U.S. Department of Labor; http://www.bls.gov/cpi/home.htm.) Because each study may contain more than one estimate of value, the end result is a collection of valuation data points that are coded by temporal (that is, time of study), spatial (place where study was done), and methodological (method used) criteria, thereby allowing the research team to derive a lower bound and upper bound estimate of dollar values for the study site. For this study, we were able to generate a total of (n=205) individual point estimates for reviewed land cover types. Given the aforementioned restrictions and gaps in the available literature, this approach yields conservative, baseline economic values for San Bernardino, Napa, and Humboldt Counties.

In sum, the transfer method adopted in this report involves obtaining an estimate for the value of ecosystem goods or services through the analysis of peer-reviewed research that has been previously collected and stored in NAIS in a standardized format so that it can further be augmented with site-specific GIS data (that is, land cover, socioeconomic characteristics) to ensure reliable valuation estimates at the study site.

Spatial Analysis Methods

Another principal goal in this study is to link the ESV estimates for ecosystem goods and service to available land cover/land use data in San Bernardino, Napa, and Humboldt Counties. Thanks to the increased ease of using GIS and the availability of land cover data sets derived from satellite images, ecological and geographic entities can more easily be attributed with ecosystem services and the values they provide to people (Wilson and others 2004; Wilson and Troy 2005). In simplified terms, the technique discussed here involves combining one land cover layer with another layer representing the geography to which ecosystem services are aggregated—that is, a watershed. While the aggregation units themselves are likely to be in vector format, because vector boundaries are most precise, the land cover layer may be either raster or vector. (The vector data model represents spatial entities with points, lines and polygons. The raster model uses grid cells to represent quantities or qualities across space.) Spatial disaggregation increases the contextual specificity of ecosystem value transfer by allowing us to visualize the exact location of ecologically important landscape elements and overlay them with other relevant themes for analysis—biogeophysical or socioeconomic. A common principle in geography is that spatially aggregated measures of geographic phenomena tend to obscure local patterns of heterogeneity (Openshaw and others 1987; Fotheringham and others 2000).

Development of Land Cover Typology

Two types of values were spatially mapped for this project: ecosystem service values and structural improvement values. These require accurate, high resolution, and categorically meaningful depictions of land cover. Before developing these maps, a land cover typology was created. To do this, we assessed available data coverages to determine which land cover classes at what level of categorical precision could be mapped at a usable scale and with acceptable levels of accuracy. Table 2 shows the resulting typology with the code name for each cover class, its description and the counties in which it was present.

Table 2—Land cover typology with applicable counties.

Code	Description	Counties
AGR	Agriculture	All
CON	Conifer	All
DSHB	Desert scrubland	San Bernardino
DWLD	Desert woodland	San Bernardino
EST	Estuary and tidal bay	Napa, Humboldt
FWET	Fresh wetland	All
HDW	Hardwood oak woodland	All
HEB	Herbaceous	All
MIX	Mixed hardwood, conifer	All
OWLF	Forested areas suitable for spotted owl habitat	Humboldt
RIPF	Riparian forests (50 m buffer)	All
RW2	Redwood-second growth	Napa, Humboldt
RWOG	Redwood-old growth	Humboldt
SHB	Shrubs	All
SWET	Salt wetland	Napa, Humboldt
URB	Urban and barren	All
URBG	Urban green (forest and grass)	All
VIN	Vineyard	Napa
WAT	Open water	All

Spatially Explicit ESV Calculation Methods

Ecosystem service values were then determined by multiplying areas of each cover type, in acres, by the dollar per acre ecosystem service value for that cover type. The economic values used to estimate the values associated with each ecosystem good or service are drawn from the NAIS ESV data. The total ESV of a given cover type for a given watershed can thus be determined by adding up the individual, nonsubstitutable ecosystem service values associated with that cover type. The following formula is used:

$$V(ES_k) = \sum_{i=1}^{n} A(LU_i) \times V(ES_{ki})$$

Where A(LUi) = area of land use (i)
and V(ESki) = annual value of ecosystem services (k) for each land use (i).

Resulting values were estimated for the entire study area using value transfer methods. Following that, the ESVs were aggregated by county study area, broken down for each county by land cover, and cross-tabulated for each study site by (1) land cover and watershed and (2) land cover and zip code. Assessed structural improvements were also summarized to generate a total economic value estimate for critical human-modified land uses.

Results

Using the value-transfer search criteria, the research team obtained data from a set of 84 viable empirical studies, whose results were then standardized to 2004 U.S. dollar equivalents per acre/per year to provide a consistent basis for comparison in the tables in this section. (All economic valuation data in this report are have been standardized to represent total net present values, not discounted. This allows for the results to be incorporated into forward-looking scenarios that might weight future costs and benefits differently than current costs and benefits when summing over time using specific discount rates; Heal 2004.) The aggregated baseline ESV results for all land cover types represented within the study area are presented in table 3.

The ESV data in table 3 show the minimum, the maximum, and the average nonmarket ecosystem service valuation estimates aggregated across all land cover types contained in the study. (Not all land cover types generated for the spatial analysis of San Bernardino, Napa, and Humbolt Counties by the Spatial Informatics Group team could effectively be matched with equivalent ESV estimates as denoted in table 4.) Clearly, not all land cover types represented in this report provide benefits to society equally. Rather, consistent with previously published literature (Daily 1997; Wilson and Carpenter 1999), the data reveal how land cover types in the study area that are associated with water (wetlands, estuaries, and riparian forest) tend to yield the largest ecosystem service values per area unit. Also consistent with previous findings, it also appears that both agricultural systems (in this report, the same ESVs were assigned to agricultural and vineyard land cover types) and urban greenspace tend to yield fairly large values per unit of measurement (Pretty and others 2000; Ricketts and others 2004). While nonriparian forest systems tend to be less valuable per acre unit, there is still a range of variability evidenced among different forest types, with old growth and spotted owl habitat yielding the highest values per unit and oak woodland yielding the least.

Table 3—Aggregate ecosystem services for all available land cover types.

Code	Description	Min $ acre/yr	Max $ acre/yr	Avg $ acre/yr
AGR	Agriculture	$83.47	$1,689.04	**$887.06**
CON	Forest-conifer	$32.48	$999.79	**$332.35**
DSHB	Desert shrub	NA	NA	**NA**
DWLD	Desert woodland	NA	NA	**NA**
EST	Estuary	$1,483.90	$5,239.01	**$2,386.75**
FWET	Fresh wetland	$1,761.07	$9,180.73	**$4,440.73**
HDW	Hardwood oak woodland	$61.68	$486.84	**$177.82**
HEB	Herbaceous	NA	NA	**NA**
MIX	Mixed hardwood, conifer	$34.32	$1,001.63	**$334.19**
OWLF	Spotted owl habitat	$100.53	$1,113.86	**$403.86**
RIPF	Riparian forest	$122.17	$15,126.99	**$3,558.03**
RW2	Redwood second growth	$29.89	$997.20	**$329.76**
RWOG	Redwood old growth	$84.63	$1,051.94	**$384.50**
SHB	Shrubs	NA	NA	**NA**
SWET	Saltwater wetland	$229.18	$8,845.04	**$2,446.06**
URB	Urban and barren	NA	NA	**NA**
URBG	Urban green	$602.29	$4,289.91	**$2,268.21**
VIN*	Vineyards	$83.47	$1,689.04	**$887.06**
WAT	Open fresh water	$227.79	$13,073.87	**$2,928.72**

*Note: Assumption that AGR and VIN ESVs are equivalent as both are intensively managed and represent human dominated systems.

Spatially Explicit Ecosystem Service Valuation Results

Building on the ESV data generated with NAIS, the research team was able to use the spatially explicit ESV calculation methods, to generate ESV results. Tables 4 and 5 provide summaries of total ESVs by land cover class and reveal that significant differences exist between the three counties in the study.

Significant economic benefits clearly accrue to society from forests in Humboldt County. As the data in table 4 show, forest-related land cover types account for an overwhelming proportion (almost 80 percent) of total ESV delivered by naturally functioning ecological systems in the study area. Thus, while on a per-unit basis, forest land types may tend to provide less economic value than nonforested systems, the large study area currently under forested cover brings the total economic value associated with forests to the foreground. After forests, it appears that freshwater wetlands (FWET) and open water (WAT) provide the next most significant ESVs in the study area.

In contrast to Humboldt County, forested systems appear to account for only approximately 30 percent of the total ESV delivered by functioning ecological systems in Napa County. Napa's open freshwater (WAT) alone in the form of streams, lakes, and rivers appears to provide a significant economic benefit to society (31 percent). And as might be expected, both agricultural land (AGR) and vineyards (VIN) also provide a substantial positive impact on the economic value associated with ecosystem services in the region (approximately 20 percent). For Napa County, the zip codes of high value (both structural and ESV) are within Napa and St. Helena.

The data in table 6 reveal that similar to Napa County, forested systems deliver approximately 31 percent of the total ESV delivered by ecological systems in San Bernardino County. Freshwater wetlands (FWET) account

Table 4—Humboldt County study areas land cover and ESV estimates.

	Study area zip codes			Entire county		
Class	Acres	ESV/acre	Total ESV	Acres	ESV/acre	Total ESV
AGR	38,973	887	34,571,513	39,380	887	34,932,508
CON	271,121	332	90,107,174	282,303	332	93,823,306
EST	4	2,387	10,085	4	2,387	10,085
FWET	23,676	4,441	105,140,399	23,704	4,441	105,261,803
HDW	272,587	178	48,471,365	277,209	178	49,293,301
HEB	201,869	NA	-	205,292	NA	-
MIX	628,282	334	209,965,524	647,218	334	216,293,687
OWLF	221,523	404	89,464,211	221,580	404	89,487,414
RIPF	117,270	3,558	417,250,658	122,248	3,558	434,960,966
RW2	230,466	330	75,998,467	246,197	330	81,185,900
RWOG	90,604	385	34,837,363	98,005	385	37,682,967
SHB	53,085	NA	-	55,556	NA	-
SWET	1,344	2,446	3,287,882	1,356	2,446	3,317,256
URB	41,821	NA	-	42,944	NA	-
URBG	8,042	2,268	18,239,981	8,043	2,268	18,242,491
WAT	17,266	2,929	50,566,177	17,655	2,929	51,707,928
		TOTAL ESV	1,177,910,801		TOTAL ESV	1,216,199,612

Known market values (study area zip codes)	
improvement value of structures	$4,376,522,485
TOTAL	$5,554,433,286

Known market values (entire county)	
improvement value of structures	$4,499,321,899
TOTAL	$5,715,521,511

Table 5—Napa County study areas land cover and ESV estimates.

	Study area zip codes			Entire county		
Class	Acres	ESV/acre	Total ESV	Acres	ESV/acre	Total ESV
AGR	26,265	887	23,298,875	27,700	887	24,571,316
CON	16,891	332	5,613,779	17,327	332	5,758,593
EST	1,110	2,387	2,648,298	1,115	2,387	2,661,834
FWET	4,409	4,441	19,577,352	4,412	4,441	19,592,412
HDW	141,771	178	25,209,687	145,867	178	25,938,010
HEB	64,207	-	-	66,148	-	-
MIX	11,704	334	3,911,425	13,619	334	4,551,190
RIPF	16,880	3,558	60,060,503	17,479	3,558	62,189,858
RW2	1,257	330	414,390	1,262	330	416,315
SHB	113,065	-	-	119,967	-	-
SWET	3,438	2,446	8,409,695	3,450	2,446	8,438,390
URB	18,408	-	-	18,462	-	-
URBG	1,808	2,268	4,099,948	1,808	2,268	4,099,948
VIN*	35,032	887	31,073,702	35,034	887	31,075,280
WAT	29,688	2,929	86,947,804	29,918	2,929	87,621,444
		TOTAL ESV	271,265,459		TOTAL ESV	276,914,591

Known market values (study area zip codes)	
improvement value of structures	$10,957,341,955
TOTAL	$11,228,607,414

Known market values (entire county)	
improvement value of structures	$11,256,915,849
TOTAL	$11,533,830,440

Table 6—San Bernardino study areas land cover and ESV estimates.

	Study area zip codes			Entire county		
Class	**Acres**	**ESV/acre**	**Total ESV**	**Acres**	**ESV/acre**	**Total ESV**
AGR	39596.26	$887	$35,124,255	71,762	$35,124,255	$63,657,272
CON	282191.6	$332	$93,786,377	333,674	$93,786,377	$110,896,564
DSHB	5260821			10,189,383		
DWLD	596696.3			606,121		
FWET	113840.5	$4,441	$505,534,805	185,251	$505,534,805	$822,650,494
HDW	37049.87	$178	$6,588,207	47,948	$6,588,207	$8,526,125
HEB	34444.69			55,833		
MIX	69668.12	$334	$23,282,391	85,968	$23,282,391	$28,729,641
RIPF	84104.76	$3,558	$299,247,244	93,540	$299,247,244	$332,816,821
SHB	384160.9			482,529		
URB	441379.6			660,011		
URBG	121.74	$2,268	$276,129	152	$276,129	$344,531
WAT	27602.46	$2,929	$80,839,872	42,117	$80,839,872	$123,347,887
		TOTAL ESV	$1,044,679,280		**TOTAL ESV**	$1,490,969,334

Known market values	
improvement value of structures	$35,770,650,855
TOTAL	$36,815,330,135

Known market values	
improvement value of structures	$68,941,985,365
TOTAL	$70,432,954,699

for the majority of ecosystem service benefits delivered to society (55 percent)—by far the single most important ecosystem type in the study area from an ecosystem services perspective. Given that desert shrub is the most predominant land cover type in the county and that no ESVs were estimated for desert land cover types in this study, we anticipate that fire-related ESVs would be forthcoming for these critical ecosystem types as this information is gathered and included in this type of analysis.

An overwhelming proportion of ecosystem service values in Humboldt County comes from its forests. Humboldt's relatively large area of forested cover accounted for nearly 80 percent of total ESV delivery by naturally functioning ecological systems in the study area. On a per-unit basis, some forest types provide a lower stream of benefits than many non-forested types, but the size of forested area in Humboldt County means that ESV benefits from forests dominate. For instance, the Six Rivers National Forest contributes $293 million in ESV to Humboldt County with an additional $19 million in market values (such as structures). This contribution is primarily due to its size, and to the dominance of redwood old growth and spotted owl habitat.

In Napa County, forested systems only accounted for 30 percent of ESVs delivered by functioning ecological systems. Napa's open freshwater, in the form of streams, lakes and rivers, provided 31 percent of measured economic benefits to society. Both agricultural land and vineyards also provide a substantial positive impact on the economic value associated with ecosystem services in the region (approximately 20 percent). The communities of Napa (zip codes 94558 and 94559) and Saint Helena (94574) have the highest estimated quantities of ESVs and structural values within Napa County (fig. 3).

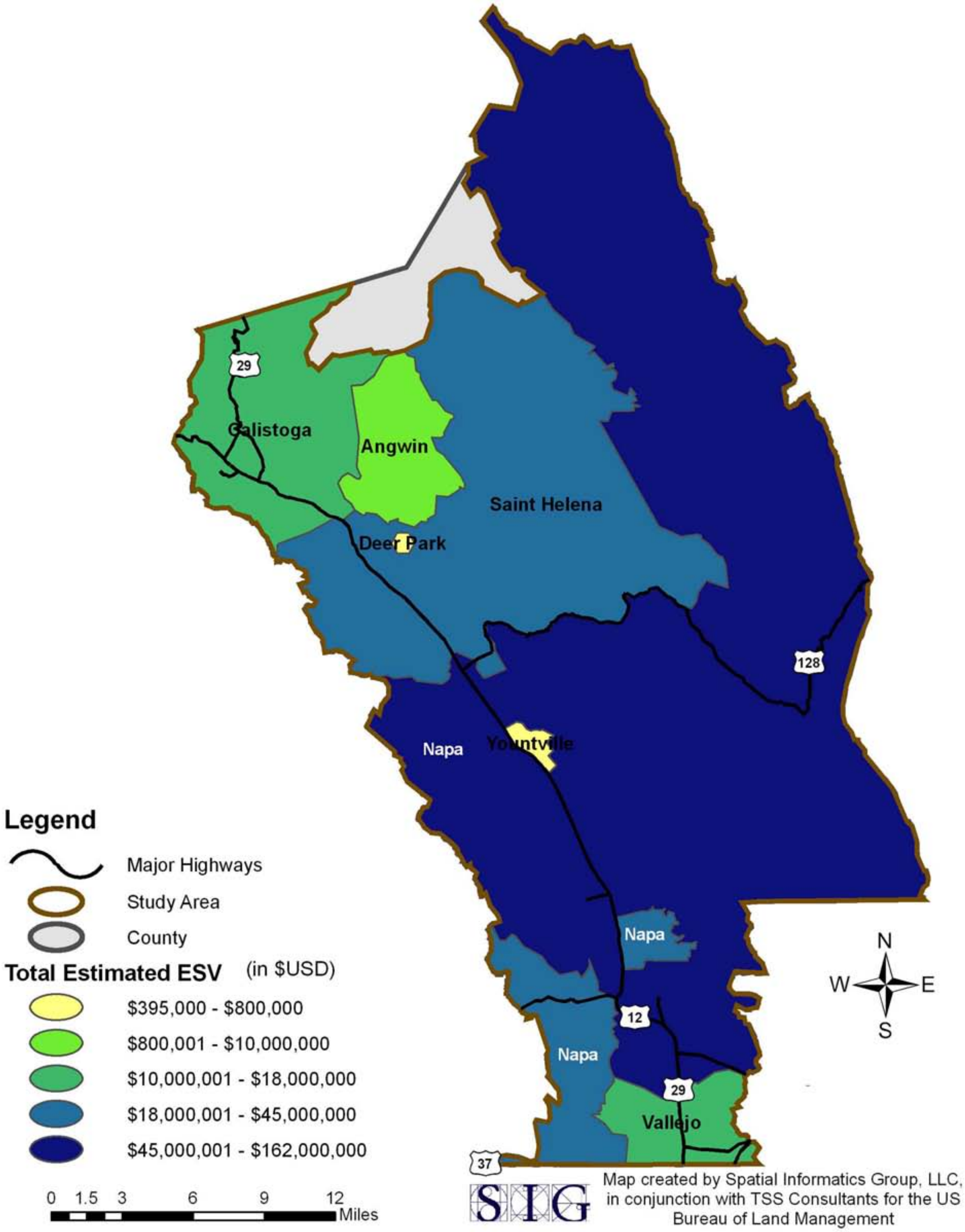


Figure 3—Total estimated ecosystem service valuation by zip code for Napa County study area.

Similar to Napa County, forested systems delivered approximately 31 percent of the total ESVs delivered by ecological systems in San Bernardino County. From an ecosystem services perspective, freshwater wetlands accounted for the majority (55 percent) of ecosystem service benefits delivered to society. For instance, the community of Twenty Nine Palms (zip codes 92277 and 92278) has low assessed structural values relative to other communities in San Bernardino County, but the freshwater resources of this community yield considerable ESVs compared with the rest of the communities within this county (fig. 4). Desert shrub is the most predominant land cover type in San Bernardino County. However, there are two reasons why this land cover shows few societal benefits in this study. First, this desert-related land cover type tends not to burn, and second, the value transfer analysis did not yield any ESV studies that estimated economic values for desert cover types.

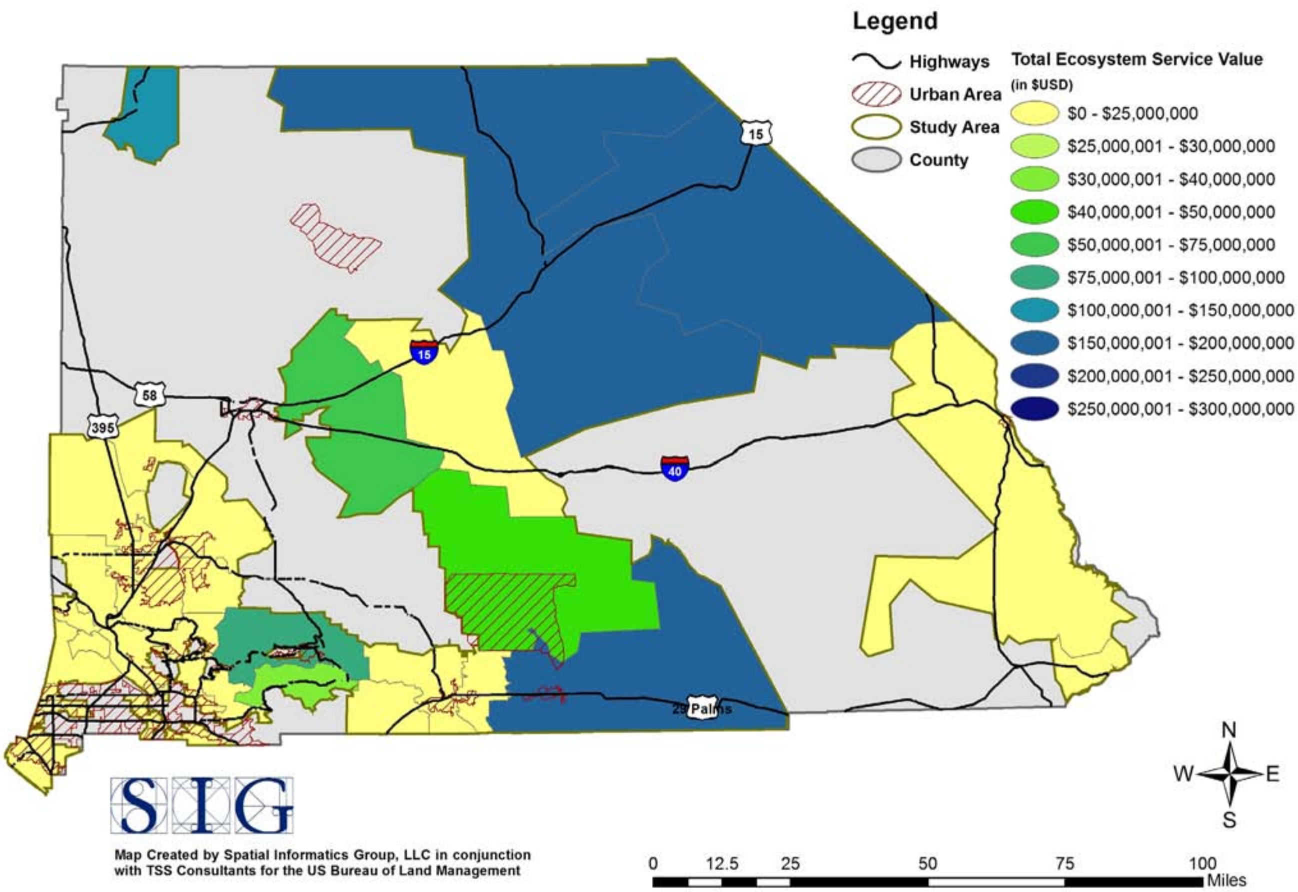


Figure 4—Total estimated ecosystem service valuation by zip code for San Bernardino County study area.

Cost Effectiveness of Fire Hazard Mitigation Efforts

In this section, we provide a cost effectiveness framework by which the BLM fuel hazard mitigation programs can be evaluated relative to their return on investment and agency management goals. This framework takes into consideration both the capital costs and the avoided losses to ecosystem services associated with fire mitigation. This will allow the BLM and other agencies to consider the real losses to ecosystem goods and services that might occur in the event that such fuel treatments were not implemented. For example, in Humboldt or Napa Counties, the treatment costs per acre range from $306 to $600/acre but the estimated benefits of fire mitigation are conservatively between $117 to $4,440/acre (using the lower range average ESV for hardwood oak woodland and higher range average ESV for fresh water wetland). Regardless of whether the proposed fuel treatment uses prescribed burning or mechanical treatment (in either of these two counties), the costs per acre to benefit ratio will be higher when we include the accounting of avoided losses of ESVs. This application is further explained in two case studies of Morongo Valley and Petrolia. Using these case studies, we compared the costs of treatment to the estimated benefits from those treatments, including both protected structures and ESVs.

An additional analysis was used to evaluate the cost effectiveness of all projects within these three counties by agency and by treatment. NFPORS is an interagency system designed to assist field personnel in managing and reporting accomplishments for work conducted under the National Fire Plan. As it is spatially explicit, NFPORS allows for the accounting of natural assets surrounding BLM projects using both artificial boundaries (like zip codes or parcels) and natural boundaries (watershed boundaries and tributaries). The NFPORS system also allows us to evaluate the contribution of the BLM projects to the overall fire mitigation framework within these three counties and compare their efficiencies with metrics such as per acre treatment costs and their ESV avoided costs. For instance, in Humboldt County, of all the money spent by Federal agencies on fuel hazard reduction treatments, BLM spent 5.6 percent of the total on fire treatments and 29 percent on mechanical treatments. For Humboldt County, the BLM spent $306/acre on fire treatments and $377/acre on mechanical treatments. In Napa County where all of the treatments were performed by the BLM, 63 percent of the treatment costs were mechanical (at $600/acre), nearly 4 percent went for fire treatments, and the remaining 33.5 percent went toward other treatments (biological and chemical). While these may seem high compared with the national averages for fire mitigation treatment, they are comparable with other parts of California. (The Congressional Research Service Report for Congress on Forest Fires and Forest Health reported a national average of treatment costs at $250/acre. On the Shasta Trinity National Forest, treatment costs for slopes <30 percent ranged from $250 to $600/acre and average $400/acre.) This would indicate that statements made about the transferability of these three counties generally apply to these treatment costs.

In an area like Humboldt County, where 6,043 acres were treated in a variety of ways by the four Federal agencies and their local partners, ESVs are estimated at $1,177,910,801 while structural values are assessed at $4,376,522,485, for a total accounting within the Humboldt study area zip codes of $5,554,433,286. Given the modeling assumptions, the net benefit of performing these treatments and protecting market and nonmarket assets on the landscape level from wildfire is $2,504/acre in Humboldt County. Using the same cost effectiveness approach, we can state that the net benefit from treatments that protect market and nonmarket assets in San Bernardino and Napa Counties are $4,994/acre and $22,904/acre, respectively. Compared with the $2,504/acre "avoided costs" of protecting market and nonmarket assets in Humboldt, we can easily see that there would be a greater net loss to society resulting from a major wildfire in Napa County. Yet by reviewing the overall treatment acreages for Napa across all Federal agencies, the numbers of acres treated are substantially less than Humboldt and San Bernardino. This is probably due to the lack of Federal agency land, the overall socio-political climate for accepting fuel reduction treatments, and the costs of doing business in Napa County.

There is a national tendency to focus on treatment costs and the total number of acres treated. These metrics tend to favor fire mitigation programs in other Western States where the costs of labor and materials are lower. Over the past 36 years, the average annual price increase in California has been 8.9 percent. In 2004, the median home price was $523,150 compared with the national average of $219,000. These housing trends are undoubtedly contributing to the differences in costs of treatment between the three counties (table 7). Humboldt County, with its dynamically lower housing costs and the presence of the timber industry, benefits in the presence of a cost competitive labor force for implementing fuel treatment projects.

Table 7—BLM planned acres, treatment costs, and costs/acre.

County	Treatment	Planned acres	Cost	$/acres
Humboldt	Fire	331	101,246	306
	Mechanical	1369	515,946	377
Napa	Fire	50	5,625	113
	Mechanical	158	94,730	600
	Other	255	50,500	198
San Bernardino	Mechanical	576	243,122	422
	Other	20	10,000	500

Source: Table generated from the NFPORS database. Data from 2004-2005

Our geographic disaggregation of ESVs by watershed (fig. 5) and zip code (fig. 3 and 4) allows us to depict ESV hotspots and assist the BLM in prioritizing funding to protect those areas with the highest values. From this analysis, we can compare the overall funds expended within the three counties and a per acre "avoided costs" using the total market and nonmarket values and the acres in the zip code study areas. This then allows for the computation of "net benefits per acre" for each study area acre. Although these costs and benefits are averaged over an entire zip code or watershed unit, in the case studies presented below, we have a spatial treatment footprint and will demonstrate the application at the finest scale possible—that is, of evaluating individual projects. From both of these examples, we can see that as the BLM partners become familiar with GIS, or as the BLM adjusts its grant tracking system to include spatial footprints, it should be possible to track costs and benefits of fuel treatments on different slopes and across different land cover types.

Case Studies

The two specific case studies, Petrolia in Humboldt County and Morongo Valley in San Bernardino County, are both within the wildland/urban interface (WUI). The Healthy Forest Restoration Act (HFRA; HR 1904) requires that 50 percent of the funds expended upon HFRA projects are within the WUI and municipal watersheds surrounding private homes and communities. In this Act, the WUI is defined as a 1.5 mile radius around communities; however, communities can define their own WUI by completing a "community fire

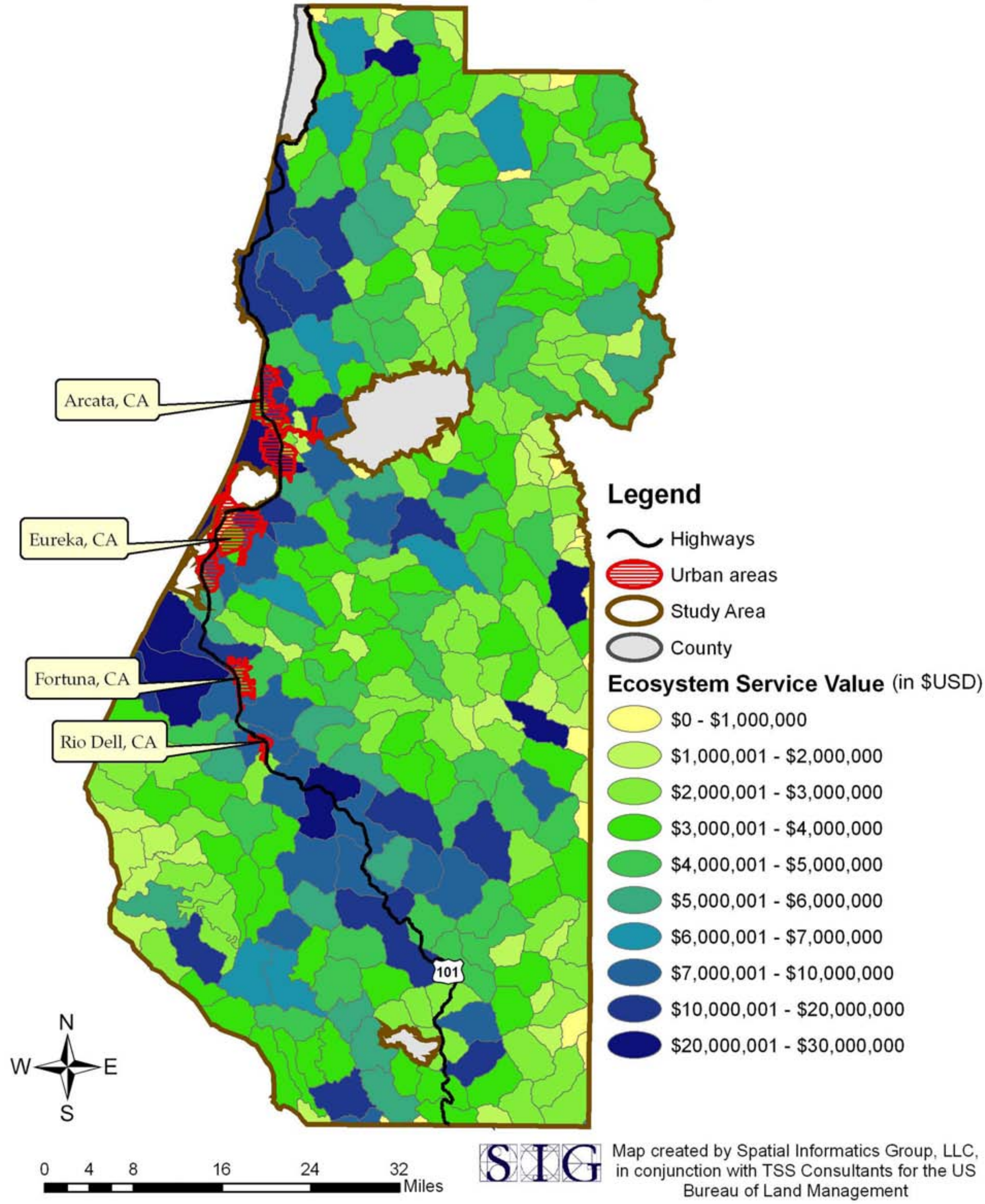


Figure 5—Total estimated ecosystem service value by watershed for Humboldt County study area.

plan." These case study sites were selected because the BLM has created a spatial foot print for the actual treatment and sphere of influence. An additional 1.5 mile "buffer" was added to each treatment site because of the Healthy Forest Restoration Act's call for vegetative buffers to protect communities. (The 1.5 mile buffer is relevant because when National Environmental Protection Act analysis is required, the study needs to include only the proposed action and no action alternative for projects within 1.5 miles of an at-risk community or in the WUI as defined in the Community Wildfire Protection Plan [CWWP].) The Total Economic Value (TEV) framework discussed in this study is used to identify and measure both the nonmarket, ecosystem service values *and* the market-based value of protected structures (such as homes) associated with hazardous fuels treatment. When compared with the actual costs of treatment for mechanical thinning and chipped/biomass utilization in Petrolia and Morongo Valley, respectively, these data can be used to evaluate the net social economic benefit associated with treatments on the ground (see table 8).

The Petrolia mechanical thinning project, implemented by the Mattole Restoration Council was selected as a case study for Humboldt County. The project is designed to protect Petrolia, a Community at Risk. It covered 85 acres, and as table 8 shows, the direct cost (excluding administrative) was $332 per acre for a total one-time cost of $28,188.

The Morongo Valley chipping and biomass removal project, implemented by the Morongo Valley Fire Safe Council, was selected as a case study for San Bernardino County. The Morongo Valley chipping and biomass removal portions of the project covered 40 acres and 35 acres, respectively, and were designed to protect Morongo Valley, a Community of Interest that is spread over a larger geographic area. The direct cost (excluding administrative) of this project was $914 per acre for a total of $69,432.

Table 8 data demonstrate, purely from the total economic value perspective, that both fire treatments considered in this case study appear to be cost effective. When both the nonmarket and market-based values of protected structures, goods, and services within the 1.5 mile buffer zone are taken into consideration, there appears to be a net economic benefit for each community. For instance, in the case of Petrolia, the data show that treatment project costs

Table 8—Cost effectiveness of treatment in two communities.*

Project community	**Petrolia**	**Morongo Valley**
Project type	Mechanical thinning	Chipped/biomass utilization
Acres treated	85	76
Total acres within buffer	**10,479**	**17,993**
Project cost	$28,188	$69,432
Project costs per acre	$332	$937
Market value of protected structures	$2,073,213	$107,494,431
Nonmarket ecosystem service values	$4,570,692	$379,680
Total economic value	$6,643,905	$107,874,111
Total economic value per acre	$634	$5,995
Net benefit per acre	**$302**	**$5,058**

* All dollar values are standardized to 2004 equivalents

were $332 per acre, yet the total economic value of market and nonmarket goods and services within the protected buffer zone yields approximately $634 per acre, resulting in a net benefit of $302 per acre. In the case of Morongo Valley, while the costs of treatment were somewhat higher at $937 per acre, the total economic value of the protected area is also considerably higher resulting in a net benefit of $5,058 per acre (fig. 6).

What the case study data also show is that the source of economic value differs considerably for each community. In the case of Petrolia, it appears that nonmarket ecosystem service values contribute approximately twice as much to the total economic value of the protected buffer as market-based values. As a result, if one were to leave out the nonmarket component of total value in the cost-effectiveness estimate, the end result would have been quite different: the total economic value would have been only $197 per acre, resulting in a net cost of $135 per acre for treatment. On the other hand, in Morongo Valley, the market-based value of homes and structures appears to far outweigh the nonmarket goods and services associated with the protected buffer zone, so that the net cost effectiveness of treatment would remain the same regardless of the nonmarket benefits.

With available time and resources, the approach used in this case study comparison could effectively be expanded to include all communities in the Hazardous Fuels Program throughout California. Given the nature of value transferability, the baseline nonmarket valuation information provided by NAIS could be linked to other land cover types affected by treatment

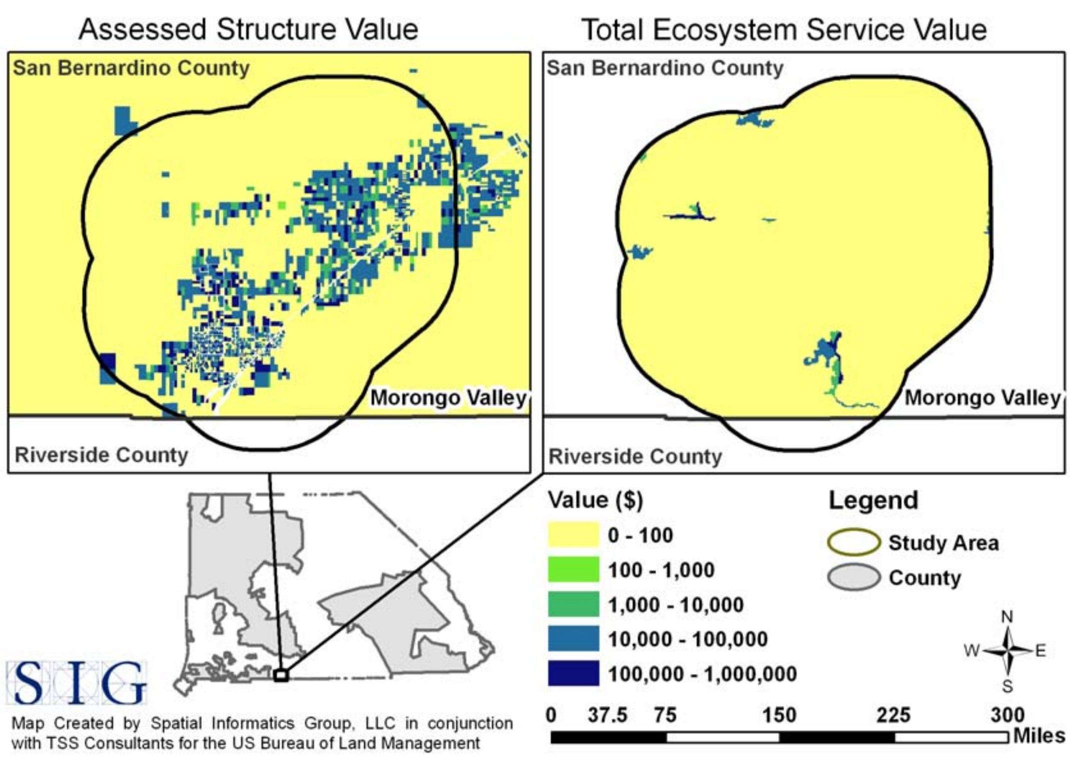


Figure 6—Morongo Valley case study area in San Bernardino County; assessed value of structures by parcel versus total ecosystem service values.

programs throughout California, and once this information is coupled with market-based value estimates, the total economic value can be estimated and compared to treatment costs. The end result would provide the possibility for a rigorous assessment of total social benefits associated with every BLM fire treatment project implemented in California. In sum, the information in this study effectively answers recent calls by policymakers to better account for the full social costs and benefits associated with environmental programs (National Research Council 2004). Armed with such information, it appears that more informed decisions can be made in the future about protecting the natural and built assets that matter most to the people in the wildland/urban interface.

References

Argady, T.; Alder, J.; and others. 2005. Coastal systems and coastal communities. Millennium ecosystem assessment: Conditions and trends. Washington, DC: Island Press.

Bingham, G.; Bishop, R.C.; and others. 1995. Issues in ecosystem valuation: Improving information for decision making. Ecological Economics 14: 73-90.

Costanza, R.; d'Arge, R.; and others. 1997. The value of the world's ecosystem services and natural capital. Nature 387: 253-260.

Daily, G.C. 1997. Nature's services: Societal dependence on natural ecosystems. Washington DC: Island Press.

Desvousges, W.H.; Johnson, F.R.; and others. 1998. Environmental policy analysis with limited information: Principles and application of the transfer method. Northampton, MA: Edward Elgar Publishing.

Downing, M.; Ozuna, T. 1996. Testing the reliability of the benefit function transfer approach. Journal of Environmental Economics and Management 30: 316-322.

Environmental Protection Agency, U.S. (EPA). 2000. Guidelines for preparing economic analyses. Washington, DC.

Everett, Y. 2002. Community participation in fire management planning: A case from California, USA. Communities in Flames Proceedings of 1st International Conference on Community Involvement in Fire Management. RAP Publication 2002/25. Bangkok, Thailand: United Nations, Food and Agricultural Organization, Regional Office for Asia and the Pacific.

Farber, S. 1987. The value of coastal wetlands for protection of property against hurricane wind damage. Journal of Environmental Economics and Management 14(2): 143-151.

Finney, M.A. 2001. Design of regular landscape fuel treatment patterns for modifying fire behavior and growth. Forest Science 47: 219-228.

Fotheringham, A.S.; Brunsdon, C.; and others. 2000. Quantitative geography: Perspectives on spatial data analysis publication. London, England: Sage.

Ganz, D.J.; Moore, P.F. 2002. Living with fire. Communities in Flames Proceedings of 1st International Conference on Community Involvement in Fire Management. RAP Publication 2002/25. Bangkok, Thailand: United Nations, Food and Agricultural Organization, Regional Office for Asia and the Pacific.

Heal, G.M. 2004. Intertemporal welfare economics and the environment. Handbook of environmental economics. K.G. Maler and J.Vincent. Amsterdam, North Holland:Elsevier Publishers.

Heberlein, T.A.; Wilson, M.A.; and others. 2005. Rethinking the scope test as a criterion for validity in contingent valuation. Journal of Environmental Economics 50(1): 1-22.

Hodgson, R. 1994. Strategies for and barriers to public adoption of fire safe behavior. The Biswell symposium: Fire issues and solutions in urban interface and wildland ecosystems. General Technical Report GTR-PSW-158. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station.

Kirchhoff, S.; Colby, B.G.; and others. 1997. Evaluating the performance of benefit transfer: An empirical inquiry. Journal of Environmental Economics and Management 33(1): 75-93.

Knapp, E.E.; Stephens, S.L.; and others. 2004. Fire and fire surrogate study in the Sierra Nevada: Evaluating restoration treatments at Blodgett Forest and Sequoia National Park_Proceedings of the Sierra Nevada Science Symposium; 2002 October 7-10, Kings Beach, CA, Gen. Tech. Rep. PSW-GTR-193. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. 287 p.

Loomis, J.B. 1992. The evolution of a more rigorous approach to benefit transfer - benefit function transfer. Water Resources Research 28(3): 701-705.

Millennium Ecosystem Assessment. 2003. Ecosystems and human well-being: A framework for assessment. Washington DC: Island Press.

National Research Council. 2004. Valuing ecosystem services: Toward better environmental decision making. Washington, DC: National Academies Press.

National Wildfire Coordinating Group (NWCG). 2001. Review and update of the 1995 Federal wildland fire management policy. . Boise, ID: National Interagency Fire Center. .

Openshaw, S.; Charlton, M.E.; and others. 1987. A mark i geographical analysis machine for the automated analysis of point data sets. International Journal of Geographical Information Systems 1: 359-377.

Pretty, J.N.; Brett, C.; and others. 2000. An assessment of the total external costs of U.K. Agriculture. Agricultural Systems 65: 113-136.

Ricketts, T.H.; Daily, G.C.; and others. 2004. Economic value of tropical forest to coffee production. Ecology 101(34).

Smith, V.K. 1992. On separating defensible benefit transfers from smoke and mirrors. Water Resources Research 28(3): 685-694.

U.S. Department of Agriculture (USDA). 1995. Course to the future: Positioning fire and aviation management. Washington, DC: USDA, Forest Service, Department of Fire and Aviation Management.

U.S. Department of the Interior-U.S. Department of Agriculture (USDI–USDA). 1995. Federal wildland fire management and policy and program review. Boise, ID: USDI, Bureau of Land Management.

Wilson, M.A.; Carpenter, S.R. 1999. Economic valuation of freshwater ecosystem services in the United States 1971-1997. Ecological Applications 9(3): 772-783.

Wilson, M.A.; Troy, A. 2005. Accounting for ecosystem services in a spatially explicit format: Value transfer and geographic information systems. International Workshop on Benefits Transfer and Valuation Databases, Washington DC.

Wilson, M.A.; Troy, A.; and others. 2004. The economic geography of ecosystem goods and services: Revealing the monetary value of landscapes through transfer methods and geographic information systems. Cultural landscapes and land use. M. Dietrich and V. D. Straaten. The Netherlands: Kluwer Academic Publishers.

Winter, G.; Fried, J.S. 2000. Homeowner perspectives on fire hazard, responsibility, and management strategies at the wildland-urban interface. Society and Natural Resources 13: 33-49.

Firefighters United for Safety, Ethics, and Ecology (FUSEE): Torchbearers for a New Fire Management Paradigm

Timothy Ingalsbee[1], Joseph Fox[2], and Patrick Withen[3]

Abstract—*Firefighters United for Safety, Ethics, and Ecology (FUSEE) is a nonprofit organization promoting safe, ethical, ecological wildland fire management. FUSEE believes firefighter and community safety are ultimately interdependent with ethical public service, wildlands protection, and ecological restoration of fire-adapted ecosystems. Our members include current, former, and retired wildland firefighters, other fire management specialists, fire scientists and educators, forest conservationists, and other citizens who support FUSEE's holistic fire management vision. FUSEE's primary function is to provide public education and policy advocacy in support of a new, emerging paradigm that seeks to holistically manage wildland fire for social and ecological benefits instead of simply "fighting" it across the landscape. We seek to protect fire-affected wildlands, restore fire-adapted ecosystems, and enable fire management workers to perform their duties with the highest professional, ethical, and environmental standards. Our long-term goal is the creation of fire-compatible communities able to live safely and sustainably within fire-permeable landscapes.*

Introduction

Firefighters United for Safety, Ethics, and Ecology (FUSEE) is a nonprofit organization promoting safe, ethical, and ecological wildland fire management. FUSEE believes firefighter and community safety are ultimately interdependent with ethical service by public agencies and private companies, and environmental protection and restoration of fire-adapted ecosystems. Our members include current and former firefighters, other fire managers and workers, fire scientists and educators, forest conservationists, and other citizens who support FUSEE's holistic fire management vision.

Triad of Safety, Ethics, and Ecology

FUSEE's alternative fire management mission is based on an interdependent *triad* of safety, ethics, and ecology (fig. 1 is our organization logo).

Figure 1—The FUSEE logo exhibits the triad of Safety, Ethics, and Ecology.

In: Butler, Bret W.; Cook, Wayne, comps. 2007. The fire environment—innovations, management, and policy; conference proceedings. 26-30 March 2007; Destin, FL. Proceedings RMRS-P-46CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 662 p. CD-ROM.

[1] Executive Director of Firefighters United for Safety, Ethics, and Ecology, Eugene, OR. fire@efn.org.

[2] Board President of Firefighters United for Safety, Ethics, and Ecology, McCall, ID.

[3] Associate Professor of Sociology, University of Virginia at Wise, Wise, VA.

Management actions that degrade ecosystems or waste taxpayer resources adversely affect firefighter and community safety. For example, use of taxpayer dollars and resources on deficit timber sales that remove fire-resilient old-growth trees and leave behind untreated logging slash, violate Federal environmental laws in planning or implementation, or are labeled as "fuels reduction" or "forest restoration" projects when they actually increase fuel hazards or degrade ecological integrity—we believe this is an *ethical* as well as an ecological issue. These kind of antiecological, unethical forest management projects also adversely affect firefighter and community safety by diverting limited Federal dollars away from genuine hazardous fuels reduction activities, and by degrading ecological conditions in ways that increase wildfire rate of spread, intensity, or severity. Ethical and efficient use of taxpayer resources coupled with environmental protection and ecological restoration are the best strategies for improving the safety and working conditions of wildland firefighters. Thus, safety, ethics, and ecology are interconnected values in FUSEE's holistic vision of forest and fire management.

FUSEE Mission: A New Fire Management Paradigm

FUSEE's mission is to promote safe, ethical, and ecological wildland fire management, and we seek to enable fire management workers to perform their duties with the highest professional, ethical, and environmental standards. Our primary function is to provide policy analysis and public education in support of a new, emerging paradigm that seeks to holistically manage wildland fire for social and ecological benefits instead of simply "fighting" it across the landscape. We want to end modern industrial society's socially conditioned fear of forest fires, and instead, wisely use fire on the landscape to benefit a multitude of ecosystem functions and processes, vegetative communities and wildlife habitats, as well as our own human communities and economies. Our long-term goal is the creation of fire-compatible communities able to live safely and sustainably within fire-permeable ecosystems.

Efforts to fundamentally shift the policy debates and change the paradigm of fire management will not work if efforts are focused solely on "top-down" strategies that appeal only to policymakers in Congress or the Administration. Unless and until public attitudes and opinions about wildland fire are changed from the "*bottom up*," progressive fire policy reforms will continue to be blocked or reversed—as evidenced by the use of wildfire to justify the roll back of environmental protection laws and regulations. Consequently, FUSEE believes in the strategic, long-term importance of educating the public, policymakers, and the press about fire ecology, and empowering people to become actively involved in fire management policies and practices.

Educating and empowering people to become informed stakeholders actively involved in fire management programs would have a number of practical benefits for land and fire managers, particularly given shrinking levels of staffing and funding within Federal agencies. For example, fire managers would benefit from greater stakeholder involvement in fire management planning when information from scientists provides the most current references from the literature, when indigenous communities offer place-based traditional ecological knowledge, and when residents give local knowledge of valued natural assets and human developments. This input would help managers better understand the local values-at-risk needed to prioritize fuels reduction and forest restoration projects, and devise suppression strategies and tactics. Greater stakeholder involvement in fire policy formation at regional and national levels would also nurture more public commitment to fire management programs—for example, taxpayer funding streams needed for long-term monitoring, research, and restoration projects. Expanding the number and kind of stakeholders actively involved in fire planning and policy development should above all include ground-level wildland firefighters—arguably the stakeholders with the most at stake in sound policies and practices. Fundamentally, the expansion of informed public involvement in all aspects of wildland fire management is an ethical calling for an expansion of democratic principles and processes.

FUSEE has a four-pronged approach to our education and advocacy work:

- First, FUSEE proactively **engages journalists and public opinionmakers** with information they can use in reporting on a broader range wildland fire issues. We emphasize working with the news media because the media are often the source of inaccurate, one-sided information and sensationalist stories that intensify the public's socially conditioned fear of wildfire. We promote alternative and investigative journalism that explores the vast breadth of fire management issues that are being neglected by the media's near-exclusive focus on emergency wildfire suppression. Our Web site (www.fusee.org) features a handbook, "A Reporter's Guide to Wildland Fire" (Ingalsbee 2005) that provides journalists with resources such as alternative story angles and new language in order to wean them away from their hackneyed use of the "war metaphor" and "catastrophe mentality" in reporting on wildfire events. We work to get reporters to expand their usual sources—official press spokespersons in fire camp—and get journalists out on the frontlines talking to ground-level firefighters, prescribed fire crews, fire effect monitors, fire planners, and other fire management workers who can articulate the diversity of fire management issues.
- Second, FUSEE actively **informs and empowers fire management workers**, especially ground-level wildland firefighters, to stand up and speak out on behalf of wildlands protection and ecosystem restoration not only in the public arena but also out on the fireline. Even minor changes in the location or intensity of fireline construction, for example, can have major effects on the impacts to soils, streams, and vegetation. We seek to change both the methods and the culture of fire management from the bottom up and inside out by instilling a renewed sense of civic duty and a new identity among firefighters as *forest protectors* and *restoration workers*. From their position on the frontlines of fire management, ground-level firefighters have the potential to fundamentally change their mission from the ground up and perform their duties with the highest professional, ethical, and environmental standards. The FUSEE Web site (www.fusee.org) hosts critical fire science papers, fire policy documents, fire education materials, personal essays, and an interactive "blogger" site that helps raise the ethical and environmental awareness of firefighters and citizens, and discusses such things as the interrelationship between firefighter safety and forest ecosystem health. This investment in firefighter education helps mitigate the firefighting damage done to forests in the present, and nurtures the kind of educated, empowered forest/fire restoration workforce needed for the future. Our hope is that one day fire-*fighters* will become something

more like "fire-*guiders*," adept at starting prescribed fires and steering wildland fires rather than just suppressing wildfires, and envision that the label "firefighter" will become as anachronistic in the future as the label "smokechaser" is today.

- Third, FUSEE **informs policymakers and decisionmakers** about fire ecology and management issues, and advocates for alternative ecological restoration policies that improve the health, safety, and working conditions of wildland firefighters. In general, policymakers propose fire-related legislation and regulations without ever consulting with wildland firefighters—arguably the "stakeholders" with the most at stake in having sound fire management policies. FUSEE approaches policymakers from the perspective of ground-level firefighters and veteran fire management experts, most of whom work for low pay, few job benefits, and have little job security. Fire management workers facing hazardous and unhealthy working conditions are often forced to do environmentally destructive activities that do not serve the public interest, yet they often feel disenfranchised, voiceless, and powerless to improve their working conditions or alter their work tasks. FUSEE offers a safe vehicle for firefighters in public agencies and private companies to speak out on fire-related policies and legislation without fearing job reprisals.
- Finally, FUSEE **educates homeowners and rural residents** living in fire-prone areas about their *rights* and *responsibilities* to manage defensible space and use fire-resistant building materials. Our Web site features "A Homeowner's Guide to Fire-Resistant Home Construction" (Fairbanks and Ingalsbee 2005) that provides tips on vegetation management and home construction to reduce the risks of wildland fire damage. We work to transcend the current defensive, narrow focus on "community wildfire protection," and instead, promote proactive community fire *preparation* for the whole array of fire management including prescribed fire, wildland fire use, as well as wildfire suppression. The sooner homes and communities are prepared for fire, the sooner ecosystems can be restored with fire. Our long-term vision is the creation of "*fire-compatible communities*" dwelling within ecologically restored "*fire permeable landscapes*" where wildland fire can safely move through fire-dependent ecosystems without causing property damage.

Conclusions

FUSEE informs, inspires, and empowers wildland firefighters, other fire management workers, and their citizen supporters to become *torchbearers for a new paradigm in fire management*. We seek a paradigm shift not only in management policies and practices, but in society's relationship with wildland fire. We work to end the public's fear of wildfire by providing information on how to protect homes and communities from wildfire damage, how native ecosystems depend upon and benefit from fire, and how society benefits from genuinely managing fire instead of endlessly "fighting" it. We also educate the press, policymakers, and the public about the safety risks, economic costs, and environmental impacts of reactive wildfire suppression, making the case for proactive ecological fire restoration to reduce the risks, costs, and impacts of firefighting. Most important, we educate firefighters and the public they serve about the many benefits from practicing safe, ethical, ecological fire management, with the goal of crafting a new identity and mission for firefighters as forest protectors and restoration workers. We invite members of the wildland fire management and forest conservation communities to visit our web site and become members and contributors of Firefighters United for Safety, Ethics, and Ecology.

References

Fairbanks, Rich; Ingalsbee, Timothy. 2006. A homeowner's guide to fire-resistant home construction. Firefighters United for Safety, Ethics, and Ecology. Online: http://www.fusee.org/content_pages/docs/homeowners_guide.pdf

Ingalsbee, Timothy. 2005. A reporter's guide to wildland fire. Firefighters United for Safety, Ethics, and Ecology. Online: http://www.fusee.org/content_pages/docs/Reporters_guide.pdf

This page is blank on purpose

Critical Elements in the Development and Implementation of Community Wildfire Protection Plans (CWPPs)

Pamela Jakes[1], Sam Burns[2], Antony Cheng[3], Emily Saeli[3], Kristen Nelson[4], Rachel Brummel[4], Stephanie Grayzeck[4], Victoria Sturtevant[5], and Daniel Williams[6]

Abstract*—Community wildfire protection plans (CWPPs) are being developed and implemented in communities across the United States. In a series of case studies, researchers found that the process of developing a CWPP can lead to benefits beyond those associated with fuels reduction, including enhancing social networks, developing learning communities, and building community capacity.*

Introduction

> The [Healthy Forest Restoration Act] provides communities with a tremendous opportunity to influence where and how federal agencies implement fuel reduction projects on federal lands. A Community Wildfire Protection Plan (CWPP) is the most effective way to take advantage of this opportunity. (Healthy Forest Initiative 2007)

Communities across the Untied States have engaged in the development and implementation of community wildfire protection plans (CWPPs) in an effort to "clarify and refine [their] priorities for the protection of life, property, and critical infrastructure in the wildland-urban interface" (Society of American Foresters 2004, p. 2). As might be expected, Western communities have embraced the idea of CWPPs; for example at least 44 counties in Idaho have developed CWPPs, 33 communities in Washington, and 28 communities in New Mexico. However, communities in Eastern States such as Arkansas, Florida, Minnesota, Virginia, and Wisconsin are also developing CWPPs. CWPPs are developed collaboratively and include (1) a prioritized list of areas requiring hazardous fuels treatments and the type of treatment to be used, and (2) recommended measures to reduce structural ignitability. In a project funded by the Joint Fire Science Program, we conducted a series of case studies to identify how CWPPs enhance collaboration between communities and fire management agencies, and how the development of CWPPs builds community capacity. We are interested in the contexts in which CWPPs are developed, processes used to develop CWPPs, and outcomes from the development of CWPPs (fig. 1).

In: Butler, Bret W.; Cook, Wayne, comps. 2007. The fire environment—innovations, management, and policy; conference proceedings. 26-30 March 2007; Destin, FL. Proceedings RMRS-P-46CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 662 p. CD-ROM.

[1] Project Leader with the U.S. Department of Agriculture, Forest Service, Northern Research Station, St. Paul, MN. pjakes@fs.fed.us

[2] Research Director, Office of Community Services, Fort Lewis College, Durango, CO.

[3] Professor of Forestry and Natural Resource Policy, and Graduate Research Assistant, respectively, at Colorado State University, Fort Collins..

[4] Professor of Human Dimensions, and Graduate Research Assistants, respectively, at University of Minnesota, St. Paul.

[5] Professor of Sociology at Southern Oregon University, Ashland.

[6] Research Social Scientist with the U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO.

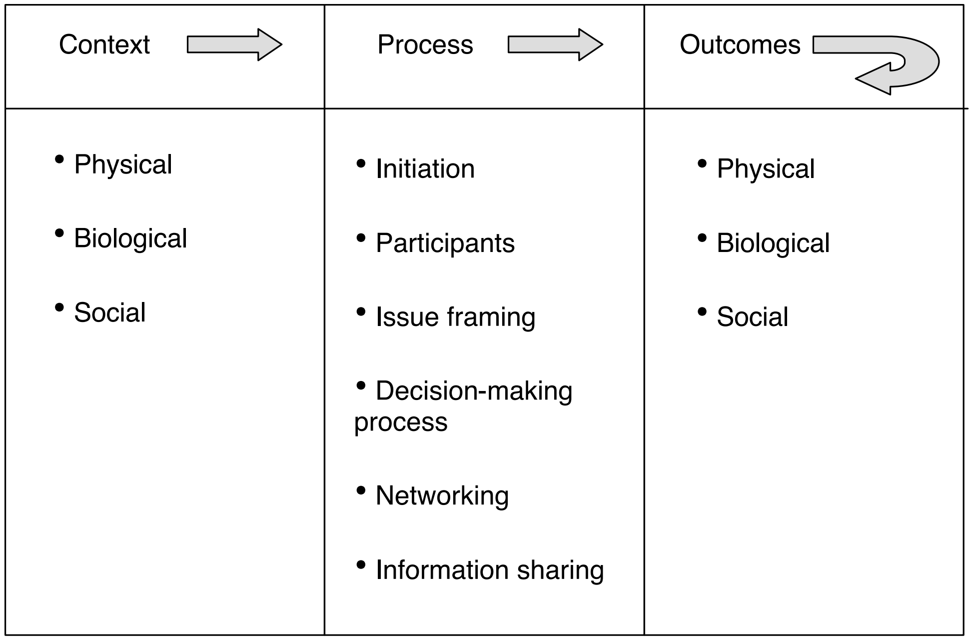


Figure 1—A model of community wildfire protection planning focusing on the context in which the CWPP is developed, the CWPP process, and the outcomes of the process.

Although data collection and analysis are ongoing, in this paper we discuss three themes that have emerged across all the communities studied to date:

- social networks
- learning communities
- community capacity

These themes emerged as critical to the CWPP process and as important outcomes resulting from the development of CWPPs.

Methods

We are conducting case studies in eight States: California, Colorado, Florida, Minnesota, Montana, Oregon, Virginia, and Wisconsin. A case, or unit of analysis, was defined as a CWPP. The case study CWPPs have been developed at several scales. The smallest geographic scale for CWPP development in our study was the neighborhood (High Knob near Front Royal, VA). We also had a small-scale CWPP made up of different holdings and a neighborhood (East Portal, CO). At a larger scale are villages and towns, unincorporated (Auburn Lake Trails, CA; Grizzly Flats, CA; Post Mountain, CA; and Taylor, FL) and incorporated (Ashland, OR). We have two cases that are multicommunity regions (the Barnes-Drummond area of northwestern Wisconsin and Harris Park, CO, southwest of Denver in Jefferson and Park Counties). The largest scale for CWPP development was at the county level (Josephine County, Oregon; Lake County, Minnesota; and Lincoln County, Montana).

Case study CWPPs can be nested in other plans. For example, Em Kayan in Lincoln County, Montana, has a Firewise Communities/USA plan that identifies projects that feed into the Lincoln County CWPP, which serves as a chapter in the county's pre-disaster mitigation plan (fig. 2). The Lincoln County Pre-Disaster Mitigation Plan is tied to the Montana Multi-Hazard Mitigation Plan. The Post Mountain CWPP is an appendix to the Trinity County Fire Safe Council Fire Plan. In turn, some case study CWPPs have other plans nested in them, such as the Josephine County CWPP, which has the Illinois Valley CWPP within it. This nestedness adds to the complexity of the context in which CWPPs are developed and makes it difficult to study one CWPP without considering linkages to other CWPPs.

Key informant interviews were conducted in each CWPP community. Interviews followed an interview guide covering the topics of inquiry identified in figure 1. Interviews were conducted with members of the CWPP team, adjacent land management agencies and local governments, and interested local residents. Each interview was audio-taped, with a transcript created of each tape. Analysis is being conducted around themes identified by the research team.

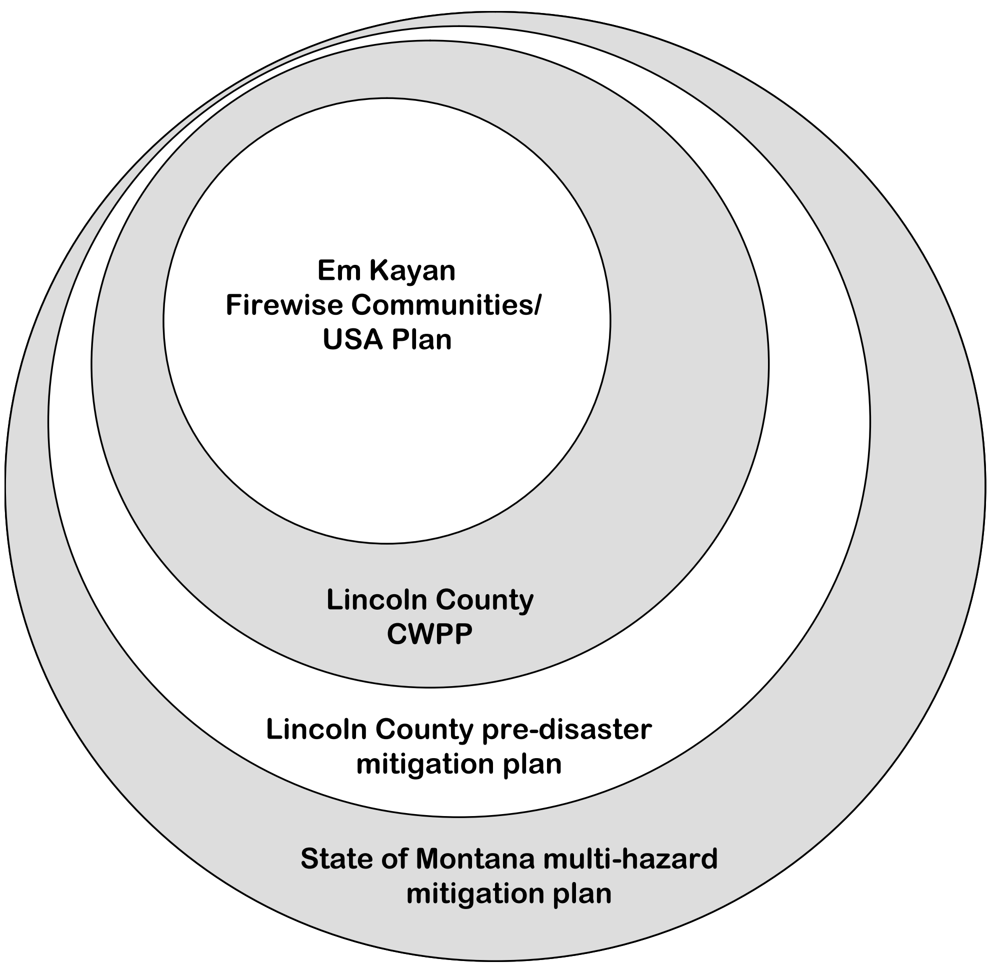


Figure 2—Community wildfire protection plans can be nested in other plans and other plans can be nested in the CWPP, as in this example from Montana.

Findings

Social Networks

A social network is "a set of individuals or groups and the ties representing some interrelationship between them" (Brass 1992, p. 300). Social networks create bridges between groups that facilitate interaction and collaboration and/or bonds that build group identity. Social networks played a critical role in the CWPP process, and the development of social networks was a positive outcome from the creation of CWPPs.

During the CWPP process, a variety of networks were used to obtain the information, skills, and resources to complete the plan. Members of the CWPP teams served as nodes, connecting the CWPP team to other networks in which members participated. For example, local fire departments often have strong networks with other fire and emergency management agencies, and in locations such as Harris Park and Josephine County, having fire department representatives at the table gives access to these networks during CWPP development. Environmental groups are linked to other environmental groups, and in Post Mountain and Ashland, representatives of these groups tap into their environmental networks to achieve CWPP objectives. Having local units of government at the table is especially important for community support and buyin. In Ashland, the city forester is connected with private landowners, and this relationship was critical for reducing fuels around homes and reducing structural ignitibility.

Representatives from non- or quasigovernmental organizations are important nodes on many networks. In our California cases, the networks developed by the local Fire Safe Councils were critical to identifying where necessary information could be obtained and where funds might be tapped to support planning activities. In Auburn Lake Trails and Em Kayan, designation as a Firewise Community/USA means that they are tied to other Firewise communities across the country, and residents have access to a vast array of resources to guide them in eliminating hazardous fuels around their homes and reducing structural ignitability. In East Portal the YMCA has strong relationships with the county mitigation specialist and Colorado State Forest Service due to previous Firewise activities, which were valuable in CWPP development. In the isolated community of Post Mountain, the strong relationships built by the Watershed Training and Research Center brought resources and expertise to the CWPP process. In communities such as Auburn Lake Trails and High Knob the local homeowners associations provide the links to local residents and other organizations that can aid in the development of CWPPs.

The CWPP processes we studied improved relationships within the community, strengthened existing networks, and developed new networks. In northwestern Wisconsin, tension between the Drummond town board and Chequamegon-Nicolet National Forest over Federal land use decisions eased as representatives of the two organizations worked on the CWPP. In Lake County, Colorado, networks that linked the fire department and community members were strengthened through the CWPP process, as were the relationships between the fire and county emergency agencies in Josephine County, Oregon. New networks among community members facilitated bonding in Grizzly Flats and High Knob.

The importance of social networks to the CWPP process and as an outcome of the CWPP process was enhanced by several process characteristics. First, it is important to have the right people at the table—meaning, people who are well connected in the community. Second, the CWPP goals and objectives must be relevant to team members so they are willing to draw on their networks to move the CWPP process forward. Third, members of the CWPP team need to have opportunities to get to know one another as representatives of their agencies or organizations and as individuals. Finally, the probability of having these process characteristics is enhanced by having a facilitator who keeps team members involved, informed, and organized.

Learning Communities

Another outcome of the CWPP process relative to social networks is the creation of learning communities. Learning communities develop in environments that encourage information sharing and are places where people come together to share knowledge that affects performance. One benefit of a learning community is that members find common ground in their areas of interest (Finneran 2007). In our cases, common ground was found in the way in which the wildland fire issue is framed, in the identification of high priority fuels reduction projects, and in approaches to reduce structural ignitibility.

Different types of knowledge are shared during the CWPP process. This knowledge varies in its complexity from relatively simple information of low complexity to multidimensional information of high complexity, and the knowledge also varies in its scale, from information that was applicable to an individual home or forest stand to information applicable to a region or landscape. Figure 3 illustrates some of the information shared in the development of our case study CWPPs. Although the placement of any one piece of information on the graph may be debated, the range of information is clearly depicted. Different members of the CWPP teams brought different information to the processes. Using East Portal as an example, we find that the USDA Forest Service provided access to GIS layers on fuel levels and topography included in a pre-existing regional risk assessment; the National Park Service provided information on forest ecology; the Colorado State Forest Service

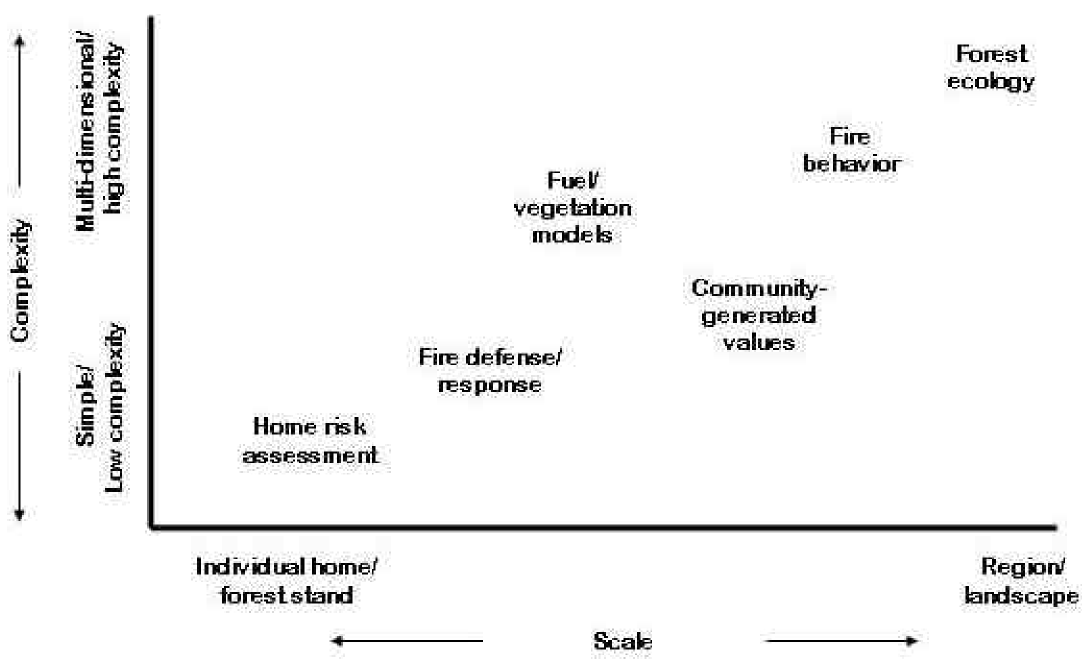


Figure 3—Knowledge shared during the community wildfire protection planning process by complexity and scale.

provided information on forest ecology, fire behavior, and forest management; the county hazard mitigation specialist provided information on fire defense and response; the fire department provided information on fire response; and community members identified and mapped community values.

An array of methods is used to share information with team members and the public. Continuing with East Portal as an example, we find that they use many different outlets to share information including team meetings, team field visits, homeowner association meetings, demonstration projects, and community events such as cleanup days. In addition, community members who heard the information at one these outlets carried that information to their groups and associations, and were effective in face-to-face interactions with neighbors and friends. Interagency funding supports a community educator who has developed and staffed booths at public events in the Estes Valley.

The development of learning communities as part of the CWPP process lead to several outcomes in regards to the CWPP document itself and community perceptions of wildland fire management and the agencies involved. We observed that strong, active learning communities tended to produce CWPPs that provide:

- strategic direction for wildland fire mitigation
- clarification and coordination of responsibilities
- information-sharing approaches that can be used in future CWPP efforts such as implementation

Learning communities resulted in (1) homeowners who are better informed about fire dependent ecosystems and wildfire risk, (2) better understanding between agencies and a community and its homeowners, (3) improved trust in agencies and among community members, and (4) increased community and homeowner support for and participation in wildland fire mitigation actions.

Community Capacity

Community capacity is the ability of a community to meet the day-to-day needs of its residents (Forest Ecosystem Management Assessment Team 1993). Community capacity is often monitored or evaluated using indicators, with one common set of community capacity indicators being the capitals. Capital is generally described as resources that are invested to create new resources (Rule and others 2000). Communities transform the capitals through policies, laws, social relations, incentives, and institutions to achieve desired outcomes such as community wildfire protection. Sustainable communities accumulate capital over time, while unsustainable communities deplete capital. In addition, Flora (2000, p. 85) argues that favoring one form of capital over other forms "can destroy the ecosystem, create a dependent, fragile economy, and increase social inequity."

Flora and others (2004) have identified seven capitals:

- financial capital
- physical capital
- natural capital
- human capital
- cultural capital
- social capital
- political capital

Financial capital is the monetary resources available for local use (Kusel 2002). Financial capital includes debt capital, investment capital, tax revenue, savings, tax abatements, and grants (Flora 2000). Rule and others (2000, p. 378) suggest that this type of capital is the "easiest to identify and the most commonly accounted for in many cost-benefit analyses." In Auburn Lake Trails, the Auburn Lake Trails Property Owners Association Board of Directors was able to create financial capital by increasing the membership fees paid by property owners. These new funds are being used to carry out fuels reduction projects on common property and to meet requirements for matching funds for some grants.

Physical capital is the local infrastructure that facilitates community activities (Pretty 2000). Physical capital includes housing and other buildings, roads and other transportation systems, communication systems, and markets. Building infrastructure was a high priority in the Grizzly Flats CWPP, as residents focused on the need for an alternative evacuation route and worked with National Forest staff to develop an egress through Federal land.

It is becoming increasingly common for communities to view ecological systems as capital assets (Wills and Gray 2001). Pretty (2000, p. 77) defines natural capital as "nature's economic and cultural goods and services." People are drawn to places like our case study communities by their natural beauty. In Lake County, Minnesota, the strong attachment to place and strong sense of responsibility that characterizes residents are due, in part, to northeastern Minnesota's natural capital.

Pretty (2000) sees human capital as the knowledge, skills, and abilities individuals develop and accumulate over time. Human capital was critical to the success of our case study communities in developing CWPPs. In Ashland, highly trained professionals, many educated in the ecological sciences, are a major influence on National Forest land management planning and CWPP development. In Auburn Lake Trails, the knowledge, skills, and abilities of retired professionals are facilitating CWPP implementation.

Some social scientists distinguish between human capital and cultural capital—with human capital acquired through education or other formal training, and cultural capital through informal learning, as a result of a person's culture or environment (Kusel 2002). We see evidence of the importance of cultural capital in Post Mountain where the experience and technical knowledge of third generation loggers is being melded with the traditional scientific knowledge of Forest Service professionals to develop and implement CWPP projects that fit the local biological, physical, and social contexts.

Social capital can be defined as "the 'glue' that binds a community together and enables collective action for the benefit of the community. It has also been referred to as the 'grease' that enables things to happen smoothly" (Kay 2005, p. 166). Local leadership is one indicator of social capital, and in East Portal there was an abundance of local leadership built through the community's Firewise activities. In the area around Libby (Lincoln County, Montana), social capital developed as community residents came together to address a number of issues, including the closing of the local mill and cleanup of an asbestos mine. Experience handling these challenges has facilitated the community coming together to address wildland fire issues. The strong neighborhood networks in Harris Park are examples of networks that build trust and facilitate collaboration, a critical component of social capital.

Some researchers have identified the networks and relations that facilitate the use of political systems to accomplish goals as a separate capital—political capital (Flora 2003). In Grizzly Flats, experience and relationships developed during the CWPP process have empowered the community to work with its local U.S. Representative to obtain funding for a new community center and fire hall. Other communities have been able to take advantage of Federal programs not directly related to wildland fire to support planning efforts. The Secure Rural Schools and Community Self-Determination Act (SRS) provides transitional assistance to counties affected by the decline in revenue from timber harvests on Federal land (FirstGov 2007). SRS authorized the establishment of 55 Resource Advisory Committees (RACs) in 13 States. The RACs have implemented more than 4,500 projects on National Forests and National Grasslands and adjacent non-Federal lands. In Josephine County and Post Mountain, county governments were willing to work with their local RACs to invest SRS funding in the CWPP process.

We discovered several truths about our communities in regards to community capacity. First, our communities had a varying constellation of capitals, and high levels of stocks were not sufficient to produce and implement a CWPP. It was critical for a community to have mobilizers (flow capitals), such as local leadership and networks, to produce a CWPP.

In addition, it was important to have participation of agencies or intermediary organizations that link the CWPP team to the resources necessary to complete the plan. An intermediary organization is typically a nongovernmental or quasigovernmental organization that serves as a bridge between private individuals and government institutions, or between neighborhoods and communities and public organizations (Berger and Neuhaus 1996). More formally, intermediary organizations help communities mobilize their own resources and gain access to outside inputs (information, technology, finances) that enhance their capacities (Lee 2006). In several communities we observed consultants playing the role of intermediary.

Community organizations provided collaborative "spaces" for the development of CWPPs. Examples of community organizations active in our case study communities include Fire Safe Councils, Firewise committees, collaborative stewardship groups, homeowners associations, public utility districts (PUDs) and water boards, regional planning commissions, and various local social groups.

In addition to providing links to outside resources, we observed community organizations and intermediaries filling a number of roles in CWPP development, including:

- generate interest in natural resource issues
- gather together residents and important players
- facilitate meetings (CWPP and community)
- provide administrative assistance with communication, organizational structure, collaboration, and monitoring
- lend technical skills (for example with GIS)
- assist in grant writing
- help implement fuels reduction in neighborhoods

As mentioned above, contractors play an important role in the development of CWPPs. When we initiated this research, we heard stories about contractors who were irresponsible in dealing with communities in the development of CWPPs, but we also saw examples of contractors who played important roles in developing networks, connecting communities to other similar communities for advice and counsel, and facilitating collaboration. In several cases these contractors were retired Forest Service employees who had valuable contacts in the local fire management community.

Finally, agencies at the county, State, and Federal level provide funding, data, and key leadership in the development of CWPPs. In Lake County, Minnesota, the Superior National Forest hired a partnership coordinator who has initiated the CWPP process in counties with large Federal holdings. She provides key leadership, is a node to a variety of networks, and facilitates access to the resources (data, maps, and staff) of the National Forest.

Case study communities that could be classified as high capacity communities based on the amount of capital at their disposal were able to engage in activities not possible for lower capacity communities. We found that several of these high capacity communities increased property owner fees to generate funds to hire contractors or to implement projects identified in the CWPP. The retired professionals found in these communities bring a high degree of human capital to any local endeavor—especially valuable in the development of CWPPs are grant writing and planning skills. Residents in our high capacity communities had experience in other programs, such as stewardship or fire programs or fire cooperatives, which could be directly applied to the development of CWPPs. Finally, agencies and programs will often target high capacity communities for collaborative projects because they believe that their potential for success is greater than in lower capacity communities. This practice can benefit the broader community or region by providing models for action, but eventually lower capacity communities will need to be brought into the process.

Although communities described as low capacity may be seen as having fewer resources to bring to the CWPP process, we found many characteristics of these communities that facilitated CWPP development. Lower capacity communities often exhibited a stewardship ethic that encourages involvement in fuels mitigation projects that would result in more healthy forests. The social cohesion and sense of mutual obligation and responsibility found in several of these communities provides a foundation for working together collaboratively on the CWPP. A history of self-reliance means that several of our low capacity communities believed that they could accomplish an objective like fuels mitigation. Communities that lack many of the characteristics that enhance community capacity can be more responsive to goals defined by agencies or organizations (such as developing a CWPP), and to offers for outside assistance. Networks in lower capacity communities tend to be informal, but they do exist, and can serve community wildfire protection planning. Leadership in lower capacity communities can be more diffuse, but the community leaders that are found tend to be more multifaceted because they need to be. Finally, community members exhibit a high degree of trust in their volunteer fire departments. The knowledge, skills, and abilities found in volunteer fire departments in lower capacity communities can provide the nucleus for broader community projects.

At the beginning of our discussion of community capacity, we cited examples of how the CWPP process contributed to each of the capitals. In summary, we observed many examples of the CWPP process increasing community capacity by:

- building leadership in communities and organizations
- strengthening relationships among agencies
- providing visibility for players
- gaining access to networks and participating in coordinated efforts
- enhancing stewardship and community buyin for projects
- facilitating social learning
- producing successful projects that spawn other projects
- creating a sense of hope and trust

The impacts of the CWPP process on community capacity were not all positive. If merely imported from another community and treated as a fill-in-the-blank exercise, the CWPP process may not realize many of the benefits listed above. If agency staff direct the process with little community involvement or collaboration, the CWPP process will build little community capacity. We also saw examples of the CWPP process creating or enhancing conflict among agencies, across programs, or among interest groups.

Several findings from our case studies related to community capacity are surprising. We have often heard that communities that are bedroom communities—with part time and/or commuting residents—will not be successful in collaborative activities requiring community involvement. This was not the case in our communities if the communities had high natural capital, human capital, and social capital (including a stewardship ethic). We found that economic advantage and political support are not enough to produce a CWPP; rather social and human capitals are most significant. Finally, early in our interviews we would hear complaints about the fact that the Healthy Forest Restoration Act did not designate a leadership agency for the development and implementation of CWPPs. However, we found that by not designating a leadership agency, there was flexibility for leadership to emerge at the scale where the capacity was the greatest.

Discussion

Agencies and groups interested in monitoring and evaluating the success of CWPPs often focus on number of plans signed or acres treated. In our preliminary analysis of findings from case studies in eight States, we find that benefits from the development and implementation of CWPPs in regards to building networks, learning communities, and community capacity may be as significant and enduring as fuels reductions. By building community capacity, CWPPs will help ensure that the initial fuels work done in communities and on public land adjacent to communities will be maintained as well as the reduction in risk from wildland fire.

There remain a number of questions yet to be answered by this and future research projects. Regarding information sharing we ask:

- What information is lacking or needed?
- What are the most effective information sharing mechanisms?
- What information sharing method would community members like to learn more about?
- How has new information improved work in CWPPs?

Regarding embedding CWPPs in other plans:

- What priorities exist for embedding CWPPs in existing plans?
- How important is this for success?
- What does it mean for CWPP implementation?

Regarding networks:

- What network lessons from CWPP planning transfer to CWPP implementation?
- How do we track resource flows along bridging networks?

Finally, regarding community capacity:

- Do CWPPs provide new opportunities for community-based organizations and for building community capacity?
- Are more low-capacity communities being reached through the CWPP process than through other wildland fire management planning efforts?
- What are the needed capacities and essential components for moving from strategic plans to sustainable implementation?
- Because intermediaries and contractors play such an important role in CWPP development, how can they receive sustained support in order to assist in implementation?

References

Berger, P.L.; Neuhaus, R.J. 1996. To empower people: from state to civil society. Washington, DC: American Enterprise Institute. 223 p.

Brass, D.J. 1992. Power in organizations: a social network perspective. In: Moore, B; Whitt, J.A. (eds), Research in politics and society. Greenwhich, CT: JAI Press: 295-323.

Finneran, T. 2007. A component-based knowledge management system. The Data Administration Newsletter. Available: www.tdan.com/i009hy04.htm [April 27, 2007].

FirstGov. 2007. Secure Rural School and Community Self-Determination Act of 2000. Available: wwwnotes.fs.fed.us:81/r4/payments_to_states.nsf [April 27, 2007].

Flora, C.B. 2000. Measuring the social dimensions of managing natural resources. In: Fulton, D.C.; Nelson, K.C.; Anderson, D.H.; Lime, D.W. (eds), Human dimensions of natural resource management: emerging issues and practical applications, workshop proceedings. 1-3 February 2000; St. Paul, MN. BRD-2000-1. St. Paul, MN: University of Minnesota and USGS-Biological Resources Division, Minnesota Cooperative Fish and Wildlife Research Unit and Cooperative Park Studies Program: 81-99.

Flora, C.B. 2003. Outcomes and measures. North Central Regional Center for Rural Development. Available: http://www.nrfc.org/ln/documents/Monitoring%20outcomes.pdf [April 27, 2007].

Flora, C.B.; Flora, J.L.; Fey, S. 2004. Rural communities: legacy and change. 2nd ed. Boulder, CO: Westview Press. 372 p.

Forest Ecosystem Management Assessment Team. 1993. Forest ecosystem management: an ecological, economic, and social assessment; Report of the Forest Ecosystem Management Assessment Team. Washington, DC: U.S. Department of Agriculture. Forest Service.

Healthy Forest Initiative. 2007. A community wildfire protection plan: how-to-guide. Available: www.healthyforests.gov/community/cwpp.html [April 4, 2007].

Kusel, J. 2002. Assessment of the Northwest Economic Adjustment Initiative. Taylorsville: Forest Community Research.

Lee, L. 2006. Social capital, the social economy and community development. Community Development Journal. 41(2):160-173.

Pretty, J. 2000. Towards sustainable food and farming systems in industrialized countries. International Journal of Agricultural Resources, Governance and Ecology. 1:77-94.

Rule, L.C.; Flora, C.B.; Hodge, S.S. 2000. Social dimensions of agroforestry. Garrett, H.E.; Rietveld, W.J.; Fisher, R.F. (eds). North American agroforestry: an integrated science and practice. Madison, WI: American Society of Agronomy: 361-386

Society of American Foresters. 2004. Preparing a community wildfire protection plan: a handbook for wildland-urban interface communities. Washington, DC: Society of American Foresters. 11 p.

Wills, L.; Gray, G.J. 2001. Exploring reinvestment from a community-based watershed perspective. Journal of Sustainable Forestry. 19(1/2): 385-399.

San Diego Declaration on Climate Change and Fire Management: Ramifications for Fuels Management

Brian P. Oswald[1] and the Board of Directors, The Association for Fire Ecology[2]

Abstract*—Climate plays a central role in shaping fire regimes over long time scales and in generating short-term weather that drives fire events. Recent research suggests that the increasing numbers of large and severe wildfires, lengthened wildfire seasons, and increased area burned are, in part, related to shifts in climate. The historical fire regimes in many ecosystems have been disrupted. Efforts to restore ecosystem structure and integrity are facing both a changed fuel load condition and a changing climate. The San Diego Declaration on Climate Change and Fire Management attempted to consolidate a variety of perspectives on climate change and wildland fire management into a common statement on the overriding need to prepare and plan for wildland fire regimes of the future. These changes will not only directly affect wildland fire events, but also require a more proactive management of fuels to reduce potential disruptions to plant communities, fire regimes, and ultimately, ecosystem processes and services. The effective management of landscapes may require novel targets for community structure and compositions, even if the specific objectives for fuels treatments may focus on measure of resilience then the restoration of presettlement conditions.*

Introduction

At the Third International Fire Ecology and Management Congress held November 13-17, 2006, in San Diego, CA, USA, the Association for Fire Ecology (AFE) presented a declaration on climate change and fire management for comment and approval. The draft presented at the Congress was the cumulative effort of many scientists within AFE as well as non-AFE members. About 200 signed the declaration at that time, and at the General AFE meeting held during the Congress, the membership of AFE also approved the declaration. The declaration attempted to consolidate a variety of perspectives on climate change and wildland fire management into a common statement on the overriding need to prepare and plan for wildland fire regimes of the future. While other forums have addressed the issue of global climate change (former Vice President Gore's movie "An Inconvenient Truth" and the more recent Intergovernmental Panel on Climate Change), this declaration was the first to approach the issue from the wildland fire perspective. Wildland fire regimes are likely to be significantly affected by global climate changes (Swetnam 1993), especially when changes in precipitation patterns (Grissino-Mayer and Swetnam 2000) and/or warmer climatic conditions (Williams and others 2001) occur. The result could be increases in the number of large fires and increases in the total area burned (Pinol and others 1998; Lefort and others 2003).

In: Butler, Bret W.; Cook, Wayne, comps. 2007. The fire environment—innovations, management, and policy; conference proceedings. 26-30 March 2007; Destin, FL. Proceedings RMRS-P-46CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 662 p. CD-ROM.

[1] Professor of Forestry, Arthur Temple College of Forestry and Agriculture, Stephen F. Austin State University, and President, The Association for Fire Ecology. boswald@sfasu.edu

[2] Davis, CA. cashaw@fireecology.net

It should be noted that the declaration represents the position of AFE and non-AFE member signatories and may not have represented the positions of organizations or agencies that sponsored the Congress. Since the Congress, the National Park Service (NPS) has launched a program to identify the most threaten resources and develop possible mitigations for future climate scenarios. In this context the AFE fire and climate change declaration has been embraced as an effective starting point to adaptive fuels management treatments designed for specific Park landscapes. The declaration has been widely distributed within the agency and is a point of specific discussion at multiple workshops addressing this issue. The declaration has helped to facilitate decisionmaking, up to the directorate level, regarding this complex and difficult issue. More recently Conservation Northwest has also endorsed the declaration.

The declaration begins with a preamble that addresses the overall issue of climate change, acknowledges the inability to identify the specific impact of climate change on specific ecosystems, and links potential changes to other important issues such as the wildland-urban interface. Some basic premises and then a short list of recommendations for research, education, and management follow the preamble.

Summary of Contents of the Declaration

Part One: Preamble

As scientists and land managers who focus on fire and its effects on natural ecosystems, we recognize that climate plays a central role in shaping fire regimes over long time scales and in generating short-term weather that drives fire events. The science surrounding human-caused climate change continues to strengthen, and the weather patterns that shape the ecosystems where we live and work may be altered dramatically over the coming decades. In anticipation of such changes it is important to consider how fire management strategies may enable us to respond to a changing global climate and thereby reduce potential disruptions to plant communities, fire regimes, and ultimately, ecosystem processes and services.

Currently, we are observing serious wildland fire conditions, such as increasing numbers of large and severe wildfires, lengthened wildfire seasons, increased area burned, and increasing numbers of large wildfires in fire-sensitive ecosystems (such as tropical rain forests and arid deserts). Recent research suggests that these trends are, in part, related to shifts in climate.

As temperatures increase, fire will become the primary agent of vegetation change and habitat conversion in many natural ecosystems. For example, temperate dry forests could be converted to grasslands or moist tropical forests could be converted to dry woodlands. Following uncharacteristic high-severity fires, seedling reestablishment could be hindered by new and unsuitable climates. Plant and animal species already vulnerable due to human activities may be put at greater risk of extinction as their traditional habitats become irreversibly modified by severe fire. Streams and fisheries could be impacted by changing climates and fire regimes with earlier peak flows, lower summer flows, and warmer water even if ecosystems don't burn. Finally, extreme wildfire events and a lengthened fire season may greatly increase the risk to human lives and infrastructures, particularly within the wildland urban interface.

We acknowledge that there are uncertainties in projecting local impacts of climate change. However, without taking action to manage fire-dependent ecosystems today and in the absence of thoughtful preparation and planning for the future, wildland fires are likely to become increasingly difficult to manage.

We, the members of the Association for Fire Ecology that endorsed this document at the Third International Fire Ecology and Management Congress, support the considerations outlined in this paper for planning and management to enhance ecosystem resiliency to wildland fire in a changing global climate.

Part Two: Background Premises

The second part of the declaration presents a number of premises that were the basis for the declaration. These premises begin with the acknowledgment of the role of fire as part of ecosystems as well as the historical disruptions of natural fire regimes. Additional premises address the potential impact of climate change on vegetation and the need to have proactive management programs to address climate change on ecosystems.

Both fire and climate regimes interact with other natural processes to direct the formation of vegetation in ecosystems. Given that climate and fire regimes are linked through vegetation, changes in climate can lead to large or small changes in fire regimes. Climate and fire regimes are also directly connected through the climate drivers of ignitions and fire weather. Climate influences both where and how vegetation grows and thereby creates the fuel conditions that drive fire frequency, intensity, severity, and seasonality. Precipitation and temperature patterns regulate the accumulation of fuels. In some ecosystems, wet years may promote "boom" vegetative (fuels) conditions, while drought years promote "bust" and the burning of the "boom" vegetation. Further, we know that the inevitable dry years, particularly when warm, are associated with larger fires, both in size and number, especially where fuel is abundant. Fire can also contribute to the problem of increasing green house gas emissions because it is a source of CO_2 and particulate emissions, which may affect local and regional air quality and worldwide climate.

Historical fire regimes have been disrupted in many ecosystems. Factors such as human activities and land development, loss of indigenous burning practices, and fire suppression have all led to changes in some plant communities historically shaped by particular fire regimes. Human activities have significantly increased the number of ignitions in many temperate, boreal, and tropical regions. Fuel loads have increased in some temperate forests where low intensity fires were historically the norm. In some rangelands, shrubs have been replaced by annual grasses or colonizing trees. Human-caused burning has increased fire frequency in some tropical regions where fire-sensitive ecosystems dominate.

Not all vegetation types have been significantly altered by fire suppression. Many shrubland ecosystems, such as California chaparral, burn with high severity under extreme weather conditions, and fire management in the 20th and 21st centuries has not appreciably changed their burning patterns. Coastal, mesic coniferous forests in the Northwestern United States have not been modified to a great extent by fire suppression policies because fire rotations in this area are much longer than the period of fire suppression. In other forests such as Rocky Mountain lodgepole pine, high severity fires every 100 to 300 years are ecologically appropriate, and fire suppression has probably not affected these ecosystems to a great extent. The ecosystems most impacted by fire suppression are forests that once experienced regimes of frequent, low-moderate intensity fires; these ecosystems are probably the most vulnerable to altered fire regimes from changing climates.

Approaches to restore fire-adapted ecosystems often require treatment or removal of excess fuels (for example, through mechanical thinning, prescribed fire, or mechanical-fire combinations), reducing tree densities in uncharacteristically crowded forests, and application of fire to promote the growth of native plants and reestablish desired vegetation and fuel conditions. Excess fuels are those that support higher intensity and severity fires than those under which the particular ecosystem evolved or are desired to meet management objectives. For example, in dry Western U.S. forests that once burned frequently, a high density of trees and a large surface fuel load often promotes crown fires that burn over large areas. Some of these same forests once flourished under a fire regime where frequent, nonlethal low-intensity surface fires were the norm, and large-scale crown fires were rare. Managers should determine if forests can be restored to what they once were or if another desired condition is more appropriate. If it is not appropriate to restore ecosystems to a previous condition because of expected novel climate conditions, then managers should develop new conservation and management strategies and tactics aimed at mitigating and minimizing uncharacteristic fire behavior and effects.

Climate change may interact with other human activities to further change fire regimes. For example, in much of the Western United States, since the 1980s, large fires have become more common than they were earlier in the century. This has often been attributed to increased fuel loads as a result of fire exclusion. However, a number of research studies suggest that climate change is also playing a significant role in some regions, elevations, and ecosystem types. In the Western United States, researchers recently identified an increase in fire season duration in mid-elevation forests. These changes were correlated with earlier spring snowmelt dates. With global temperatures projected to rise throughout this century, increases in fire season length and fire size can be expected to continue.

Climate change can lead to rapid and continuous changes that disrupt natural processes and plant communities. Are managers safe in assuming that tomorrow's climate will mimic that of the last several decades? Increased temperatures are projected to lead to broad-scale alteration of storm tracks, thereby changing precipitation patterns. Historical data show that such changes in past millennia were often accompanied by disruption of fire regimes with major migration and reorganization of vegetation at regional and continental scales. Exercises in modeling of possible ecological responses have illustrated the potential complex responses of fire regimes and vegetative communities. These exercises indicate that dramatic changes in fire regimes and other natural disturbance processes are likely. Indeed, some believe that the impacts of climate change may already be emerging as documented in widespread insect infestations and tree dieoffs across some areas in the Western United States and British Columbia, and more rapid and earlier melting of snow packs. Developing both short- and long-term fire and fuels management responses that improve the resilience of appropriate ecosystems while reducing undesired impacts to society will be critical.

Changes in climate may limit the ability to manage wildland fire and apply prescribed fire across the landscape. Under future drought and high temperature scenarios, fires may become larger more quickly and could be more difficult to manage. Fire suppression costs may continue to increase, with decreasing effectiveness under extreme fire weather and fuel conditions. In some temperate and boreal regions, it is expected that more acres will burn and at higher severities than historically observed. In humid tropical regions exposed to severe droughts, vast forests could burn making it difficult for forest managers to prevent farmers from entering destroyed forests and establishing new farms. Globally, new fire regimes would be associated with shifts in ecosystem structure and function and, likely, changes in biodiversity.

Approaches to fire management that recognize the potential for greater variability and directional change in future climates may help to reduce ecological and societal vulnerability to changing fire regimes. Such approaches are likely to improve fire management and ecosystem health. A goal could be to reduce the vulnerability, both ecologically and socially, to the uncertainties that accompany a changing climate. For example, if managers restore some forests as a means to increase ecosystem resiliency to climate change, they will also be improving biodiversity and protecting important forest resources. In the humid tropics, if managers make a concerted effort to prevent fire from entering rain forests during drought years, then they would be reducing the risk of future fires and illegal logging, even if droughts did not become more frequent and severe with a changing climate.

Part Three: Considerations for Management, Research, and Education

The last section of the declaration presents some specific recommendations or considerations for management, research, and education. Fuels management is an important part of the suggested activities, since it is with fuels management that we can remediate ecosystems from past fire regime disruptions while also preparing for changes in those same ecosystems as a result from climate change.

Recent changes in climate and fire patterns have been observed in many areas of the world, and current projections are that ongoing and long-term changes are likely. We believe that the actions outlined below could help managers to be better prepared to anticipate and mitigate potential negative effects of variable and changing future environments.

Fire and ecosystem management

- Incorporate the likelihood of more severe fire weather, lengthened wildfire seasons, and larger sized fires in some ecosystems when planning and allocating budgets, which traditionally are based on historical fire occurrence.
- Make use of both short-term fire weather products AND season-to-season and year-to-year climate and fire outlooks that are increasingly available from "predictive services" groups in Federal agencies, and particularly the sub-regional variations in anticipated fire hazards that enable strategic allocation of fire fighting and fire use resources nationally.
- Continually assess current land management assumptions against the changing reality of future climates and local weather events.
- Develop site-specific scenarios for potential weather events linked to climate change, and redesign fire management strategies to make room for rapid response to these events.

- Consider climate change and variability when developing long-range wildland fire and land management plans and strategies across all ownerships.
- Consider probable alternate climate scenarios when planning postfire vegetation management, particularly when reseeding and planting.

Fuels management

- Prepare for extreme fire events by restoring some ecosystems and reducing uncharacteristic fuel levels through expanded programs of prescribed burning, mechanical treatments, and wildland fire use to meet resource objectives. Burning under the relatively mild weather conditions of a prescribed fire produces lower intensity burns and, generally, less carbon emissions than would a fire burning under wildfire conditions. Burning and thinning treatments should be strategically placed on the landscape in locations where they are more likely to influence fire spread. Some ecosystems will continue to burn in high severity stand replacement fires, and this is appropriate for their sustainability.
- Incorporate emerging scientific information on the impact of changing temperature and precipitation on plant communities into fuels management project design and implementation at the local level.
- Expand wildland fire use at the landscape scale in fire-adapted ecosystems to restore fire regimes and reduce fuel loads. Be more aggressive in promoting fire use during lower hazard fire seasons, and fire use in landscapes that offer particular opportunities for relatively low-risk, large-scale burning. This will allow more acres to be burned under less extreme fire weather conditions than fires that might occur in the future under extreme heat or drought conditions.
- Control highly flammable nonnative plant species and develop management options to address their increased spread and persistence. In some ecosystems appropriately timed prescribed fires can be used to reduce nonnative species, while in others, continued fire exclusion may be the best management strategy. In some areas, reseeding and active restoration may be the best option.
- In some cases the removal and use of small diameter forest products (engineered lumber, pulp and paper, biofuels) and chipped fuels (for electrical energy generation) could be used to reduce fire hazards in appropriate vegetation types. Burning excess fuels in a cogeneration plant has the additional advantage of producing lower emissions when compared to prescribed fires.

Research, education, and outreach

- Implement long-term biodiversity and fuels monitoring programs in the fire-adapted ecosystems that are expected to undergo the widest range of change and variability linked to climate change, such as those that once experienced frequent, low-moderate intensity fire regimes.
- Expand interdisciplinary research to forecast potential fire season severity and improve seasonal weather forecasts under future climate change scenarios.
- Integrate the subject of climate change and its influence on ecosystem disturbance into curricula within natural resource management programs at the university and continuing education levels, and in science programs within primary schools.
- Disseminate information to the general public and government agencies regarding the potential impacts of changing climate on local natural resources and disturbance regimes, particularly those that interact with fire.

- Hold conferences or symposia to enhance communication among researchers and managers and to engage the general public in discussion on how best to adapt public land management to cope with fire in a changing environment.
- Form interdisciplinary teams of researchers that include fire ecologists and climate scientists to identify and pursue emerging areas of climate and fire research.

Conclusions

The San Diego climate change declaration was an attempt by AFE to enunciate how this issue may impact fire regimes across the country. The issue of global climate change will be in the forefront of worldwide discussions on land management for decades to come. For those of us involved in natural resource management, proactive management will be required to minimize the potential negative impacts of climate change. Fuels management is, and will be, one of the most important tools we have available. It is with fuels management that we can rectify the effects of past actions that resulted in modified fire regimes and restore both ecosystem sustainability and landscape-level processes. Fuels management will also give us the opportunity to mitigate potential negative effects of changing future environments.

References

Grissino-Mayer, H.D.; Swetnam, T.W. 2000. Century-level climate forcing of fire ergimes in the American Southwest. The Holocene 10:213-220.

Lefort, P.; Gauthier, S; Bergeron, Y. 2003. The influence of fire weather and land use on the fire activity of the Lake Abitibi area, eastern Canada. Forest Science 49:509-521.

Pinol, J.; Terradas, J.; Lloret, F. 1998. Climate warming, wildfire hazard and wildlfire occurrence in coastal eastern Spain. Climate Change 38:345-357.

Swetnam, T.W. 1993. Fire history and clamate change in giant sequoia groves. Science 262:885-889.

Williams, A.A.; Karoly, D.J.; Tapper, N. 2001. The sensitivity of Australian fire danger to climate change. Climate Change 49:171-191.

This page is blank on purpose

Analysis of the Risk Management Decisionmaking Processes and the Decision Support Systems in the Wildland Fire Agencies

Patrick Withen[1]

***Abstract**—This paper offers an analysis of the strengths, weaknesses, opportunities, and threats in the risk management process, decision support systems (DSSs), and other types of decisionmaking, including recognition primed decisionmaking, bricolage with the goal of improving DSSs and decisionmaking. DSSs may be thought of as any technology or knowledge that is used as an aid in decisionmaking. Many types of risk management processes and DSSs exist in wildland fire, wildland fire, and prescribed fire at the tactical, operational, and strategic levels. In the wildland fire community, DSSs exist as check-lists, handbooks, implementation guides, computer programs, and more. Many wildland fire suppression agencies and other high reliability organizations have embraced what may be called a rationalistic based decisionmaking process in the form of risk management, programmed decisions, and more. Critics charge that while an attempt is made to rationalize decisions, many "judgments" within the rationalistic systems reduce their logic, making their rationality questionable. While rationalistic based decisionmaking processes exist at all levels of the fire suppression agencies, naturalistic decisionmaking is found primarily at the tactical level in the form of recognition primed decisionmaking, or bricolage. Many argue that the risk management decisionmaking school of thought is contraindicated by the naturalistic decisionmaking school of thought. Finally the role of DSSs in the naturalistic and rationalistic based decisionmaking is explored.*

Introduction

This paper is based on the premise that the decision support systems (DSSs) used in wildland fire suppression should be integrated so that they function optimally together in a seamless manner. Ultimately this type of integration would begin to integrate the DSSs and their uses at the tactical, middle, and strategic levels of action. DSSs may be thought of as any technology or knowledge, whether in a material or immaterial form, that is used as an aid in decisionmaking. Many types of DSSs exist in wildland fire, wildland fire use, and prescribed fire at the tactical, middle, and strategic levels. In the wildland fire community, DSSs exist as check-lists, handbooks, implementation guides, computer programs, and more.

The decision support systems examined here include the 59 fire guidelines (which include the 10 Standard Firefighting Orders, the 18 Watch Out Situations, the seven Downhill Line Construction Checklist, the four Common Denominators of Fire Behavior on Tragedy Fires, the seven Look Up, Down & Around Factors, the four LCES Components, and the nine Wildland Urban Watch Outs) and the Region 4 Incident Organizer (Version 2004). It is believed that these DSSs (the 59 fire guidelines and the incident organizer) should be integrated with the basic components of an incident

In: Butler, Bret W.; Cook, Wayne, comps. 2007. The fire environment—innovations, management, and policy; conference proceedings. 26-30 March 2007; Destin, FL. Proceedings RMRS-P-46CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 662 p. CD-ROM.

[1] McCall Smokejumpers, U.S. Department of Agriculture, Forest Service, McCall, ID, and University of Virginia at Wise, Department of Social Sciences, Wise, VA. pwithen@virginia.edu

action plan (IAP), the Wildland Fire Use Implementation Procedures Reference Guide, and the proposed new fire doctrine. These documents provide the entire spectrum of rules and strategies that guide the fire and fire use communities. Despite the fact that such a large-scale project is beyond the scope of this paper, it is nevertheless important to address the issue of a "full spectrum" of integration of DSSs because they operate at all levels of action from the tactical level, to middle level, to the strategic level. They operate on all sizes of fire and fire use. The levels operate independently of each other, in other ways they are closely tied together, and an action or aim at one level may impact one or more of the other levels. So while this project is just beginning the discussion of the integration of rules, actions, and aims, the integration proposed here is only part of the picture, and it must be taken in a context of all levels of action and all levels of DSSs.

The need for the integration of the DSSs and planning and action at the tactical, middle, and strategic levels can be seen in two manners. First, the examination below will demonstrate that the 59 fire guidelines and the typical incident organizer (IO) (as well as the typical IAP, WFU Guide, and other DSSs not covered here) do not have any overlap written into them, and yet conceptually they have much in common. Second, Vergari demonstrated in "Back to Basics for Fire Program Managers" (2005) that there is little consistency in the manner in which firefighters plan and act, and also that there is a wide variance of understanding and usage of tactics, objectives, and strategies. The present study attempts to integrate two DSSs, the 59 fire guidelines, and the typical IO, in order to gain efficiency and effectiveness by allowing the overlap between the DSSs to create a more seamless operating tempo, by gaining consistency in operation, and by integrating tactical, middle, and strategic level planning through a common body of DSSs.

Because the DSSs have never been integrated, this analysis will address only some of the possibilities in integrating the documents. First the integration of the 59 fire guidelines and the incident organizer will be presented.

Information Overload

The very necessity of using checklists, shortcuts, handbooks, DSSs, and so forth demonstrates that there are innumerable factors impacting any given situation on the fireline. And because the environment is turbulent—that is, changing rapidly in real time—the factors impacting fireline situations also change rapidly. Furthermore, while there are innumerable factors impacting a typical situation on a fireline, in a crisis situation, with the additional factors that arise, the number of factors interacting becomes infinite in a practical sense.

In other words, the fireground and the firefighter training—factors creating an extremely large body of situational knowledge and background knowledge—are both capable of creating information overload on the fireline. Some people use the existence of information overload to argue that a development of integrated, comprehensive DSSs or standard operating guidelines (SOGs) is impossible. Their solutions lie in either eschewing rational decisionmaking (for recognition primed decisionmaking, RPDM, or bricolage) or in standing by the status quo. I contend that it is quite possible to overcome information overload, and that integrated and systematized DSSs can operate well using the decisionmaking styles of risk management, RPDM, or bricolage.

However, there are principles of information organization that need to be looked at.

Standard Operating Guidelines

Recently, I presented work consolidating the 59 fire guidelines into the 10 essential factors in (wildland) firefighting (TEFF). The TEFF consolidated 59 firefighting guidelines, including the 10 Standard Firefighting Orders, the 18 Watch Out Situations, the seven Downhill Line Construction Checklist, the four Common Denominators of Fire Behavior on Tragedy Fires, the seven Look Up, Down & Around Factors, the four LCES Components, and the nine Wildland Urban Watch Outs, into 10 essential factors in wildland firefighting. (See appendix A for more on the TEFF.) The principles behind the development of the TEFF are important in understanding both the purpose and the functioning of an integrated set of DSSs. As was reported in the TriData studies (1998) after the South Canyon Fire of 1994, firefighters and fire managers do not believe any more checklists or other DSSs are needed. Despite this, rules and guidelines have continued to grow. As a result of the 30 Mile Fire, Incident Organizers and other documents and procedures have been changed and expanded. It is not clear what changes will occur as a result of the Cramer Fire, and all the implications of the 30 Mile Fire have not yet played out. And it is likely that tactical level rules and guidelines will continue to growth despite the pleas to the contrary. The analysis presented here holds that the solution to this problem is not to force a moratorium on guidelines, but rather it is to systematize and organize them in order to eliminate fluff, redundancy, and confusion and replace them with a tighter, more efficient system. Ultimately that system would develop from what it is now, a series of "orders," "watch outs," "checklists," "common denominators," and so on, and replace them with standard operating guidelines (SOGs) that direct flexible action with greater clarity than currently exists. An example of the weakness of the current system can be seen in the debate within the wildland fire community that occurred in the years following South Canyon over whether the fire orders were in fact invioble orders or whether they were simply guidelines. (No clear policy directive on this debate was ever reached even though consideration of it occurred in the upper echelons of the firefighting community.) A clear set of SOGs would end such a debate because they would clearly state where a standard operating procedure functioned and where it did not. And as discussed at the end of this document, there are methods for addressing situations where SOGs usefulness ends.

While the principle of establishing SOGs is not the focus of this paper, the integration of the 59 fire guidelines, the IO, and other DSSs is a step in that direction. And both SOGs and the integrated DSSs aim to systematize and standardize planning and action, as well as offer an aid to dealing with information overload.

Nesting

The TEFF consolidated the 59 fire guidelines into just 10 factors or guidelines that the firefighter on the ground needs to follow. The TEFF was designed so that if firefighters notice or sense that there is a problem meeting the requirements of an individual TEFF, then they need to refer to the numerous rules that resulted in the formulation of that individual TEFF. For example, if a firefighter notices that communications are problematic, under a fully developed TEFF system, the firefighter might refer to any or all of the appropriate former guidelines such as Fire Order 7: Remain in communication w/ crew members, your supervisor, & adjoining forces; or Fire Order 8: Ensure instructions are given & understood; or Watch Out 5: Uninformed on strategy, tactics, & hazards; or Watch Out 6: Instruction & assignments not clear;

or Watch Out 7: No communication link w/ crew members or supervisor; or Downhill Line Construction Rule 3a: Crew supervisor is in direct contact w/ lookout who can see the fire; or any of a total of nine fire guidelines dealing with communications that are scattered throughout the 59 fire guidelines. In addition, as my analysis of the 59 fire guidelines demonstrated, there are also gaps and omissions of common situations, indicating that there may need to be new tactical guidelines added to any comprehensive curriculum on tactics and tactical DSSs.

The principle demonstrated here is that, like the TEFF, the DSSs are always shortcuts with a large body of knowledge, or rules, behind them. Large amounts of knowledge are nested within shortcut guidelines such as the TEFF, the Fire Orders, and many other fireline guidelines. Thus, under the proposed new system of integrated DSSs and SOGs, no information is lost, it is only organized or nested for easy access.

Hierarchicization

The existence of information overload and the necessity of nesting that information implies that information must be arranged in a hierarchy—in other words, that some information is more important than other information. The principle of hierarchy implies that the firefighting community must decide the best short-hand methodology and terminology for its DSSs so that general categories are examined first, and then as they either become problems or enter into the risk management decisionmaking process, the information that backs them up would become apparent.

Status of Information Use

If these principles of standardization, nesting, and hierarchicization were firmly established in wildland fire, then both the curriculum and the DSSs that attempt to summarize the curriculum would be arranged so that firefighters could address problems with the most general rules, and then address finer points by moving into the more detailed levels of the nested hierarchy of information.

Returning to the example of the firefighter who notices that communications are problematic: if that firefighter had a DSS, backed by a parallel training curriculum, she or he would examine that problem in a similar manner to any other firefighter and presumably in a more efficient manner than a firefighter would today. My research confirms Vergari's (2004) contention that there are only minimal *standard* operating procedures in that most firefighters report that they rarely refer to any of the Fire Orders, Watch Outs, or any of the other fire guidelines or DSSs, and that they interpret and utilize them in different manners. Most firefighters have their own personal "core" of the 59 fire guidelines that they use regularly. Any of the DSSs or anything that looks like a SOG is only referred to when there is some minor or major crisis that makes a decision difficult.

Today none of the DSSs are good examples of dealing with information overload, standardization, nesting, or the hierarchicization of knowledge. The existence of 59 fire guidelines that have been compiled over the entire history of modern wildland fire suppression, the fact that many locales have their own model of an incident organizer, their own model of an IAP, or their own model of a Fire Plan, and the fact that locales are left to interpret strategic direction in such a way that results in different policies all demonstrate that there is little coordination in the wildfire suppression community.

Integrating the Fire Guidelines and the Incident Organizer

How might the 59 fire guidelines and the incident organizer be integrated? First, many IOs today are designed to meet 30 Mile Accident Prevention requirements. This is fine, but in the interest of integration, the 30 Mile Accident Prevention requirements should not be the center around which an IO is formulated. Below are some suggestions as to how IOs and the 59 fire guidelines might be improved through integration, standardization, recognizing information overload, nesting, or the hierarchicization of knowledge.

Because the curriculum of fire training is not nested or hierarchicalized, the fact that the 59 fire guidelines and the IOs are not nested or hierarchicalized is not readily apparent. Firefighters have not been trained to think or operate based on any hierarchy of knowledge or SOGs. This point is important for the following analysis because the integrations proposed here would be much more valuable if firefighters were trained in a manner that encouraged the use of SOGs, nested knowledge, and hierarchicalized knowledge. This analysis' proposal for the integration of all DSSs, for the integration of tactical, middle, and strategic level planning and action implies that such an integration of all firefighter training would also prove valuable. In fact, the wildland fire agency's development of a new foundational doctrine is a good beginning.

Currently the organization of the IO is accomplished in 14 sections:

1. size up
2. resource summary
3. objectives
4. organization
5. map sketch
6. radio frequencies
7. risk management
8. decision points
9. risk analysis
10. incident complexity analysis
11. summary of actions
12. spot weather forecast
13. work rest ratio documentation
14. the after action review

Most IOs begin appropriately with a fire size up section. The size up should clearly be divided into two segments: the physical fire size up, and the resource size up. Currently this is done in section 1: the size up; and section 2: the resource summary. Some of the information about resources is done in its own section and is not seen as part of the size up. Some of the fire size up is done in section 10: the incident complexity analysis; and section 12: the spot weather forecast. It is important to integrate the fire and resources size up so that the incident commander (IC) and firefighters start their planning based on what they can do, rather than simply on what needs to be done. This ties both the IO and the incident's plan to the strategic plans of the administrative unit under which this fire suppression effort is operating in that the IC may request more resources, but the fire program manager (FPM) may want to allocate those resources to another incident. The pairing of the fire situation with the available resources establishes the idea that a safe incident is one that accomplishes what it can with the available resources. It is felt that this would minimize any chance of "over-zealousness" as spurious as that argument was.

The fire size up itself should be divided into clear segments that address the TEFF factors of fire behavior, fire status, fuel type, weather, and terrain. In combination, these five factors represent more than 40 fire guidelines including some of the Fire Orders, Watch Outs, Urban Watch Outs, and others. This focuses the firefighters' thinking in terms of these five critical factors related to the physical fire, and should be accompanied by a similar focus on the fire guidelines that apply to these critical physical fire factors.

A radical change from current practice would have the IC, or the person filling out the size up, indicate both current conditions, *as well as expected conditions.* While admittedly this is not standard practice today, training firefighters to track specific conditions and to tie these conditions to the 59 fire guidelines and the IO would integrate the practice of tracking trends, tying trends to specific actions on the fireline, and to link both of these to the incident's plan in the form of the newly integrated IO. Tracking conditions is inherently part of the risk management process in that one is to engage another iteration of risk management any time conditions change, whether these be physical or firefighting resource conditions on the fireground. The 59 firefighting guidelines also inherently require trend tracking in, for example FO 3: Base all action on current and expected fire behavior; Downhill Line Construction Guideline 7: Bottom of the fire will be monitored; if the potential exists for the fire to spread, action will be taken to secure the fire edge; WO 11: Unburned fuel between you & fire; and more. Tracking conditions on the fireline is another DSS schema to encourage firefighters to link SOGs, conditions, and tactics (or actions). An example of one possible method to track trends can be found in appendix A: "Side 1 of the TEFF card."

As discussed above, section 2: the Resource Summary should be part of the initial size up in order to facilitate the standard procedure of establishing a plan that fits the resources. This should emphasize the principle that the IC and the firefighters need to be aware of the situation and the resources that they have to deal with that situation. The Resource Summary should divide resources into the categories of those actually on scene, those assigned to the incident but not yet on scene, and resources who are unfilled requests. Again the purpose is to emphasize the importance of ingraining into the thinking of firefighters the necessity of matching plans and tactics to resources. My analysis of the 59 fire guidelines, and the development of the TEFF indicate that the fire guidelines, as currently constructed, do not emphasize the necessity of matching tactics to available resources unless one counts "Fight fire aggressively, but provide for safety first." There are six other fire guidelines that refer to firefighting resources (see appendix A), such as FO 9: Retain control at all times. And all of the other resource oriented fire guidelines, as currently constituted, refer to controlling people, and not to matching available resources to tactics. This is one of the critical lapses in our fire fighting guidelines that have resulted from the haphazard development of these guidelines, SOGs, over the decades of modern fire suppression.

Next in the IO is the tactical planning section. The tactical planning section might include the already existing section of Incident Objectives, the Incident Organization, the Map, and Radio Frequencies. Following that, in the existing IO are the sections on Risk Management & Decision Points, Incident Risk Analysis, Incident Complexity Analysis. These sections should be integrated in a different manner in order to solidify the linkages between the fire guidelines, which are the best axioms that we have for SOGs, tactics, and decisionmaking.

Note that while IOs could be reformulated in such a manner as to integrate in SOGs, this analysis focuses only on integrating in the DSSs that we have: the 59 firefighting guidelines and the IO.

In the present IO, the first Incident Objective is written in: SAFETY of firefighters and public. After that, the IC is free to enter in one or more objective of her or his own. Because it was not their original intended purpose, there are no specific objectives written into the current firefighting guidelines; however, some objectives are implied in WO 8: Constructing line without safe anchor point; WO 9: Building fireline downhill with fire below; and several implied objectives in the Downhill Line Checklist. These firefighting guidelines imply a direct or indirect line placement objective. Thus, the current firefighting guidelines are noticeably lacking in supporting the development of objectives. The generalist nature of all the current firefighting guidelines fails to provide clear direction for the setting of objectives that make it clear that, while these guidelines do present the firefighter with the possibility of information overload, they are nonetheless incomplete. While the current 59 firefighting guidelines do not address incident objectives, incident objectives are perhaps the most important single factor impacting firefighter safety. Safe objectives make for safe operations.

Next in the current IO is the Risk Management & Decision Points, Incident Risk Analysis, Incident Complexity Analysis. These sections have many facets that strongly imply, but do not make, connections to the 59 firefighting guidelines and other DSSs, especially the Incident Response Pocket Guide (IRPG 2006). For example, in the Decision Points Section, firefighters are asked to confirm that "Controls in place for identified hazards?" Here is the connection to the 59 firefighting guidelines that could be made more apparent, nested, and hierarchicalized. The Incident Risk Analysis (215a) has a similar connection that needs to be integrated with the 59 firefighting guidelines in that certainly some of the Fire Orders, nearly all of the Watchouts, as well as many others may be applied here under the rubric in the Incident Risk Analysis of "Hazardous Actions or Conditions."

In the Incident Complexity Analysis (Type, 3, 4, 5) many of the 59 firefighting guidelines can be implied, but none are directly referenced. For example, under the sub-section Fire Behavior, one of the components is "Weather forecast indicating no significant relief or worsening conditions." This component of the IO is represented in several of the weather related 59 firefighting guidelines such as FO 1: Recognize current weather conditions & obtain forecasts; WO 14: Weather becoming hotter & drier. WO 15: Wind increases and/or changes direction; CD 3: When there is an unexpected shift in wind direction or in wind speed; UW 8: Strong winds. Certainly the references to weather could be improved in both the IO and the 59 firefighting guidelines. Many other components in the IO Fire Behavior section and sub-sections could be more effectively integrated with the 59 firefighting guidelines creating a seamless set of DSSs.

While many of the components of the IO Incident Complexity Analysis are closely related to the DSS of the 59 firefighting guidelines, there are also components of that are not found in the those guidelines, and probably should be. For example, the sub-section Firefighter Safety has three components: (a) Performance of firefighting resources affected by cumulative fatigue; (b) Overhead overextended mentally and/or physically; (c) Communication ineffective with tactical resources or dispatch. The only firefighting guideline referred to here is, possibly, WO 18: Taking a nap near the fireline. This demonstrates again that the current 59 firefighting guidelines are incomplete. And perhaps in an integrated set of DSSs, these factors would be addressed more effectively.

The Decisionmaking Process

Inherent in the argument for a seamless integrated set of DSSs that function to integrate tactical, middle, and strategic planning and action is an argument for a particular type of decisionmaking. Recent discussions within the wildland firefighting community have often implied that rational decisionmaking, such as that found in the risk management decisionmaking process, is inadequate. Many wildland fire suppression agencies and other high reliability organizations have embraced naturalistic decisionmaking, often specifically in the form of recognition primed decisionmaking (RPDM) (Klein 1993) and bricolage (Weick 1993, 2001) wherein the decisionmaker's expertise allows him or her to make the correct decision. RPDM is a method of decisionmaking wherein the decisionmaker utilizes a first impression, through intuitive or blink decisionmaking, to develop an alternative that is then analyzed to develop the final decision that is implemented. Weick holds that the bricoleur demonstrates intimate knowledge of the situation, makes careful observations, listens, trusts her or his ideas, and proceeds while being open to feedback.

On the other hand, one of the primary models of decisionmaking used by wildland fire suppression agencies is the risk management. The risk management process is listed on page 1 of the Incident Response Pocket Guide (USDA 2006). Many argue that the risk management decisionmaking school of thought is contraindicated by the naturalistic decisionmaking school of thought. However, this is not the case. I contend that all of these widely varied decisionmaking systems can, and indeed do, work together in a manner that is beneficial to all. The system proposed here is one that would employ a seamless set of DSSs, SOGs and the risk management process of decisionmaking to plan and act on fires at the tactical, middle, and strategic levels. RPDM and bricolage are in many ways based on this system in that, however different, they take as their starting point the examination of excellent decisions made by accomplished actors. While standard operating procedures as embodied in DSSs and SOGs are designed to address all contingencies, in practice this is impossible. When standard models reach their limits, when as Weick (1993) calls it, there is a "collapse of decisionmaking," RPDM and bricolage are useful decisionmaking strategies.

As discussed above, the line between the use of the risk management process and RPDM and bricolage appears clear. However, the distinction is seldom clear in practice. Utilizing Weber's analysis of the types of rationality (1948), RPDM and bricolage operate via substantive rationality, which is the dominance of norms and values in the rational choice of means to ends. Substantive rationality creates the ability to draw on norms and values to make decisions and to motivate people to behave in a rational manner. The values and norms (social rules) used by RPDM or the bricoleur are effectiveness and success. The risk management decisionmaking process operates via intellectual rationality, also known as instrumental rationality or the rational cognitive process, which is the ability to utilize people's rational problem solving capacities. In practice most people rely on several decisionmaking processes at once. For example, in the risk management process in the situation awareness sub-process, one is to judge fire behavior. Because of the state of fire behavior analysis on the fireline today, most firefighters make their best estimate of that fire behavior, thus employing substantive rationality within the process of instrumental rationality. The people who successfully use RPDM or bricolage successfully are usually accomplished in their field. Thus, they have employed instrumental rationality many times, and it is based on this unquantifiable body of expertise that they make their substantive decisions.

In figure 1, Legarza (2006) exemplifies the situations firefighters find themselves in. The DSSs, SOGs, and instrumental rationality in the form of the risk management process, operate best in the zone of optimal performance, that is, between the dashed red lines. The ultimate goal of the DSSs, SOGs, and instrumental rationality must be to expand the area between the dashed red lines. But as Legarza recognizes, because firefighters are operating in a turbulent, high tempo environment, even if firefighters do everything right, they may find themselves outside of the zone of optimal performance. Then one has the option: (1) use one's training and education to gain the awareness or choices one needs to return to normal operations, or (2) operate on instinct, using one's best estimate, possibly using RPDM or bricolage, to choose a path of operation. Killion (2000) notes that RPDM can also be used by those with a large reservoir of experience to make decisions more quickly than would be possible using what he calls multiattribute decisionmaking, which is a form of instrumental decisionmaking similar to the risk management process.

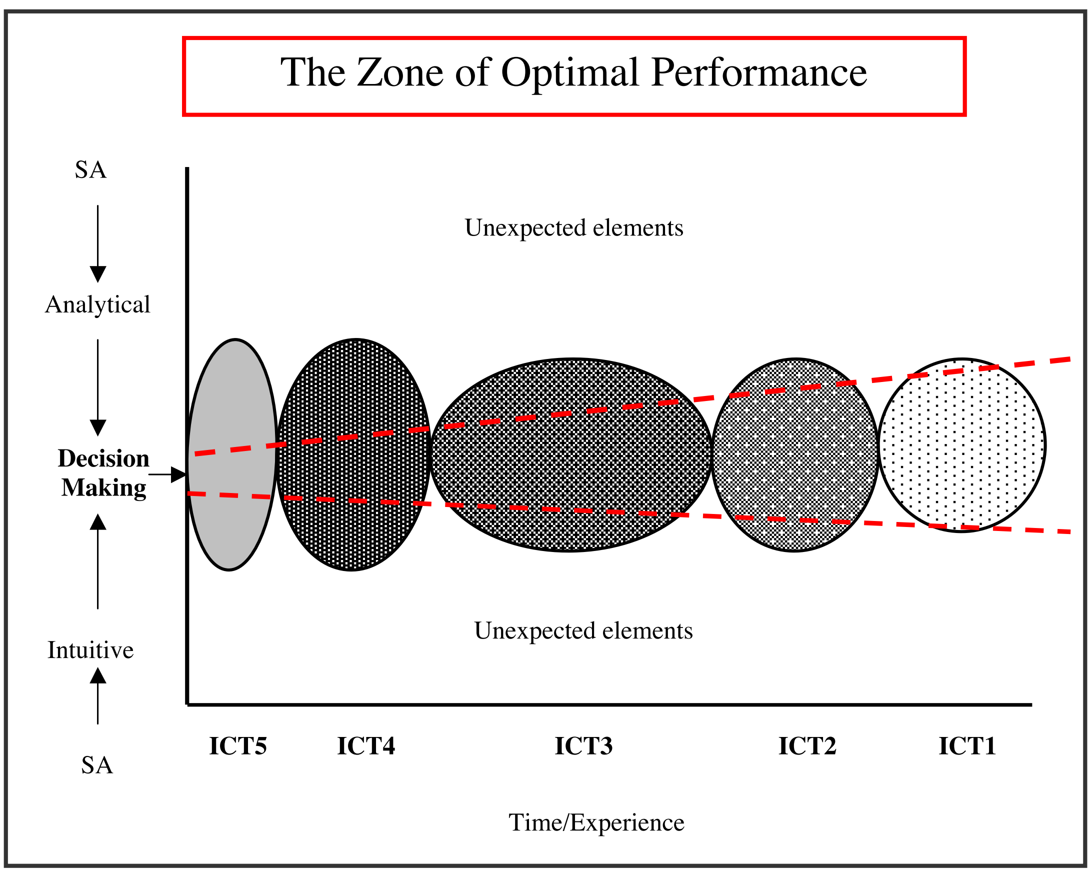


Figure 1—The Zone of Optimal Performance occurs in the middle of each circle, respectively, inside of the dashed red lines. @Legarza

The importance of understanding these varied decisionmaking processes is that in the development of DSSs, decisionmaking skills, plans of action, and so forth, it is useful for actors to understand how and why they are making particular decisions based on particular decisionmaking schemas. As we train and educate ourselves and others in fireline decisionmaking, we must realize that we can move ahead on several fronts. We can move ahead in the integration of the DSSs, and we can move ahead in advancing the skills of RPDM and bricolage.

References

Gerth, H.H.; Mills, C. Wright. 1948. From Max Weber: Essays in Sociology. London: Routledge.

Killion, Thomas H. 2000. Military Review. November-December: 66-70.

Klein, G.A. 1993. A Recognition-Primed Decision (RPD) Model of Rapid Decision making. In: Decision Making in Action: Models and Methods. Norwood, NJ: Ablex Publishing.

Legarza, Shawna. 2006. The Zone of Optimal Performance. Unpublished manuscript.

TriData Corporation. 1998. Wildland Firefighter Safety Awareness Study: Phase III—Implementing Cultural Changes for Safety. Arlington, VA: TriData.

U.S. Department of Agriculture. 2006. Incident Response Pocket Guide. PMS #461, NFES #1077. Boise, ID: National Interagency Fire Center, National Wildfire Coordinating Group.

Vergari, Greg. 2005. Back to Basics for Fire Program Managers. Eighth International Wildland Fire Safety Summit, April 26-28, 2005, Missoula, MT.

Weick, K. 1993. The Collapse of Sensemaking in Organizations: The Mann Gulch Disaster. Ithaca, NY: Administrative Science Quarterly. 38: 628-652.

Weick, K.; Sutcliffe, K. 2001. Managing the Unexpected. San Francisco, CA: Jossey-Bass, Inc.

Withen, Patrick. 2005. TEFF: The Ten Essential Factors In Firefighting: Lookouts, Communications, Escape Routes, Safety Zones, Firefighting Resources, Fire Behavior, Fire Status, Fuel Type, Weather, Terrain (LCES FFFF WT). Eighth International Wildland Fire Safety Summit, April 26-28, 2005, Missoula, MT. http://www.myfirecommunity.net/documents/Withen.pdf

Appendix A: TEFF—The Ten Essential Factors in Firefighting

This table shows the breakout of the 59 firefighting guidelines within TEFF.

TEFF	**Number of firefighting guidelines included**
1. Lookouts	5
2. Communications	9
3, Escape Routes	4
4. Safety Zones	4
5. Fire Resources	7
6. Fire Behavior	6
7. Fire Status	10
8. Fuel Type	7
9. Weather	8
10. Terrain	10
Total	**70 (some guidelines appear in more than one TEFF)**
Average	**7 per TEFF**

Definitions of the factors listed above:

TEFF 1: Sufficient **Lookouts** are in place given the hazard assessment.

TEFF 2: Sufficient **Communications** are in place: generally communications are needed w/ lookout(s), crews, supervisors, & adjoining forces, but there may be other critical links.

TEFF 3: A suitable **Escape Route**(s) is known to all.

TEFF 4: A suitable **Safety Zone**(s) is known to all. The Safety Zone may be to exit the fire area.

TEFF 5: While more **Firefighting Resources** may be on order, Firefighting Resources are sufficient for firefighters to remain safe & to successfully implement current tactics.

 Factors over which you have total or limited control.

 Factors over which you have no control, but must monitor.

TEFF 6: **Fire Behavior** is understood in light of Weather, Terrain, & Fuel Type. Fire behavior is not doing anything unexpected, thus Firefighting Resources' tactics are succeeding as expected.

TEFF 7: The **Status or Scope of the Fire** is known to Firefighters, & current tactics are successful in light of amount of Firefighting Resources & to keep current Firefighters safe.

TEFF 8: **Fuel Type** is understood, and is exhibiting expected Fire Behavior

TEFF 9: The **Weather** is doing what is expected; no RH or wind trigger points have been crossed.

TEFF 10: The **Terrain** is not causing unexpected fire behavior, creating a hazard for Firefighting Resources, or compromising the Escape Route.

Side 1 of the TEFF card, which provides a matrix:

	Ten Essential Factors in Firefighting (TEFF)	Good			Trends Matrix Medium					Extreme
		1	2	3	4	5	6	7	8	9
L	Lookouts									
C	Communication									
E	Escape Routes									
S	Safety Zones									
Fr	Firefighting Resources									
Fb	Fire Behavior									
Fs	Fire Status									
Ft	Fuel Type									
W	Weather									
T	Terrain									

Side 2 of the TEFF card, which provides a brief overview of Fire Suppression Tactics trisecting them into Engagement, Modification, and Disengagement:

	Fire Suppression Tactics Guide	
Engagement		Send Comments on TEFF to Patrick Withen
Anchor & Flank		McCall Smokejumpers, PO Box 1065,
Direct Attack		McCall, ID 83638 Cell: 276-275-1927
Frontal Assault on Head		pwithen@virginia.edu www.fireworld.info
Indirect	**Modify**	
Backfire/Burnout	Change Engagement Tactics	
	Pull Back to better line location (indirect)	
	Consolidate Forces	**Disengagement**
	Hold, Improve, Reinforce	Pull back closer to safety zone & break
	Patrol, Hold what you have	Retreat
		Evacuate
		Last Resort

Appendix

This
page is
blank
on purpose

Appendix: Presentations for Which Papers Were Not Submitted for These Proceedings

Invited Speakers

Susan G. Conard, USDA Forest Service, Washington Office
Joe Ferguson, USDA Forest Service, Washington Office
Michael C. Long, State Forester, Florida
William F. Paleck, USDI National Park Service, retired
Sally Shaver, U.S. Environmental Protection Agency, North Carolina
Karl E. Weick, Professor of Organizational Behavior and Psychology, University of Michigan, Ann Arbor

Panels

Extreme Fire Behavior—What is It?
Moderator: Robert Ziel, Michigan Department of Natural Resources
Panelists: Jack Cohen, Research Forester, USDA Forest Service Research
Mark Finney, Research Forester, USDA Forest Service Research
Brian Potter, Research Meteorologist, USDA Forest Service
John Saltenberger, Fire Weather Program Manager, Northwest Interagency Coordination Center
Tim Sexton, Wildland Fire Use Program Manager, USDA Forest Service

The Human Element in Forest Fire Operations: Thinking, Deciding, Acting, Learning
Moderator: Dave Thomas, Consultant, Renoveling; USDA Forest Service (retired)
Panelists: Riva Duncan, Deputy Forest Fire Management Officer, USDA Forest Service
Paula Nasiaka, Center Manager, Wildland Fire Lessons Learned Center
Larry Sutton, Fire Operations Risk Management Officer, USDA Forest Service
Jennifer Thackaberry Ziegler, Assistant Professor, Purdue University
Karol E. Weick, Professor, Organizational Behavior and Psychology, University of Michigan

Workshops

Fire Regime Condition Class: Concepts, Methods, and Applications
Stephen Barrett

WindWizard: A New Tool for Fire Management Decision Support
Rick Stratton, Jason Forthofer, Kyle Shannon

BehavePlus Fire Modeling System
Patricia L. Andrews, Tobin Kelley

Mapping Fire Regime Condition Class: Using LANDFIRE Data and the FRCC Map Tool
Wendel Hann, Morgan Pence

Use of FlamMap for Fire and Fuels Planning
Mark A. Finney, Rob Seli, Rick Stratton

FLAME, Fire Science for the Fireline
Jim Bishop

From Start to Finish: Creating an Effective Outreach Program for Educators
Christine Denny

FireFamily Plus
Larry Bradshaw, Stuart Brittain, Luck Shelvan

Advanced Meteorology for Fire Behavior Analysis
John Saltenberger

Smoke Monitoring Techniques
Andy Trent

Measuring Canopy Fuels and Assessing Crown Fire Potential
Joe Scott, Elizabeth Reinhardt

The Canadian Forest Fire Danger Rating System: Interpretation and Implementation Outside of Canada
Mike Wotton, Nathalie Lavole, Grant Pearce

A Suite of Fuel of Fuel Management Tools: Fuel Characteristic Classification System, Natural Fuels Photo Series, and Consume 3.0
Roger D. Ottmar, Susan J. Prichard, Clint S. Wright, Bob Vihnanek

BlueSkyRains
Miriam Rorig, Sim Larkin, Robert Solomon

Oral Presentations

Evaluating the Benefits and Costs of Project Level Fuel Treatments
Karen Abt, Alan A. Ager, Robert J. Haggett Jr., Eric D. Twonbly, Jeffrey P. Prestemon, Mark Finney, Aaron M. Ortego

A Fire Spread Model for Calculating Emissions Productions from Prescribed Burns
Gary Achtemeier

Evaluation of Methods to Represent Local Winds in Mountainous Areas of Eastern United States in Support of Prescribed Burning and Wildfire Suppression
Gary Achtemeier, Warren E. Hellman, Scott Goodrick, Joseph J. Charney, Bret Butler, Xinndi Bian

Field Validation of a Model to Predict the Movement of Smoke Along the Ground at Night
Gary Achtemeier

On the Roles of Prescribed Burn "Engineering" on Degraded Air Quality Over an Urban Area of 18 March 2006—Experimental Results with Daysmoke
Gary Achhtemeier, Scott A. Goodrick, Yongqiang Liu, William Jackson

Fire Emissions, Regional Haze, and Air Quality in the Upper Midwest
Gordon Andersson

Examination of Fire Behavior and Fire Danger Rating Systems in the Context of a Temporal-Spatial Framework
Patricia L. Andrews

National Wildland Fire Weather Needs Assessment
David Andrus, Samuel P. Williamson, Robert J. Dumont

Smoke on the Horizon—The Future of the Partnership
Chadwick Avery

Getting Fire on the Ground
J.J. Bachant-Brown

Factors Influencing Ponderosa Pine Seedling and Sapling Mortality after Prescribed Burns in the Black Hills, South Dakota
Mick Battaglia, Frederick W. Smith, Wayne D. Shepperd

Prescribed Burning Impacts on Urban Air Quality
Karsten Baumann, Eric S. Edgerton, Sangill Lee, James J. Schauer, Donald R. Blake, Luke P. Naeher, John J. Brent

Assessing High Reliability Practices in the Wildland Fire Community
Anne Black, Michhelle Barton, Deirdre Dether

Prescribed Fire Lessons Learned Center
Anne Black, Paula Nasiatka, Deirdre Dether

The Nez Perce Tribe Go/No-Go Decisionmaking Process
Andrea Boyer

FireFamily Plus, Version 4
Larry Bradshaw

What is a Fond? And Why Does it Burn GREEN!
James Brenner, Tim Elder, Deborah Hanley

A Climatology of North American Fire Danger from the North American Regional Reanalysis Dataset
Timothy Brown, Matt Jolly, Beth L. Hall

Verification of North Carolina Mixing Height Forecasts for Smoke Management
Timothy Brown, Gary Curcio, Beth L. Hall, Doug Pibal

What is the Value of Climate Information for Smoke Management?
Timothy Brown, Pete Lahm

Future Range of Variability: Landscapes as Probabilities
Teresa Burcsu, Miles A. Hemstrom, James Merzenich, Allison Reger

External Human Factors in Incident Management Team Decisionmaking
David Calkin, Janie C. Canton-Thompson, Krista M. Gebert, Brooke Y. Thompson, Geoffrey H. Donovan, J. Greg Jones

Improving Calculation of Values at Risk for Burned Area Emergency Response
David Calkin, Kevin Hyde, Peter Robichaud

Wildland Fire Decision Support System and Rapid Assessment of Values at Risk
David Calkin, John Szymoniak, Mark Finney, Kevin Hyde

Field Evaluation of a Next-Generation Dead Fuel Moisture Model versus Currently Used Dead Fuel Moisture Algorithms in the National Fire Danger Rating System
J.D. Carlson, Larry S. Bradshaw, Ralph N. Nelson Jr., Randall R. Bensch, Rafal Jabrzemski

OK-FIRE: A Weather-Based Decision Support system for Wildland Fire Managers in Oklahoma
J.D. Carlson, Terry G. Bidwell

The Potential Impact of Smoke from Prescribed Burns in Southern Missouri
Joseph Charney, Xindi Bian, Warren E. Heilman, Lesley A. Fusina

A Sub-Grid Mixture-Fraction-Based Thermodynamic Equilibrium Model for Gas Phase Combustion in FIRETEC: Development and Results
Michael M. Clark, Rodman R. Linn

Fire Incident Mapping Tools
Tim Clark

Plume Energetics and Dynamics of Grass Fires
Craig Clements, Zhong Shiyuan

Examining Crown Fire Behavior with Implication for Modeling
Jack D. Cohen, Mark A. Finney, Kara M. Yedinak

The Home Ignition Zone Principally Determines the Potential for Wildland-Urban Interface Fire Disasters
Jack Cohen

Laying the Foundation for Success
Vernon Compton

Does Fire Behavior Change with Stand Age in Black Spruce Forest of Interior Alaska?
James Cronan, Ann. E. Camp

Investigating the Dynamics of Fire Behavior in Grasslands Using a Physics-Based Fire Model
Phillip Cunningham, Rodman R. Linn

Modeling Buoyant Plumes from Wildland Fires: Fundamentals and Applications
Phillip Cunningham, Scott L. Goodrick, Michael J. Reeder

Using a PC Based Smoke Plume Dispersion Model (VSMOKE) and the National Fire Danger Rating System in Support of Go-No GO Decisions for Prescribed Fire
Gary Curcio

Development and Implementation of a National Fuel Moisture Database
Edward Delgado, Shelby I. Sharples, Annie Brown, Chuck Buescher

Facts About Fire-Increasing Public Awareness and Support of Prescribed Burning through the Fire in Florida's Ecosystems Program
Christine Denny, James Brenner

Process Modeling of First Order Fire Effects: Science and Application
Matthew Dickinson, Bret Butler, William Massman, Elizabeth Reinhardt, Anthony Bova, Todd Engstrom, Kathleen Kavanagh, Kirsten Stephen, Alistair Smith, Robert Kremmens

Tree Heating in Surface Fires and the Injury That Results
Matthew B. Dickinson, Bret W. Butler, Anthony S. Bova

Ignition and Flame Travel on Realistic Building and Landscape Objects in Changing Environments
Mark A. Dietenberger

Fire History of Red Pine-Dominated Forests of Seney Wildlife Refuge, Upper Michigan
Igor Drobyshev, Charles P. Goebel, David Hix, Marie Semko-Duncan, Greg Corace III

Experiments on Fire Spread in Discontinuous Fuelbeds
M.A. Finney, J.D. Cohen, I.C. Grenfell, K.M. Yedinak

Approving Prescribed Burns in Arizona
Mark Fitch

Applications of a Fire Acceleration Model for Firefighters Safety
Jo Ann Fites-Kaufman

In Situ Fire Wildland Fire Behavior, Fuels and Immediate Postfire Effects
Jo Ann Fites-Kaufman, Alicia Reiner

Collaborative Process for Priorization of Hazard Fuel Reduction Needs
Eric Geisler, James Twoteeth, Frank Roberts

Effects of Single Season Mechanical and Prescribed Fire Treatments in Restoring Inland Pitch Pine Scrub Oak Barrens
Neil Gifford, G. Thoman Dooley, Jason Bried, Craig Kostrzeski

A Prototype Fire Activity Database for Tracking Prescribed Fire Emissions
Scott Goodrick

Smoke Screening with Google Earth
Scott Goodrick

Silvicultural Smoke Management and the "Go/No Go" Decision Process in Washington
David Grant

Cleared for Take-Off: Smoke Management and the Military Mission
Sonny Green, Marty Martin

The History and Role of Prescribed Fire Councils: a Success Story
Lane Greene

Smoldering Combustion of Biomass Fires—Modeling and Experimental Results
Carlos Gurgel Veras

Institutional Factors Affecting the Use of Decision Support Tools and Ecological Data in Fuels Management a the Project Planning Level in the U.S. Forest Service
Erick Hakanson

Fire Situation Reporting
Deb Hamill, Marco Perea, Charlie Leonard

Florida Fire Season 2006
Deborah Hanley

Comparison of Fire Regime Condition Class Results
Wendel Hann, James Smith, Ted Tower, Douglas W. Havlina, James Smith

A Suite of Multiscale Remote Sensing Approaches for Measuring Thermal Characteristics and Their Relationships to Associated First-Order Fire Effects
Colin Hardy

National Seasonal Assessment Workshops
Robyn Heffernan

Evaluating Wildland Fire Hazard and Prioritizing Vegetation and Fuels Treatments—A Multiscale Decision Support System
Paul Hessburg, Keith M. Reynolds, Robert E. Keane

Assessing the Role of the Fine Scale Heterogeneity in Fuels and Fire Behavior in a Low-Intensity Surface Fire Regime
John Hiers, E. Louise Loudermilk, Wendell P. Cropper Jr., K. Clint Slatton, Joseph J. O'Brienn, Robert J. Mitchell

Where to Burn? A GIS-Based Prioritization Tool
Kevin Hiers

Application of the Ventilation Index in Smoke Management
Jeanne L. Hoadley

Application of Online Fire Knowledge Management Tools in the United States
William Hubbard, Greg Gollberg, Ken Outcalt, Jennifer Pollock

The Future of Fire Regime Condition Class—Where We Have Been, Where We Need to Go
Menakis James, Wendal Hann

The Influence of Live Fuels on the Rothermel Surface Fire Spread Model
William Jolly

Regional Changes in Effective Growing Season Lengths Under Future Climate Scenarios
William Jolly

A Cost Effectiveness Analysis of Preventative Mitigation Options for Wildland Urban Interface Homes Threatened by Wildfire
J. Greg Jones, Keith D. Stockman, David E. Calkin

Analysis of Fuel Loading-Variability and Burn Severity within the Landscape-Scale of Grand Teton National Park-Bridger Teton National Forest, Wyoming: Integration of Field Data, Geospatial Information, and Geospatial Statistics
Mohammed Kalkhan, Karl E. Brown

How to Keep Plantations from Burning: the Efficacy of Fuels Reduction Treatments in a Sierra Nevada Pine Plantation
Leda Kobziar, Scott L. Stephens, Joe R. McBride

Different Species, Different Patterns: the Predictors of First-Order Fire Mortality in Seven Trees of the Sierra Nevada Mixed-Conifer Forest
Leda N. Kobziar, Jason Moghaddas, Scott L. Stephens

Fire Spread Model Applied to Prescribed Burns in Chaparral
Eummo Koo, Patrick J. Pagni, Scott L. Stephens, David R. Weise

The Studies to Support a Fire Danger Rating System in Turkey
Omer Kucuk, Bulent Saglam, Bahar Dinc Durmaz, Ismail Baysal

Fire History and Vegetation Change in a Network of Pine-Oak Stands in the Central Appalacian Mountains
Charles Lafon

The BlueSkyRAINS West Project: Lessons Learned and Plans for BlueSky
Narasimhan Larkin, Susan O'Neill, Robert Solomonn, Sean Raffuse, Dana Sullivan

Verification of the Lightning Ignition Efficiency Map Using Lightning Discharge and Fire Occurrence Data from the Northern Rockies in 2003
Don Latham, Paul Sopko

Simulated Fire Behavior in Shrubs and Canopies Using HIGRAD/FIRETEC
Rodman R. Linn, J. Winterkamp, F. Pimont, J. Dupuy, D. Weise, J. Sauer, J. Canfield

Simulation and Real-Time Prediction of Air Quality Effects of Prescribed Burns in Florida with SHRMC-45
Yongqiang Liu, Gary Achtemeier, Scott Goodrick

Developing a New Monitoring Tool: the Integration of FEAT and FIREMON
Duncan Lutes, Nate Benson, Martha Isbister, Kim Johnson, Austin Streetman, Carter Barnes, John Caratti

The Montana/Idaho Prescribed Burn Reporting System
Lee Macholz, Carol A. Seielstad, Eric Tangedahl, Haiiying Liang, Limel Piao, Lloyd Queen, Don Helmbrechht, Dave Grace

Marginal Burning in Chaparral—Experiments and Models
Shandar Mahalingam, David R. Weise

On the Size and Mass Distribution of Firebrands Generated from Burning Korean Pine Trees
Samuel Manzello, Aleander Maranghides, William Mell, Yoshihiko Hayyashi, Daisaku Nii

Firebrand Generation from Vegetation and the Ignitability of Fuel Beds of Firebrands
Samuel L. Manzello

Heat Release Rate and Mass Loss Experiments of Douglas Firs
Alexander Maranghides, William Mell, Samuel Manzello

Assessing the Impact of Fuel, Weather, and Fire Suppression Effort on the Area Burning by Lightning-Caused Forest Fires in Ontario
David Martell, Hua Sun

Daily Regional Fire Weather and Fire Behavior Graphical Products
Chuck Maxwell, Timothy C. Stubbs

Agricultural Burning in the Southeastern United States Detected by MODIS
Jessica McCarty, Chris O. Justice, Stefania Korontzl

Using Spatial Technologies to Assess Historical Fire Data Trends in Florida's Wetland Ecosystems for Improved Fire Planning and Response
Susan McLellan, James Brenner, Jeff Vowell, Karen L. Cummins

Numerical Simulations of Burning Vegetation: Laboratory Experiments and Crown Fires
William Mell, Bret Butler, Alexander Maranghides, Samuel Manzello, Shankar Mahalingham

Firespread in the Wildland Urban Interface
William Mell, Ron Rehm, Alexander Maranghides, Samuel Manzello

Creating a Coalition of Prescribed Fire Councils: Taking It Up a Level
Mark Melvin, Pete Kubiak

Building a National Coalition of Prescribed Fire Councils
Mark Melvin, Pete Kubiak, Lane Green

WUI Microenvironment
Robert Meroney

Communicating the Wildland Fire Use Message
Punky Moore

Spatial Modeling of Fire in Shrublands with HFire
Max Moritz, P.E. Dennison

Interagency Prescribed Fire Planning and Implementation Reference Guide
David Mueller, Kim Van Hemelryck, Dan Buckley, Ed Bratcher, Gene Lonning, Dan Severson

Fire Regimes and Management Strategies for Restoring Cascadian Whitebark Pine Ecosystems
Michael Murray

Organizational Tips and Tactics for Moving Forward in Wildland Fire Use
Paula Nasiatka, Jonetta Holt

Innovations in Fuels Management, Demonstrating Success in Treating a Serious Threat of Wildfire in Northern Minnesota
Dennis Neitzke, Ellen Bogardus-Szymaniak, Patricia J. Johnson

US FS RMC: Real-Time Fire-Weather Intelligence and Smoke Forecast for the West
Ned Nikolov, Karl Zeller

Bark, Duff, and Soil Temperatures in Smoldering Duff Fires
Joseph J. O'Brien, J. Moran Varner, J. Kevin Hiers, F.E. Putz, Doria Gordon

Physiological Effects of Duff Fires on Longleaf Pines
Joseph J. O'Brien, J. Kevin Hiers, Kathryn Mordecai

Predictive Services Round Table Discussion
Rick Ochoa, Brenda L. Belongie, Deb Hamill, Tom A. Wordell

Litter and Duff Depths and Bulk Densities in the Southern United States
Roger Ottmar, Anne G. Andreu, Robert E. Vihhnanek

Fuels Management Options for the Longleaf Pine Ecosystem of the Gulf Coastal Plain
Kenneth Outcalt, Dale G. Brockway

Wildfire Mapping in the 21st Century
Tom Patterson

Fuel Assessment Techniques: Technology Transfer by the National Interagency Fuels Technology Team
Morgan Pence, Kathy H. Schon

Measurements of Mass and Temperature During Ignition of Fresh Foliage
Brent M. Pickett, Thomas H. Fletcher, David R. Weise

The Fire Strike Team Concept—Getting Fire on the Ground
Zachary Prusak

Lessons Learned Information Sharing
John Rabin, Jennifer Smither

Integration and Reconciliation of Satellite Detected and Incident Command Reported Wildfire Information in the BlueSky Smoke Modeling Framework
Sean Raffuse, Narasimhan K. Larken, Robert Solomon, Dana C. Sullivan, Lyle R. Chinkin, Lawrence Friedl, Amber Soja

Updating Wildland Fire Susceptibility Index Inputs I: Change Detection and Classification and Regression Tree Analysis to Develop Surface Fire Fuel Models and Canopy Cover
Andrew Ralowicz, Jim Brenner, Sue McLellan, Don Charlton

Fire Emissions and Regional Modeling—Specific Case Studies from the WRAPs Regional Haze Modeling. How Small Fires and Plume Rise Techniques Influence Near- and Far-Field Model Results
David Randall, Mark J. Fitch

WRAP Fire Emission Tracking System
David Randall, Mark J. Fitch

WRAP Seasonal Suites of Emission Reduction Techniques Developed for Implementation of Smoke Management Programs and Regional Modeling Applications (Projections)
David Randall, Mark J. Fitch

Salvage Logging and Fuel Treatment
Elizabeth Reinhardt

Expediting the Community Wildfire Protection Plan
Cheryl Renner, Terry K. Haines, Margaret A. Reams

Forecasting Significant Fire Potential
Tom Rolinski

The Hazard Mapping System—Fire and Smoke Detection Utilizing Environmental Satellites
Mark Ruminski

LANDFIRE: Providing Geospatial Products in Support of Fire and Fuel Management
Kevin Ryan, Matthew G. Rollins, Matthew C. Reeves

Effects of Fire on Conifer Survival: Practical Considerations for Fuels Treatments Projects
Kevin Ryan

Statewide Mapping of Fire Hazard Zones in California
David Sapsis, Mark Rosenberg, James G. Spero, Elsa K. Hucks

Regional Monitoring of Key Fire Weather Parameters
Kevin Scasny

Nomographs for Predicting Surface Fire Behavior without a Computer
Joe Scott

Developing Multitiered Portable Wireless Weather Monitoring Networks for Wildland Fire
Carl Seielstad, Richard Han, Regan Zane, Carl Hartung, Saxon Holbrook, Lloyd P. Queenn, Jim Riddering

Using Laser Altimetry-Derived Surface Roughness to Predict Coarse Woody Debris Volume in Mixed Conifer Forests
Carl Seielstad, Eric Rowell

Communication Strategies for Fire Management: Effective Citizen-Agency Partnerships
Bruce Shindler, Ryan Gordon

LANDFIRE East of the Rockies: Challenges and Responses
James Smith, Zhi-Liang Zhu, Kevin Ryan, Wendel Hann

How Well Does Satellite Data Quantify Fire in the United States?
Amber Soja, Jassim A. Al-Saadl, Louis Giglio, R. Brad Pierce, Dave Randall, Sean Raffuse, James Szykman

Evaluation of the BlueSky smoke Modeling Framework
Robert Solomon, Susan M. O'Neill, Sim Larkin

A Fuel Hazard Model for Forests of the Missouri Ozark and Illinois and Indiana Interior Lowland Plateau Ecoregions
Michael Stambaugh, Richard P. Guyette, Daniel C. Dey

Planning for Success: Leveled Supply of Woody Biomass with Coordinated Resource Offering Protocol and Strategic Placement of Treatments
Sue Stewart, Edmund A. Gee

Applying Remote Mobile Weather Observations to Tactical Operations in the Wildland Fire Urban Interface
Carter Stone, Deborah E. Hanley

Current Status of the Ozone National Ambient Air Quality Standard Review and Potential Revision to the Air Quality Index for the New PM2.5 Standard
Susan Stone

Burning and Mulching to Reduce High Fuel Loading in Beetle-Killed Stands: Effects of Fuel Reduction Treatments on Ectomycorrhizal Inoculum Potential
Aaron Stottlemyer, G. Geoff Wang, Christina E. Wells, Thomas A. Waldrop, Mac A. Callaham

Current Operations and Ongoing Development of the BlueSky System of Smoke Impact Predictions
Dana Sullivan, Narasimhan K. Larkin, Robert Solomon, Sean M. Raffuse, Lyle R. Chinkin, Christian D. Ovard, Lawrence Friedl

An Investigation of Unsteady Effects on the Dynamics of Crown Fire Initiation
Watcharapong Tachajapong, David R. Weise

Sparks That Started the Fire
Gary Taylor

Capturing the Deep Smarts of Fire Behavior and Fuels Experts
Dave Thomas, Dorothy A. Leonard, Carol Miller, Paula Nasiatka

Effect of Fire on Ant Assemblages in Central Semi-Arid Argentina
F. Rodrigo Tizon, Daniel V. Pelaez, Roberto M. Boo, Omar R. Elia, Mirta D. Mayor, Dolores Rodriguez-Rey

Comparison of Real-Time Smoke Particulate Monitors
Andy Trent

Advancing the Understanding of Postfire Tree Death
J. Morgan Varner

Identification of User Errors in Modeling Fire Behavior and Effects
J. Morgan Varner, Christopher R. Keyes

The ClearSky Field-Burning Decision Support System
Joseph Vaugh, Kyle Heitkamp, Rahul Jain Rahhul, Charleston Ramos, Brian K. Lamb

The National Fire and Fire Surrogate Study in Eastern Hardwoods—Early Results and Future Challenges
Tom Waldrop, Daniel A. Yaussy

Firebrand Review
David Weise, Eunmo Koo, Patrick J. Pagnil, David R. Weise

"Ecosystem Support Team"—Kindling the Flame
Brett Williams

Forecasting Fire Danger Indices
Thomas Wordell, Timothy J. Brown

I Need It and I Need It Now: Improving Predictive Services Outreach to Fire Managers
Thomas Wordell, Heidi Bigler-Cole, Patricia L. Winter

Meeting Predictive Services User Needs: An Assessment Survey
Thomas Wordell, Patricia L. Winter, Heidi Bigler-Cole

Relationships Influencing Forest Fire Occurrence in Canada
Mike Wotton, David L. Martell

Investigation of the Laminar Flame Assumption
Kara Yekinak, Jason M. Forthofer, Jack D. Cohen, Mark A. Finney

Testing and Classification of Individual Plants for Fire Behavior
Wayne C. Zipperer, Robert H. White

Poster Presentations

Landscape-Level Assessment of Prescribed Fire Effects on Oak Regeneration
Heather Alexander, Mary A. Arthur, David Loftis, Stephanie R. Green

Use of the BehavePlus Fire Modeling System for Prescribed Fire Planning
Patricia Andrews, Tobin M. Kelley

BehavePlus Fire Modeling System, Version 4.0 Overview
Patricia Andrews, Collin D. Bevins

Modeling Temporal Dynamics to Fuels Management Treatments
John Bailey, Masashi Konoshima

The Development of a Grassland Fire Breaching Model
Gregory Baxter, Martin E. Alexander, Rex Hsieh

Fire Effects on Chaparral-Associated Mammals: Responses to Fire Severity and Distance from Unburned Edge
Jan L. Beyers, Jay E. Diffendorfer, Wayne D. Spenser, Paul Schuette, Scott B. Tremor, Genie M. Fleming, Paul Schuette, Julio Angel Sato-Centeno

Quantifying Burn Severity in Alaska's Boreal Black Spruce Forest: Comparing Composite Burn Index and a Destructive Assessment Method
Leslie Boby

Comparison of Live Fuel Moisture Sampling Methods for Big Sagebrush in Utah
Annie Brown, Phillip N. Omi, Jolie Pollet

Southeast Fire Ecology Partnership
David Brownlie, Caroline L. Noble, Bruce Davenport, Paula Seamon, Kevin Robertson, Ronald E. Masters

Determining Alaska Values for Denali Wildland Fire Use Reference Guide
Brad Cella, Dan Warthen, Larry L. Weddle, Brian Sorbel

Historical Fire Regimes and Fire Climatology in Utah Forests
Linda Chappell, Peter M. Brown, Emily K. Heyyerdahl, Stanley Kitchen, Marc H. Weber

Tools for Estimating Contributions of Wildland and Prescribed Fires to Air Quality in the Southern Sierra Nevada
Ricardo Cisneros, Haiganouch Preisler

An Index of Crown Fire Potential Based on LIDAR Measurements
Kenneth Clark, John Hom, Nicholas Skowronski, Steve Van Tuyl, Jason Cole, Matt Patterson, Matthew Duveneck

Characterizing Moisture Dynamics for Assessing Fuel Availability in North Carolina Vegetation Communities
Gary M. Curcio, Roberta A. Bartlette, James J. Reardon

Retrospective Fire Modeling to Quantify the Cumulative Effects of Suppression
Brett Davis, Carol Miller

Using Fire to Restore Pine/Hardwood Ecosystems Severely Impacted by Southern Pine Beetle in the Southern Appalachians
Katherine Elliott, James M. Vose, Jennifer D. Knoepp, Barton D. Clinton

Wildland/Urban Interface of the Ancients—A Strategy for Reducing Fire Risk in the Canyons of the Ancients National Monument
Allen Farnsworth, Linda C. Farnsworth

The Fire Research and Management Exchange System (FLAMES): Technology in Support of Wildland Fire Research and Management
Greg Gollberg, Jean Freeney

Reducing Wildfire Risk in the Wildland-Urban Interface: State, County, and Municipal Governments' Initiatives to Protect Human Assets and Natural Resource Values
Terry Haines, Cheryl R. Renner, Margaret Reams

Fire Behavior Analysis to Evaluate the Clearance Requirements Around Structures
Carol Henson, David D. Kerr

The Effects of Architecture and Loading on Timelags in Longleaf Pine Needles
Kevin Hiers, Ralph M. Nelson

Integrating Fire Weather, Fuel Mapping and Atmospheric Science Research in New Jersey: National Fire Plan and Eastern LANDFIRE Prototype
John Hom, Kenneth Clark, Steve Van Tuyl, Jason Cole, Yude Pan

Parcel-Based Fire Hazard Rating with Hyperspectral Imagery
Tonya L. Hoover, Brian Collins, Richard Burch, Carol Rick, Chris Hallford

Relationship of Prescribed Burning and Wildfire Occurrence at Fort Benning 1985-2006
Thomas F. Hutcherson, Stephen J. Hudson, Jack M. Greenlee

Fire Fighter Math
Daniel M. Jimenez, Brad J. Monnahan

Optimizing Spatial and Temporal Treatments to Maintain Effective Fire and Nonfire Fuels Treatments at Landscape Scales
Greg Jones, Woodam Chung, Janet R Sullivan, Kurt J. Krueger

Fuels Management and Structural Complexity: Silvicultural Alternatives for Discordant Forest Objectives
Christoper Keyes, J. Morgan Varner

Efficient Landscape Fire Risk Management: A Spatial Endogenous Risk Framework
Masashi Konoshima, Heidi J. Albers, John D. Bailey

Validation of the BlueSky Smoke Modeling Framework: Field Campaigns
Candace Krull, Miriam Rorig, Robert Solomon, Narasimhan K. Larkin

Prescribed Fire Notification in Urban Palm Beach County, Florida
Kraig Krum

The Fire Modeling Institute—Connecting Management and Research
Laurie Kurthh, Duncan Lutes, Jim Menakis, Jane Kapler Smith, Don Helmbrecht

Sensitivity of CMAQ-Daysmoke Simulations to Smoke Properties and Ambient Conditions
Yongqiang Liu, Gary L. Achtemeier, Scott Goodrick, William A. Jackson

Seasonal Response of Elk to Forest Fuels Reduction
Ryan Long, Janet L. Rachlow, John G. Kie

Predictive Services Weather Support to Prescribed Fire and Wildland Fire Use Fire Operations
Stephen Marien, Brenda Belongie

Linking State Prescribed Fire Councils as a Coalition: An Initiative to Promote Public Understanding of Rx Fire, and to Nationally Address Key Management, Policy, and Regulatory Issues
Mark A. Melvin, Johnny P. Stowe, Frank T. Cole, Lane Green, Peter Kubiak

Climate Drivers of Regional Fire Years in the U.S. Northern Rockies: Past, Present, and Future
Carol Miller, Emily Heyerdahl

Evaluating Approaches to Mapping Burn Probability: Phase I
Carol Miller, Marc Parisien, Mark Finney, Alan Ager

Communicating the Wildland Fire Use Message
Punky Moore

The Savannah River Smoke Project—Measurements of Ground-Level PM2.5 smoke Concentrations Downwind from Prescribed Burns
Luke P. Naeher, Gary L. Achtemeier, John Blake, John Pierce, David MacIntosh

Light Versus Litter: What Limits Understory Diversity in Unburned Xeric Longleaf Stands
Joseph O'Brien, J. Kevin Hiers, Robert Mitchell, Rodney Will

Compiling, Synthesizing, and Analyzing Existing Boreal Forest Fire History Data in Alaska
Diana Olson, James B. Cronan, Ann E. Camp, Jennifer L. Allen, Donald McKenzie, Jennifer Hroback, Mike Tjoelker

The Agricultural Burn Outlook—Using Forecast Mesoscale Meteorological Parameters to Predict Windows of Opportunity for Agricultural Burn Operations
Susan O'Neill, Rob Wilson, Sue McCarthy, Ray Peterson

Fire Reintroduction in Fire Dependent Conifer Ecosystems—Unintended Pathological Consequences
William Otrosina, Pauline C. Spaine

Predicting and Mapping Canopy Parameters to Aid in Fire Management at the Savannah River Site
Bernard Parresol, Dan Shea, Roger Ottmar

Understory Vegetation Responses to Thinning and Prescribed Fire in Dry Coniferous Forests of Washington State
David W. Peterson, Erich K. Dodson, Richy J. Harrod

Fire Councils in Florida: A Success Story
Zachary Prusak

Wildland Fire Decision Support System in Aggtelek National Park, Hungary
Agoston Restas, Daniel Nagy, Sandor Rozsa

The Effects of Prescribed Fire on Amphibian and Reptile Biodiversity Patterns in Northern Longleaf Ecosystem Restoration
Leslie Rissler, Jimmy Stiles, Sierra Stiles

Prescribed Fires Affect Seedling Establishment and Survival in a Central Appalachian Forest
Jacob Royse, Mary A. Arthur, David Loftis

The National Wildfire Coordinating Group's Fire Environment Working Team
Paul Schlobohm, Larry Bradshaw

Tribal Smoke Management in the Southwest
Ronald Sherron

LANDFIRE Vegetation Models: Description, Effects, and Applications
Jim Smith, Elena Contreras, Kori Blankenship, Darren Johnson, Ayn Shlisky, Randy Swaty

Continental and Landscape-Scale Approaches to Modeling Historic Spatio-Temoral Variability in Fire Frequency from Fire Scar Data
Michael Stambaugh, Richard P. Guyette, Daniel C. Dey

The Southern Fire Portal: Science and Technology for the Fire Community
Christopher Szell, David Brownlie, Shelaine Curd-Hetrick, Greg Gollberg, Kevin Hiers, Bill Hubbard, Kevin Robertson

Comparison of Browns Planar Intercepts and Photo Series for Fuel Loading at Sagehen Creek Basin, Truckee, CA
Nicole Vaillant, Scott I. Stephens, John J. Battles

BlueSky/AIRPACT-3 Predictions of Wildfire Air Quality Impacts
Joseph Vaughan, Jack C. Chen, Brian K. Lamb, Jeremy C. Avise, Susann M. O'Neill, Sim Larkin, Robert Solomonn

Fuel Loading Across the Southern Appalachian Landscape
Tom Waldrop, Lucy Brudnak, Sandra Rideout-Hanzak

Modeling Fire-Induced Mortality of Longleaf Pine
Geoff Wang, Steve R. Wangen, William D. Boyer, E.D. Reinhardt, K.W. Outcalt, J.L. Walker, T.A. Waldrop

Delayed Mortality of Eastern Hardwoods—A Function of Fire Behavior, Site, or Pathology?
Dan Yaussy, Tom Waldrop

Plant Flammability Key for Creating a Firewise Plant List
Wayne C. Zipperer, L. Annie Hermansen-Baez, Alan J. Long, Marthha C. Monroe, Cotton K. Randall, Anna L. Behm

Publishing Services Staff

Managing Editor · Lane Eskew

Page Composition & Printing · Nancy Chadwick

Editorial Assistant · Loa Collins

Contract Editor · Kristi Coughlon

Page Composition & Printing · Connie Lemos

Distribution · Richard Schneider

Online Publications & Graphics · Suzy Stephens

RMRS
ROCKY MOUNTAIN RESEARCH STATION

The Rocky Mountain Research Station develops scientific information and technology to improve management, protection, and use of the forests and rangelands. Research is designed to meet the needs of National Forest managers, Federal and State agencies, public and private organizations, academic institutions, industry, and individuals.

Studies accelerate solutions to problems involving ecosystems, range, forests, water, recreation, fire, resource inventory, land reclamation, community sustainability, forest engineering technology, multiple use economics, wildlife and fish habitat, and forest insects and diseases. Studies are conducted cooperatively, and applications may be found worldwide.

Research Locations

Flagstaff, Arizona
Fort Collins, Colorado*
Boise, Idaho
Moscow, Idaho
Bozeman, Montana
Missoula, Montana
Reno, Nevada
Albuquerque, New Mexico
Rapid City, South Dakota
Logan, Utah
Ogden, Utah
Provo, Utah

*Station Headquarters, Natural Resources Research Center, 2150 Centre Avenue, Building A, Fort Collins, CO 80526

Federal Recycling Program Printed on Recycled Paper