POSTER SESSION

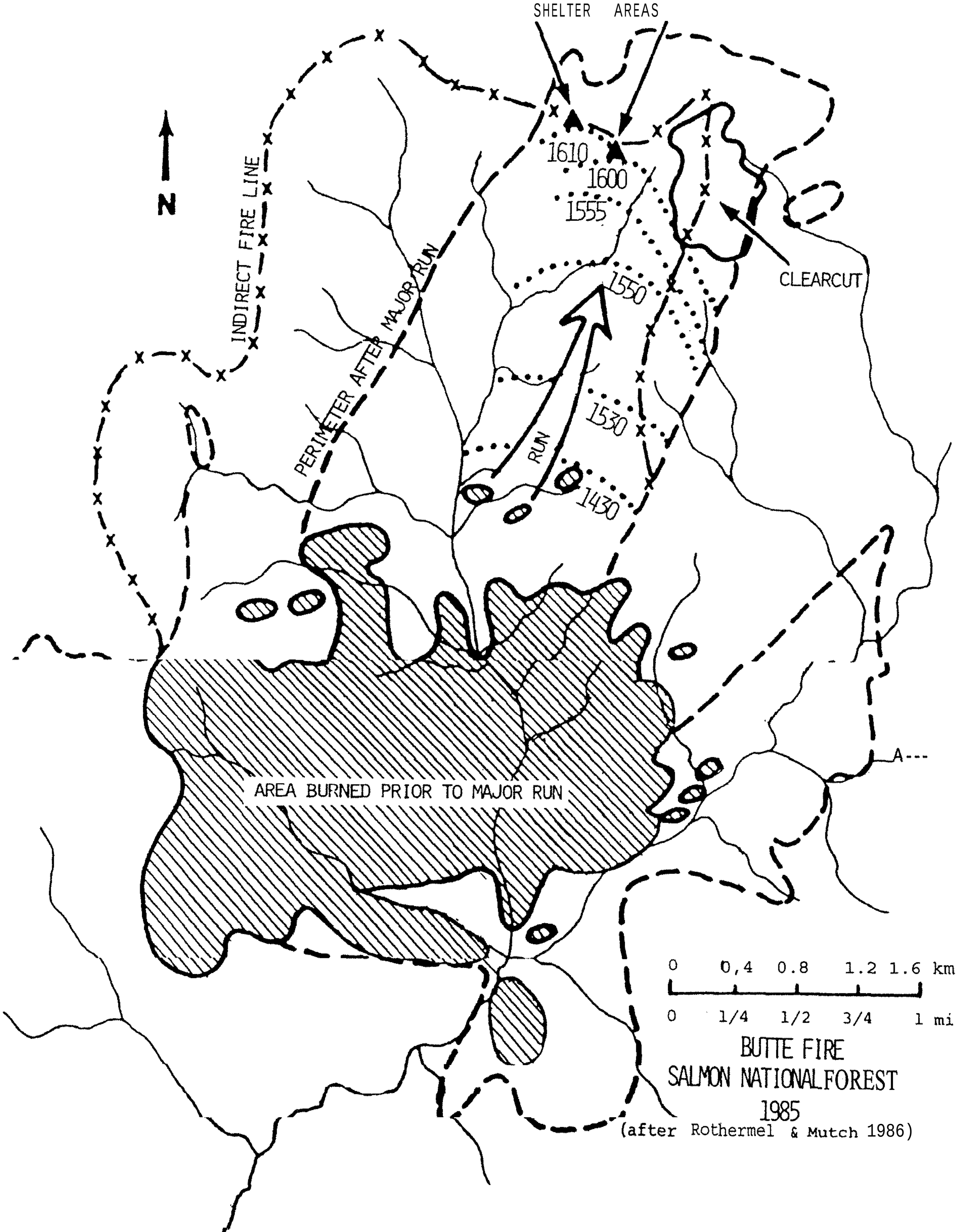

Figure I.--Fire progress map for the Butte Fire, Salmon National Forest, central Idaho, August 28-29, 1985 (after Rothermel and Mutch 1986).

THE 1985 BUTTE FIRE IN CENTRAL IDAHO: A CANADIAN PERSPECTIVE ON THE ASSOCIATED BURNINGCONDITIONS

Martin E. Alexander[1]

Abstract-During the afternoon of August 29, 1985, the Butte Fire made a high-intensity crown tire run, covering a distance of 2.22 km in one hour and 40 minutes, and forcing 73 tire fighters to deploy their protective tire shelters. This paper presents a retrospective analysis of the fire behavior in terms of the two major subsystems of the Canadian Forest Fire Danger Rating System. The fuel moisture codes (FFMC 94.6, DMC 172, DC 744) and tire behavior indexes (ISI 22.5, BUI 218, FWI 65) of the Canadian Forest Fire Weather Index System were indicative of extreme fire behavior and ignition potential. The predictions of headfire rate of spread (24.6 m/min or 1.48 km/h) and intensity (43,320 kW/m) based on the Canadian Forest Fire Behavior Prediction System were remarkably close to the observed tire behavior characteristics.

INTRODUCTION

The Butte Fire occurred on the Salmon National Forest toward the end of the 1985 fire season in central Idaho. Seventy-three fire fighters were forced to deploy their protective survival shelters in preestablished safety zones when the fire made a major run during the afternoon of August 39 (Mutch and Rothcrmel 1986). Fortunately, no one was seriously injured. As a result of this incident, the Butte Fire has attained a considerable degree of notoriety in the United States. Several published accounts of the fire's behavior (Aronovitch 1989; Mutch and Rothermel 1986; Rothcrmel 1991; Rothermel and Gorski 1987; Rothermel and Mutch 1986; Werth and Ochoa 1990) and the shelter deployment (Jukkala and Putnam 1986; Turbak 1986) have already appeared, and there is a 33-minute videotape featuring interviews with those involved and photos taken during the episode (National Wildfire Coordinating Group 1989). Since a great deal of American information on wildland fire behavior finds its way into Canada, some means of relating it to Canadian conditions is often desirable. Thus, this paper offers a hindsight analysis of the Butte Fire in terms of the two primary subsystems of the Canadian Forest Fire Danger Rating System (CFFDRS) (Stocks and others 1989). Emphasis is placed on the documentation of fuel moisture codes and fire behavior indexes of the Canadian Forest Fire Weather Index System and the quantitative prediction of forward rate of spread and frontal intensity based on the Canadian Forest Fire Behavior Prediction System. Some familiarity with the CFFDRS on the part of the reader is presumed.

[1] Fire Research Officer, Forestry Canada, Northwest Region, Northern Forestry Centre, 5320-122 Street, Edmonton, AB T6H 3S5; at the time this paper was prepared the author was Visiting Fire Researcher, National Bushfire Research Unit, CSIRO Division of Forestry and Forest Products, and Ph.D. Scholar, Department of Forestry, Australian National University, Canberra, ACT.

Table I.--Analysis of spread rates associated with the major run of the Butte Fire on August 29, 1985 (after Rothermel and Mutch 1986).

Time interval (hours MDT)	Elapsed time (min)	Forward spread distance (m)	Headfire Rate of Spread (m/min)	(km/h)
1430-1530	66	515	8.6	0.52
530-1550	20	772	38.6	2.32
550-1555	5	467	93.4	5.66
1555-1600	5	225	45.0	2.70
1600-1610	10	241	24.1	1.45
1430-1610	100	2,220	22.2	1.33

OBSERVED FIRE BEHAVIOR

The Butte Fire was started by lightning on July 20, 1985. By the afternoon of August 29 approximately 10,500 ha had been burned over and the northern perimeter of the fire was uncontaincd (fig. 1). On August 29 the Butte Fire made a forward advance of about 2,220 m between 1430 and 1610 hours Mountain Daylight Time (MDT) (table 1). This translates into an average headfire rate of spread (ROS) of 22.2 m/min or 1.33 km/h for the 100-minute run. For short time intervals, the main fire front travelled considerably faster. The maximum observed headfire ROS was 93.4 m/min or 5.6 km/h. The convection column associated with the major run (fig. 2a) was characterized by dense, black smoke and eventually reached an estimated height of nearly 5,000 m above the ground surface. The behavior exhibited by the Butte Fire on the afternoon of August 29 represents a classical case of a high-intensity crown fire event. Flames were observed to stand nearly vertical and greatly exceeded the height of the forest in which the tire was spreading (figs. 2b and 2c). A photograph taken from one of the shelter sites around 15.50 hours MDT, about 30 minutes before the arrival

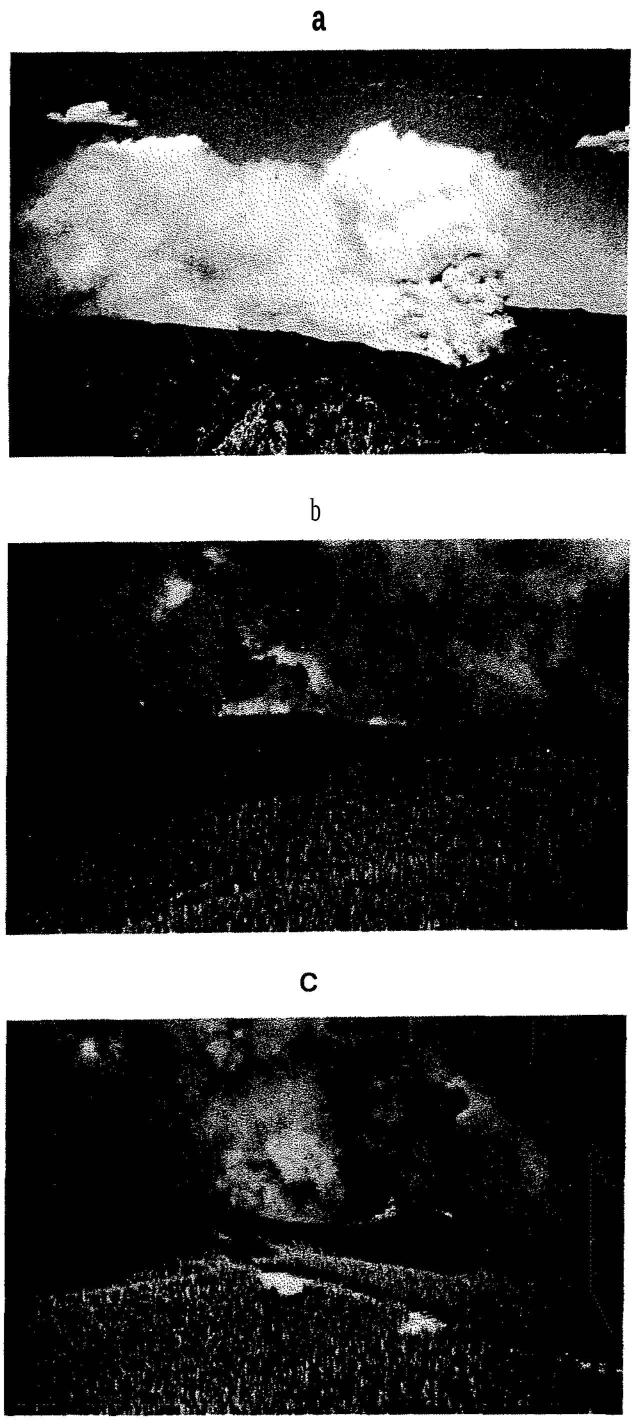

Figure 2.-- (a) convection column development over the Butte Fire at about 1520 hours MDT on August 29, 1985. (b & c) views of flame front approaching shelter areas (latter photo taken at about 1605 hours MDT). All photos reproduced from 35 mm slides taken by L. Duncan, USDA Forest Service.

of the active flame front, has been reproduced on the cover of Fire Management Notes Volume 46, issue Number 4 in 1986, and certainly attests to the severity of the tire behavior during the major run.

THE FIRE ENVIRONMENT

The fire environment is defined as "the surrounding conditions, influences, and modifying forces of topography, fuel and fire weather that determines tire behavior" (Merrill and Alexander 1987). The fire environment concept (Countryman 1972) as applied to the Butte Fire is described in the following sections.

Fuels

Forest cover types in the area of the major run consisted of Engelmann spruce (Picea engelmanii) - subalpine fir (Abies lasiocarpa) associations in the drainage bottoms and lodgepole pine (Pinus contorta) - subalpine fir stands at higher elevations (Steele and others 1981). The average tree height was considered to be about 18 m (Rothermel 1990) to 23 m (Patten 1990). Surface fuel loads (i.e., downed dead woody and forest floor materials) ranged from about 180 to 225 t/ha in the lower canyon slopes to about 55 to 90 t/ha in the midslope to upper slope areas (Rothermel and Mutch 1986). These figures appear quite reasonable in comparison to other areas in the Northern Rocky Mountains (Brown and Bevins 1986; Brown and See 1981; Fischer 1981). The forest floor depth varied from 2.5 to 10 cm (Patten 1990). Most of the tire area could be categorized by tire behavior fuel models 8 (closed timber litter) and 10 (timber-litter and understory) as described by Anderson (1982).

Topography

The general aspect of the fire area was southerly (fig. 2a). The tire swept up a well-defined north-south drainage that became progressively steeper near the shelter sites. Elevations from the start to the termination of the major run of the fire varied from 2,146 m to 2,341 m above mean sea level (MSL) (fig. 3). This vertical rise of 195 m coupled with the horizontal distance represents an average terrain slope of 9 percent (fig. 3). One unusual feature of the topography in the tire area was the dome-like nature of the upper slopes with continuous forest canopy cover.

Weather

In the spring of 1985, snow-free cover in the tire area probably occurred in early May (Finklin 1988, 1989). The area normally receives about 200 mm of precipitation between early May and late August according to data presented in Finklin (1988). A manually operated tire weather station at the Indianola Guard Station (GS), located 21 km east of the tire area at an elevation of 1,052 m MSL, reported 48.8 mm of precipitation in May but only 8.0 mm in June. The Skull Gulch remote automatic weather station (RAWS) (Warren and

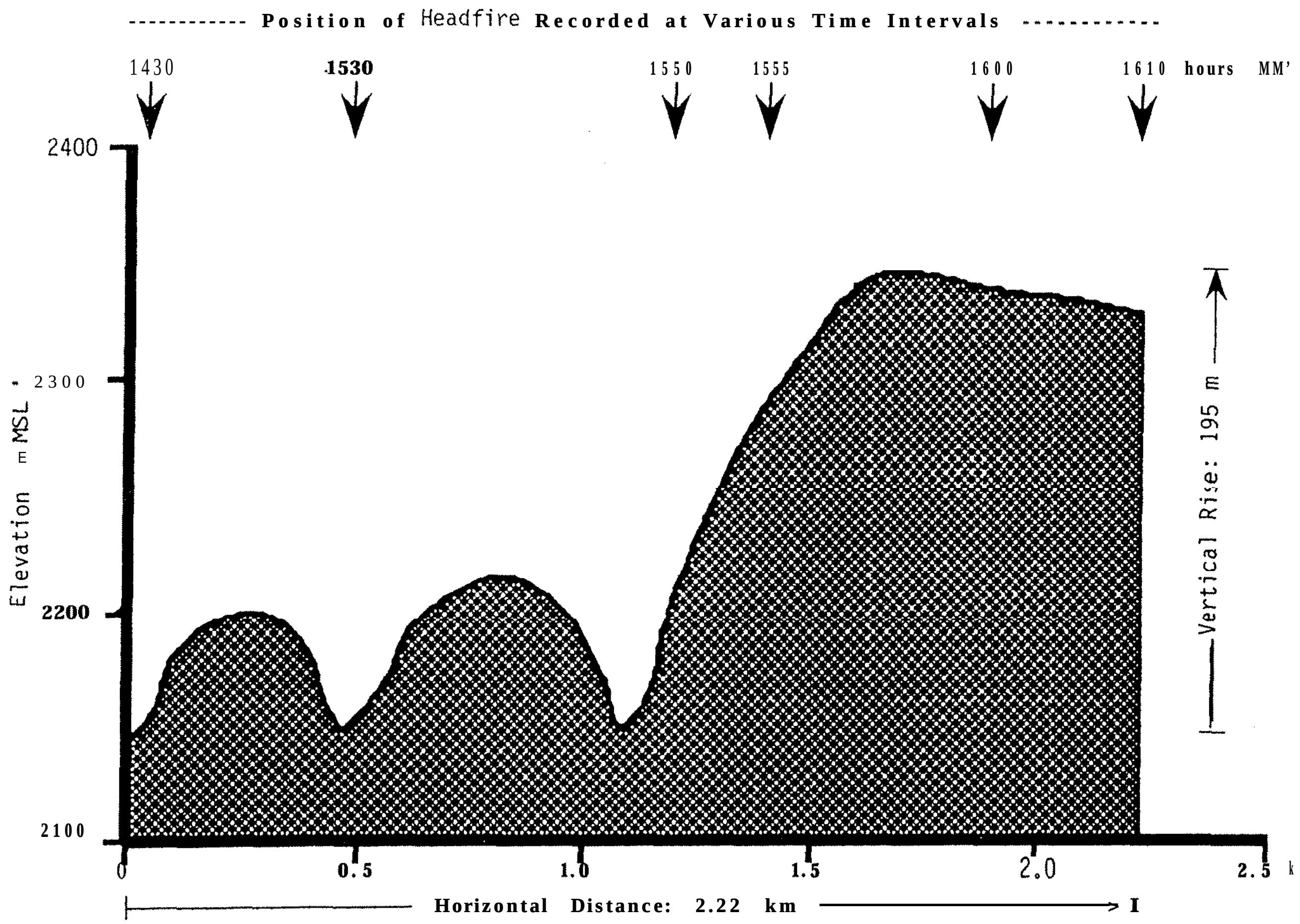

Figure 3.--Topographic profile for the area traversed by the major run of the Butte Fire on August 29, 1985. Note that the differences in the scales for the two axes (5.0:1) does accentuate the terrain relief.

Vance 1981), situated 14 km south of the fire area at 1,554 m MSL, recorded just 2.4 mm and 16.6 mm in July and August, whereas the lndianola GS measured 6.4 mm and 38.0 mm, respectively. The last significant rain (i.e., > 0.6 mm) received at the Skull Gulch RAWS prior to the major run of the Butte Fire occurred on August 2 and 3 (14.8 mm total). At Indianola GS, the last rainfall of any significance occurred on August 19 (3.0 mm).

A U.S. National Weather Service mobile fire weather unit was established at the base camp (2,256 m MSL), approximately 9.1 km southwest of the area involved in the fire run by the early afternoon of August 26. Weather observations taken prior to and on the day of the major run indicate relatively mild air temperatures with fairly low relative humidities but only moderately strong winds (table 2).

Table 2. --Dally 1399 hours MDT observations and extremes recorded at the temporary fire weather station at the Long Tao II Complex base camp (after Gorski 1999).

Calendar date (1985)	Dry-bulb temperature (°C)	Relative humidity (percent)	10-m open wind. Speed[a] (km/h)	Direction (from)	24-h rain (mm)	Maximum temperature (°C)	Minimum relative humidity (percent)
August 26	21.7	27	14	south	0.0	23.9	21
August 27	22.8	23	13(31)	southwest	0.0	25.6	17
August 28	21.1	20	14	southwest	0.0	22.8	18
August 29	19.4	20	13(31)	southwest	0.0	23.9	17

[1]1-minute average. Reported gusts noted in parentheses.

Table 3.--Hourly observations recorded at the temporary fire weather station at the Long Tom II Complex base camp on August 29, 1965 (after Gorski 1990).

Local time (hours MDT)	Dry-bulb temperature (°C)	Relative humidity (percent)	10-P open wind Speed[a] (km/h)	Direction (from)
0800	12.2	49	3.7	east
0630	15.0	40	9.3	east
1000	16.1	38	5.6	east
1045	17.2	36	5.6	east
1120	18.9	32	0	
1290	21.1	29	13.0	southeast
1315	21.1	20	13.0(31)	southwest
1400	21.7	24	22.2(37)	south
1500	21.7	20	18.5	south
1535	22.2	19	23.1	south
1630	23.9	17	14.8	south
1720	23.3	19	15.7	sontb
1830	21.1	17	7.4	west
2030	16.7	31	11.1	sontb
2145	15.0	25	0	

*1-minute average. Reported gusts noted in parentheses.

According to the observations made on August 29 (table 3), the following weather conditions would have been rcprcscntative of the period during the fire run:

Dry-bulb temperature: 22°C
Relative humidity: 19 percent
1 O-m open wind: 20 km/h
Wind direction: south
Days since rain: 26

Relative humidities as low as 6 percent and air temperatures of around 30°C were recorded at the Skull Gulch RAWS site during the major fire run (table 4); winds were generally southwest and averaged about 17 km/h.

Table 4.--Hourly fire weather observations recorded at tbe Skull Gulch RAW site on August 29, 1985.

Local time (hours MDT)	Dry-bulb temperature (°C)	Relative humidity (percent)	10-m open wind Speed[a] (km/h)	Direction (from)
0800	11.2	37	3.0	80
0900	13.9	37	0.7	206
1000	16.3	29	6.3	163
1100	19.8	24	10.0	149
1200	22.6	22	9.3	184
1300	25.7	18	10.7	145
1400	28.1	10	15.9	-[b]
1509	30.0	8	12.6	257
1666	30.4	6	23.0	281
1700	30.0	6	17.0	256
1899	29.6	6	19.8	292
1990	28.1	6	26.7	292
2060	25.3	7	18.0	300
2166	24.1	7	13.9	285
2266	21.8	9	0.2	196

[a] lo-minute average.
[b] Not available.

FIRE DANGER INDICES

The weather data used in calculations of CFFDRS values were obtained from the U.S. National Fire Weather Data Library (Furman and Brink 1975). These data were daily measurements of dry-bulb temperature, relative humidity, wind velocity, and 24-hour accumulated rainfall taken at 1300 hours MDT at Skull Gulch RAWS and Indianola GS during the 1985 fire season. Emphasis was placed on using the Skull Gulch readings since it was more representative of the fire area. The Indianola GS weather record was used for missing observations. Winds measured at the U.S. standard of 6.1 m or 20 ft in the open were adjusted to the CFFDRS standard of 10 m by means of the factor suggested by Turner and Lawson (1978). All weather data were converted to metric units. The standard components of the Canadian Forest Fire Weather Index (FWI) System (Van Wagner 1987) were calculated by computer program (Van Wagner and Pickett 1985). Calculations were begun on May 1, using the standard fuel moisture code starting values (Canadian Forestry Service 1984), and continued until August 25. Calculations for the subsequent period were based on weather observations made at the base camp immediately adjacent to the fire area.

Table 5 .--Fire danger indices calculated at 1300 hours MDT for the temporary fire weather station at the Long Tom II Complex base camp.

Calendar date (1985)	Fine Fuel Moisture Code (FFMC)[a]	Duff Moisture Code (DMC)[a]	Drought Code (DC)[a]	Initial Spread Index (ISI)	Buildup Index (BUI)	Fire Weather Index (FWI)
August 26	94.5	160	723	16.4	207	53
August 27	94.5	164	730	15.6	211	52
						54
August 2[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	65

[a]The FFMC, DMC, and DC at Skull Gulch RAWS on August 25, 1985, were 97, 157, and 716, respectively.

The three fuel moisture codes and three fire behavior indexes comprising the FWI System arc listed in table 5. Readers should consult Canadian Forestry Service (1984) for definitions of the six components. The moisture code values are all indicative of very low moisture contents for the types of fuels they are designed to represent. For example, litter and duff reprcsented by the Fine Fuel Moisture Code (FFMC) and Duff Moisture Code (DMC) would probably have been 6.1 and 25 percent (Van Wagner 1987). A Drought Code (DC) value of 500 is generally considered to be a critical threshold for deep-drying conditions in forest floor and mineral soil layers (Muraro 197.5; Muraro and Lawson 1970). The Initial Spread Index (ISI), Buildup Index (BUI), and the Fire Weather Index (FWI) component itself, representing fire spread rate, fuel available for combustion, and fire intensity are all suggestive of extreme suppression difficulty (Alexander and De Groot 1988; British Columbia Ministry of Forests 1983; Muraro 1975). In most regions of Canada, an FWI value of greater than 30 would be rated as an extreme fire danger class (Stocks and others 1989). The fire danger ratings which prevailed on August 29 would also be considered extreme according to the criteria used by the British Columbia Ministry of Forests (1983).

PREDICTED FIRE BEHAVIOR

In an earlier paper by the author (McAlpine and Alexander 1988), a hindsight prediction of the August 29 run of the Butte Fire was made using the interim edition of the Canadian Forest Fire Behavior Prediction (FBP) System (Alexander and others 1984; Lawson and others 1985). This prediction was based on the ISI calculated for the Skull Gulch RAWS and the terrain slope. A crown fire spreading at 24.1 m/min was predicted. In the present paper, the basis for predicted tire behavior is a draft version of the first complete edition of the FBP System (Van Wagner 1989)[2]. The following predictions are based on the most representative FBP System fuel type (C-3: mature jack *or* lodgepole pine), a 9-percent slope, 10-m open wind of 20 km/h, FFMC 94.6, and BUI 219 for a line-source ignition spreading directly upslope with the prevailing wind during the late afternoon over a period of one hour and 40 minutes:

Headlire rate of spread:	24.6 mlmin or 1.48 km/h
Forward spread distance:	2,460 m
Fuel consumption:	58.7 t/ha (surface and crown)
Headlire intensity:	43,320 kW/m
Type of fire:	continuous crowning (> 99 percent crown fuel involvement)

In the above calculations, a foliar moisture content (FMC) of 105% (oven-dry weight basis) for lodgepole pine was used based on an on-site sample taken two days after the fire run by Rothermel (1990), and not the computational scheme for determining FMC according to calendar date, geographical location (i.e., latitude and longitude), and elevation. Fire intensity was computed, assuming a low heat of combustion value (reduced for fuel moisture) of 18,000 kJ/kg, on the basis of the predicted rate of advance and amount of fuel consumed (Alexander 1982).

DISCUSSION

The major runs of other well-documented wildfires in the United States such as the 1967 Sundance Fire in northern Idaho, the 1980 Mack Lake Fire in northern lower Michigan, the 1980 Lily Lake Fire in northeastern Utah, the 1983 Rosie Creek Fire in south-central Alaska, and the 1989 Black Tiger Fire in north-central Colorado, all occurred like the Butte

[2]To appear in final published form, authored by the Forestry Canada (ForCan) Fire Danger Group, as an Information Report issued by ForCan headquarters entitled "Development and Structure of the Canadian Forest Fire Behavior Prediction System" in 1991.

Table 6.--Canadian fire danger indices associated with five other major well-known U.S. wildfires.

Name of wildfire	Fine Fuel Moisture Code (FFMC)[a]	Daff Moisture code (DMC)[a]	Drought code (DC)"	Initial Spread Index (ISI)	Buildup Index (BUI)	Fire Weather Index (FWI)
Sundance"	96.1	318	752	23.8	318	68
Mack Lake[b]	94.6	35	59	43.2	35	50
Lily Lake"	95.0	66	107	562	66	77
Rosie Creek[d]	92.7	114	299	18.0	114	49
Black Tiger"	95.2	111	269	24.5	111	59

' Reference: Anderson (1968). The FWI System components were calculated on the basis of the 1606 hours Pacific Daylight Time (PDT) fire weather observations for the Priest Lake Experimental Forest, ID (winds were converted to 10-m open standard according to T-r and Lawson 1978); data were kindly provided by A.I. Finklin, Research Meteorologist (retired), USDA Forest Service! Intermountain Fire Sciences laboratory, Missoula, MT. Dry-bulb temperature and relative humidity were adjusted based on data presented in Fiaklia (1983), by (-) 1 .4°C and (+) 5.0 percent, respectively. in order to approximate the 1300 PDT values. The 1399 bows PDT fire weather observations on September 1, 1967, were: dry-bulb temperature 30.8°C; relative bamidity 18%; 10-m open wind 17 km/h; and 25 days since > 0.6 mm of rain.

'Reference: Simard and others (1983). The FWI System components were calculated on tbe basis of the 1300 hours Eastern Daylight Time (EDT) weather data given in Table 1 of Simard and others (1983) for Mio, MI (winds were converted to 10-a open staadard according to Tamer and Lawson 1978). The 1306 hours EDT fire weather observations on May 5, 1980, were: dry-bulb temperature 26.7°C; relative humidity 24%; 10-a open wind 33 km/h; and 6 days since > 0.6 mm of rain.

"Reference: Rothermel (1983, 1991). The FWI System components ware calculated oa tbe basis of the 1300 hours MDT fire weather observations for the Bear River Guard Station, Wasatch-Cache National Forest, UT (winds were converted to 10-m open staadard according to Tamer and Lawson 1978); these data are on file with the National Fire Weather Data Library (Furman and Brink 1975) under station number 420703. The 1300 boars MDT fire weather observations on June 23, 1930, mere: dry-bulb temperature 20.6°C; relative humidity 16%; 10-r open wind 37 km/h; and a minimum of 12 days since > 0.6 mm of rain.

[d]Reference: Juday (1985). The FWI System components were calculated on tbe basis of the 1300 hours Alaska Daylight Time (ADT) weather data for the international airport at Fairbanks, AK; data were kindly provided by P. Perkins, formerly with the USDI Bureau of Laad Management, Alaska Fire Service, Fairbanks, AIL The 1300 hours ADT fire weather observations on June 2, 1983, were: dry-bulb temperature 23.5°C; relative humidity 33%; 10-m open wind 21 km/h; and 4 days since > 0.6 mm of rain.

"Reference: National Fire Protection Association (1999). The FWI System components were calculated on the basis of the 1300 boars MDT weather data for tbe Betasso station operated by the Sherrif's Department, Boulder County, Co (winds were converted to lo-s opea staadard according to T- and Lawson 1978); these data are on file with the National Fire Weather Data Library (Furman and Brink 1975) under station number 056604. The 1300 boors MDT fire weather observations on July 9, 1989, were: dry-balb temperature 36.7°C; dative humidity 24%; 10-m open wind 20 km/h (based on an on-site estimate of add-flame wind speed): and 13 days since > 0.6 mm of rain.

Fire, under exceedingly severe burning conditions according to the FWI component (Table 6)'. Although extreme fire behavior was observed in all these cases, there were differences in forward spread rates and frontal intensities. This is to be fully expected given difference's in wind velocity, dead and live fuel moisture levels, fuel types (e.g., closed vs. open conifer stands), and the topographic situation (e.g., level ground vs. steep and complex mountainous terrain). The FWI System components offer a general indication of fire potential based largely on short- and long-term surface weather; presently there's no provision made in the FWI System to account for the influences of upper atmospheric conditions on tire behavior such as instability or low-level jet winds (Turner and Lawson 1978). It's the role of the FBP System, which depends in part on the FWI System for input, to consider the differences in fuel characteristics and topography on potential fire behavior.

The FBP System did, although admittedly in retrospect, a remarkably good job of estimating the actual fire behavior characteristics associated with the major run of the Butte Fire on August 29. Head fire ROS and forward spread distance are of course more easily verified in this particular case. A predicted spread rate approaching the maximum observed

'The major run of the 1971 Little Sioux Fire (Sando and Haines 1972) in northeastern Minnesota also occurred under an extreme fire danger rating; the FWI System componentsand 1200 hours local standard time tire weather observations are presented in Alexanderand Sando (1989).

value would be possible if a 45 percent slope were used (Van Wagner 1977b), as done by Rothcrmel and Mutch (1986), and if winds momentarily exceeded the mean value (Crosby and Chandler 1966). Patten (1990) has indicated that surface fuel consumption was perhaps 7.5 to 100 percent complete, and so the predicted value (47.3 t/ha) is quite reasonable given the fuel moisture levels and prcbum fuel loads. The predicted level of frontal fire intensity and type of tire are certainly indicative of a fully-developed crown fire (Alexander 1988; Alexander and Lanoville 1989; Anderson 1968; Simard and others 1983; Stocks 1987; Van Wagner 1977a) and certainly match the general impression obtained by viewing slides taken during the fire run.

CLOSING REMARKS

The CFFDRS can be, if properly applied, a useful tool in research and training for interpreting fire behavior information emanating from wildfire case histories completed in the United States. The present example has in fact been used since 1987 in the annual advanced fire behavior course held at the Forest Technology School in Hinton, Alberta. If the required weather observations are available, then it is possible to redescribe the burning conditions of previously documented forest fires in terms of the weather-dependent components of the FWI System, thereby permitting correlation with observed tire behavior and comparison with predicted fire behavior using the FBP System.

ACKNOWLEDGMENTS

I wish to sincerely thank several members of the USDA Forest Service for their assistance in the analysis of the Butte Fire and in the preparation of this paper. These include T. Patten (Salmon National Forest), R.C. Rothermel and A.I. Finklin (Intermountain Research Station), B.J. Erickson and L. Jakubowski (Boise Interagency Fire Center), and D.A. Thomas (Lo10 National Forest). C.J. Gorski of the U.S. National Weather Service at Boise, Idaho, was also very helpful.

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BEHAVIOR OF HEADFIRES AND BACKFIRES ON TALLGRASS PRAIRIE

Terrence G. Bidwell and David M. Engle[1]

Abstract-Byram's fireline intensity model and time-temperature relationships at 0, 30, and 60 cm above the soil surface were used to characterize the behavior of headfires and backfires on tallgrass prairie during the spring. Weather and fuel parameters were used as independent variables in regression models of fire behavior. Byram's fireline intensity was greater in headfires than backfires. Residence time for backfires was not significantly different from residence time for headfires. Degree seconds for backfires was not significantly different from degree seconds for hcadfires. Maximum temperature at 60 cm was greater in headfires than backfires. Fire type (head fire or backfire) and variables related to fuel continuity, fuel loading, and fuel moisture were related to time-temperature relationships. Variables related to fuel load and weather were related to Byram's fireline intensity for headfires and backfires and for rate of spread for hcadfires.

INTRODUCTION

Data about the behavior of fire in the tallgrass prairie arc needed in order to increase our understanding of the interactions of fire behavior, fire environment, and fire cffccts. Previous studies of firc behavior have been confined primarily to wildfire in forests and shrublands and described mainly in terms of fireline intensity (Byram 1959; Wright and Bailey 1982). Because fire intensity is related to crown scorch of conifers (Van Wagner 1973) and because fireline intensity is used for describing wildfire behavior (Albini 1976), fireline intensity has been suggested for describing fire behavior in grasslands (Rothermc] 1972; Albini 1976) and for predicting scorch height on rangeland shrubs (Roberts and others 1988). Although fireline intensity accounts for the heat or energy released in the initial tire front, it does not account for energy released over the entire depth of the combustion zone (Tangrcn 1976; Alexander 1982). Combinations of fire temperatures and time-temperature relationships, rather than fireline intensity, have been used to quantify fire behavior in the residual combustion zone in tallgrass prairie fires (Engle and others 1989) and to relate fire behavior to tire effects on herbaccous vegetation (Stinson and Wright 1970; Wright 1971; Hobbs and Gimingham 1984; Ewing and Engle 1988; Bidwcl] and others 1990).

Research has not established whether grassland backfires or headfires produce higher maximum temperatures at the soil surface (McKell and others 1962; Daubenmirc 1968; Bailey and Anderson 1980). Because both fire types arc used in prescribed spring bums in the tallgrass prairie, it would enhance our knowledge of fire effects to elucidate their behavior. The fuel, topography, and weather in which a fire occurs dictates its behavior and may explain the contradictions regarding the behavior of headfires and backfires. Parameters of the fire environment that are easily measured by rangeland fire managers may also bc useful for predicting fire behavior in tallgrass prairie. Time-temperature relationships may be useful in describing differences between headfires and backfires by quantifying energy release in the entire combustion zone in tallgrass prairie fires. The objectives of our study were to compare the behavior of headfires and backfires and to explore the relationship between the behavior of tallgrass prairie tires and commonly measured variables of the fire environment.

STUDY AREA

Our study area is located on the Agronomy Research Range 15 km west-southwest of Stillwater, Oklahoma. Mean annual precipitation is 81 cm. The study area is a shallow prairie range site in the Central Rolling Red Prairies Land Resource Area (USDA Soil Conservation Service 1981). The soil is Grainola clay loam with a clay B horizon and is a member of the fine, mixed thermic family of Vertic Haplustalfs. Dominant grasses on the site include big bluestem (*Andropogon gerardii* Vitman), switchgrass (*Panicum virgatum* L.), indiangrass (*Sorghastrum nutans* (L.) Nash), and little bluestem (*Schizachyrium scoparium* (Michx.) Nash). The study area was grazed at a moderate to heavy stocking rate (2.4 AUM ha") from mid-July to mid-November in 1985 and 1986 before the treatments were applied in the spring of 1986 and the spring of 1987.

METHODS AND MATERIALS

We replicated treatments four times in a randomized complete block design. The 10 m by 20 m plots were located on nearly level terrain (< 2 percent slope), and oriented southeast to northwest so the direction of their long axes would correspond to the direction of the prevailing southeast spring wind. Each replication consisted of a headfired plot and a backfired plot. We used a drip torch to set the fires at plot borders. Burning treatments began in March and ended in April. Each replication was burned within a 4-hour burning period, and weather variables and fuel load were sampled

[1]Assistant Professor and Professor of Range Science, Grazing Lands Ecology and Management Group, Oklahoma State University, Stillwater OK.

immediately before each bum. Weather variables included ambient air temperature, relative humidity, and wind speed 2 m above the ground and were measured by means of a belt weather kit Fuel load was estimated by weighing clipped herbaceous material from five quadrats (0.5 m by 0.5 m) per plot. Clipped herbage was separated into standing tine fuel and fallen tine fuel (litter and mulch) before weighing. Fuel moisture, expressed on a dry weight basis, was determined after samples were oven dried at 70 °C for 72 hours.

We measured tire temperatures at 2 second intervals by means of high-temperature, chromel-alumel thermocouples at three stations per plot and at three heights relative to the soil surface (0 cm = soil surface; 30 cm = top of herbaceous canopy; 60 cm = above the herbaceous canopy). The thermocouple wire was 24 AWG with thermojunctions approximately 6 mm long and 1 mm in diameter and with 5- to 7-m leads overbraided with high temperature ceramic fiber insulation. An electronic data logger (Campbell Scientific model 21X with multiplexer) with tape data storage was used to record time-temperature data. Traces of time-temperature that were recorded for each thermocouple allowed estimates of degree seconds above ambient temperature (Potter and others 1983), maximum temperature, and residence time (the time from initial temperature rise to time of definite temperature drop) (Rothermel and Deeming 1980). A program in Turbo Pascal for IBM compatible microcomputers was used to generate each of these variables from the thermocouple data. A discrete summation algorithm was used to arrive at an estimate of degree seconds, which is the area above ambient temperature and under the time-temperature curve. The points of definite temperature rise and drop for computing residence time were determined numerically by sequential reverse progression through a IO-second interval of the time-temperature curve to points of 2 °C or greater departure from the postburn ambient temperature (Engle and others 1989).

Byram's (1959) fireline intensity model is expressed as I=Hwr, where I is fireline intensity, H is the fuel's low heat of combustion (LHOC)(kJ kg"), w is the weight of fuel consumed per unit area (kg m^{-2}), and r is the rate of spread (m s^{-1}). Low heat of combustion was determined by bomb calorimetry for the total fuel sample (standing and fallen). Fuel consumed was considered to be equal to fuel load because of the completeness of the bums. Rate of spread was reported in m min^{-1}. We measured rate of spread with a stopwatch and photographically with a 35 mm camera time-mode device in a manner similar to that employed by Britton and others (1977).

Approximate T tests were performed on tire behavior data (SAS, Inc. 1985). Differences between means of tire behavior variables were considered significant at the 1 0-percent probability level. Stcpwise multiple regression techniques were used to construct models of fire behavior (Table I) from the mean **values** of the environmental variables

Table 1. Fire behavior variables used in regression modets for relating fire environment to fire behavior on tat lgrass prairie

Variable	Code	Headfire (n=5)				Backfire (n=7)				P>F
		Min	Max	Mean	SE	Min	Max	Mean	SE	
Fireline intensity (Kw m^{-1})	BFI	75	2778	1167	445	31	146	97	16	0.02
Rate of spread (m min^{-1})	ROS	1	35	12	6	.5	2	1	.2	0.04
Degree seconds 0 cm (°C x s)	DS0	2504	8260	5941	997	1035	31136	9508	4001	0.48
Degree seconds 30 cm ("C x s)	DS30	993	10993	6096	1727	2863	21523	10244	2731	0.27
Degree seconds 60 cm (°C x s)	DS60	551	6465	4962	1115	198	7767	4149	1249	0.65
Residence time 0 cm (s)	RT0	111	705	250	114	74	589	255	75	0.97
Residence time 30 cm (s)	RT30	158	553	337	a2	151	756	465	70	0.26
Residence time 60 cm (s)	RT60	92	779	429	139	116	749	487	77	0.70
Maximum temp. 0 cm (°C)	MT0	48	386	216	59	73	687	215	81	0.99
Maximum temp. 30 cm (°C)	MT30	67	537	307	a3	108	634	270	68	0.74
Maximum temp. 60 cm (°C)	MT60	44	378	274	83	24	132	78	14	0.094

Table 2. Mean independent environmental variables from headfires (n=5) and backfires (n=7) used in multiple regression models

Variable	Code	Min	Max	Mean	SE
Relative humidity (%)	RR	18	51	34	2
Air temperature C"	TMP	15	26	21	l
Wind speed (km hr.')	WIND	3	24	10	l
Fuel load dry weight (kg ha")"	FLD	2372	5584	3570	260
Fuel load fresh weight (kg ha')	FLF	2720	6576	4707	298
Fuel moisture (standing) (%)	FMS	5	59	28	4
Fuel moisture (fallen) (%)	FMF	13	148	46	9
Fuel moisture (total) (%)	FMT	12	60	31	4
Quadrat fresh weight STD[b]	QFFS	18	56	42	3
Quadrat dry weight STD	QFDS	11	50	32	3
Quadrat fresh weight min."	QFFMIN	15	122	69	8
Puadrat dry weight min.	QFDMIN	12	100	54	26
Quadrat fresh weight CV (%)[d]	CVF	12	74	36	17
Puadrat dry weight CV (%)	CVD	15	70	37	15

[a] All quadrat values (weight) in g $0.25m^{-2}$
[b] STD = standard deviation
[c] Minimum quadrat value within a plot
[d] CV = coefficient of variation

(Table 2) and tire type as a dummy variable (I for headfire and 2 for backfire) (SAS, Inc. 1985). Measures of variation associated with fuel load, standard deviation, and coefficient of variation for a plot, were included as measures of fuel continuity. Minimum quadrat sample values within a plot were included to provide an estimate of minimum fuel loading which, from observation, may affect fire spread over the fuel bed. Variation and minimum values of fuel loading were derived from five quadrats per plot. Five headlires and 7 backfires were used in the analysis because of wind shifts away from the longitudinal axis of the plots.

RESULTS

Byram's fireline intensity (BFI) of headlires averaged 1167 ± 445 kWm^{-1}, which was 12 times greater than fireline intensity of backfires (97 ± 16 Kw m^{-1}) ($P=0.03$). Rate of spread (ROS), the main influence on BFI, was 10 times greater for headfires (12.6 ± 6.0 m min^{-1}) than for backfires (1.0 ± 0.2 m min^{-1}) ($P=0.09$). Regression models explained more than 90 percent of the variation in BFI for both headlires and backfires and in ROS for headfires (Table 3). Degree

Table 3. Regression models relating environmental variables to Byram's fireline intensity (BFI) and rate of spread (ROS) on tallgrass prairie

Dependent Variable	b_0	b_1	X_1	b_2	X_2	R^2	P>F
Headfires							
BFI	-2274	0.39	FLF	24	FMF	0.94	0.0001
ROS	0.07	0.005	FMF	-0.604	RH	0.95	0.0001
Backfires							
BFI	497	-6	RH	-3	TMP	0.92	0. oool
ROS	0.04	-0.0006	FMS	-0.0001	QFDMIN	0.63	0.0001

seconds and residence time did not differ by fire type at any height ($P > 0.10$) (Fig. la, lc). Head fires produced greater maximum temperatures than backfires at 60 cm (P-0.004) (Fig. lb).

Parameters related to fuel load and fuel moisture were the most important variables entering regression models of time-tcmpcraturc relationships for all heights (Table 4). Fire type occurred as a first-entered variable in four of nine models. Environmental parameters and tire type explained at least 70 percent of the variation in each regression model (Table 4).

DISCUSSION

Behavior of Headfires and Backfires

Fireline intensity of headfires and backfires in our study were similar to those observed in other grassland fire studies (Engle and others 1989; Roberts and others 1988). The greatest fireline intensity we measured in a headfire, 2778 Kw m $^{-1}$, was one-third as great as that observed in homogeneous grass stands in West Texas (Roberts and others 1988), but was comparable with the greatest fireline intensity in a summer head fire in a moderately grazed tallgrass prairie (Englc and others 1989). The magnitude of the difference between the ROS of our headfires and the ROS of our backfires is consistent with the rate of spread in two grassland communities in west Texas (Roberts and others 1988). Rate of spread and fuel consumption are the major variables in Byram's model of fireline intensity. Although fireline intensity and rate of spread were greater in headfires in our study, several time-temperature parameters did not differ between fire type because time-temperature profiles reflect both the intensity (heat release rate) and heat transfer for the entire combustion period. Headfires are considered more intense than backfires because they consume fuel more rapidly and spread more rapidly than backfires (Lindcnmuth and Byram 1948; Trollope 1984). In contrast, the difference between degree seconds for headfires and degree seconds for backfires were much smaller. Degree seconds relate to the heat released over the entire combustion period, whereas fireline intensity represents only the rate of release of heat energy from the flaming front. Thus, the rate of release of heat energy is greater in headfires, but the two fire types release similar total amounts of heat energy.

Both fire types have been reported to be hotter above the herbaceous canopy (Fahnestock and Hare 1964; Bailey and Anderson 1980; Trollope 1984). Although mean maximum temperatures were not significantly different between headfires and backfires, they were highest at 30 cm in both backfires and headfires. Maximum temperature declined more from 30 cm to 60 cm in backfires. Maximum temperature above the herbaceous canopy is higher in head fires because the rate of energy release and convection are greater in headfires. Thus, differences between above

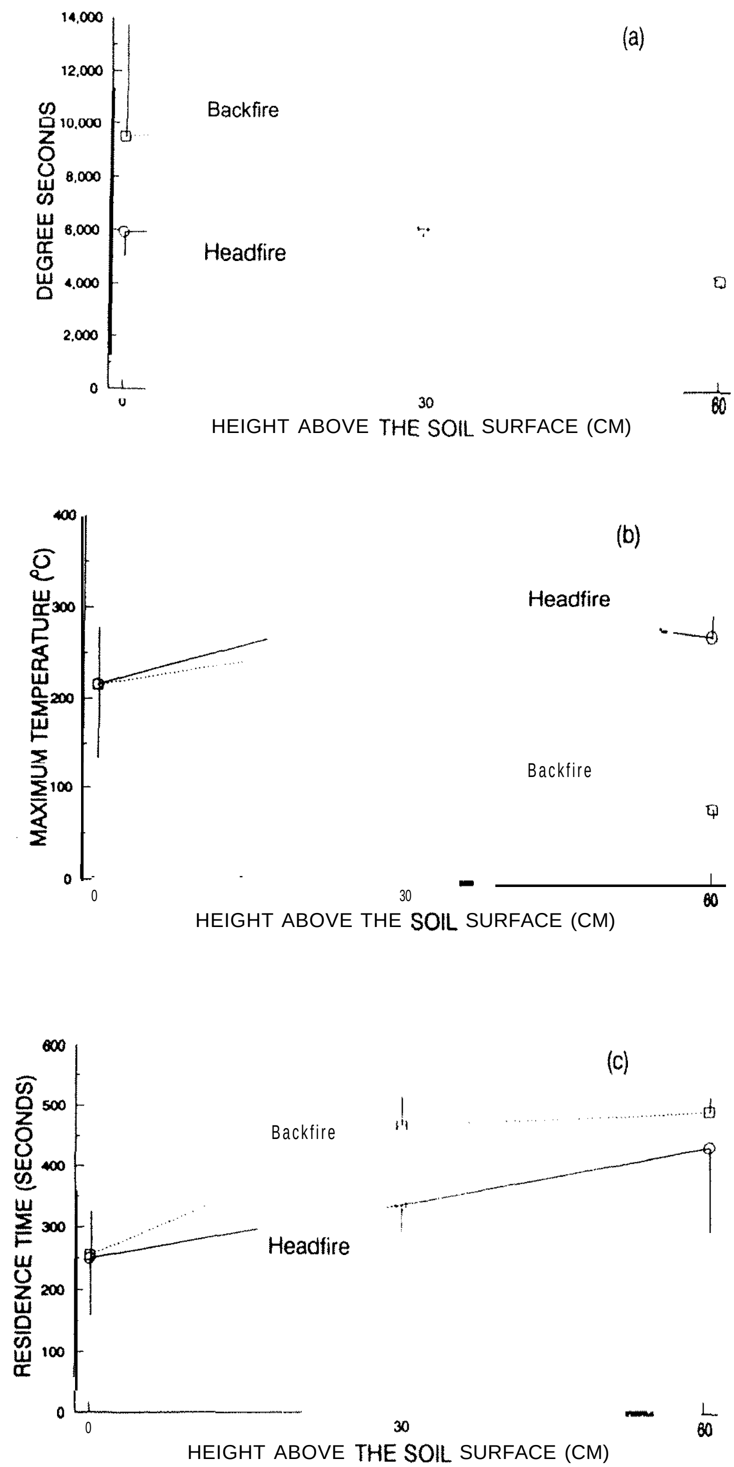

Figure 1. Time-temperature relationships in tallgrass prairie headfires and backfires for degree seconds (a), maximum tcmpcraturc (b), and residence time (c). Bars are plus or minus one standard error.

Table 4. Regression models relating fire type and environmental variables to time-temperature relationships of spring fires on tallgrass prairie'

	b_0	b_1	X_1	b_2	X_2	b_3	X_3	b_4	X_4	R^2	P>F
Degree seconds at 0 CM											
	23027	-462	FMT	1255	WIND	478	QFFS	-1049	QFDS	0.75	0.03
Degree seconds at 30 CM											
	27647	4561	TYPE	-2	FLD	-250	RH	25466	CVO	0.81	0.01
Degree seconds at 60 CM											
	17183	1	FLD	32	FMF	-212	RH	-140	TMP	0.88	0.02
Residence time at 0 CM											
	18	-1	FMF	48	WIND	2674	CVF	-3251	CVD	0.70	0.06
Residence time at 30 CM											
	2597	2.51	TYPE	-16	RR	-24	TMP	-1151	CVF	0.93	0.0004
Residence time at 60 CM											
	4048	212	TYPE	-27	RH	-31	TMP	-1362	CVF	0.89	0.002
Maximum temperature at 0 CM											
	1403	-0.19	FLD	-11	FMT	12	OFFS	-1798	CVD	0.79	0.02
Maximum temperature at 30 CM											
	1016	-0.08	FLF	2	FMF	-8	RH	-474	CVD	0.73	0.04
Maximum temperature at 60 CM											
	605	-206	TYPE	-9	RR	10	QFFS	-8	QFDS	0.87	0.003

'See Table 2 for descriptors

canopy maximum temperatures for prairie headfires and backfires reflect differences in rate of energy release much as did differences in fireline intensity between headfires and backfires.

Disagreement exists in the literature as to which tire type produces the hotter tire at the soil surface. McKell and others(1962) found that backfires produce higher temperatures at the soil surface than head fires do, but Daubenmire (1968) directly contradicts McKell and others Although maximum temperature was highly variable in both tire types we did not find that it differed significantly between fire types.

Fire temperature in the combustion zone is primarily dependent upon the quantity of fine fuel consumed (Stinson and Wright 1969; Engle and others 1989). Fine fuel load also has a pronounced effect on residence time, which increases proportionally to fuel load (Stinson and Wright 1969), especially with accumulation of mulch on infrequently burned tallgrass prairie (Engle and others 1989). The time required for active combustion was very nearly the same in both tire types in our study, and we would expect a difference in residence time measured by thermocouples placed on the soil surface only where there are differences in fuel loading or fuel consumption.

Regression Models

Fuel load and fuel moisture variables rather than weather variables were the tire environment parameters most strongly related to tire behavior. Fuel load was an important variable in our models. Fuel load accounted for 30 to 60% of the variation in fireline intensity in grassland fires in Africa (Trollope and Potgieter 1983). Our results were similar to those of other studies showing that fuel moisture affects ignition and combustion more than any other environmental factor (Byram 1957; Brown and Davis 1973).

Fuel continuity variables appeared in all but two models. Fuel continuity is a primary factor in tire behavior but is less important when heavy fuels arc available or wind speed is high (Brown and Davis 1973). Wind speed is an important influence on tire behavior including rate of spread (Rothermel 1972; Albini 1976), but fuel discontinuity may alter the influence of wind so much that mathematical tire models become poor approximations of tire behavior (Brown 1982). Mathematical models assume uniform fuel (Brown 1982), which seldom occurs in tallgrass prairie. Wind speed (< 24 km h^{-1}) was not an important variable in our tire behavior models (Table 3).

CONCLUSIONS

Fireline intensity and rate of spread, measures of 'fire behavior that relate to behavior of the flaming fire front and rate of energy release, indicate that headfires are at least ten times more intense than backfires in grazed tallgrass prairie. Time-temperature measures of fire behavior that account for energy released across the entire combustion zone indicate lesser differences between fire types. The behavior of backtires is more variable than headfires in discontinuous fuels.

In addition to tire type, fuel loading and fuel moisture were important variables in regression models of fire behavior. Fuel load largely determines the amount of energy available for combustion. Fuel continuity measures were important variables in regression models of fue behavior because they reflect the subtle fuelbed and microclimate differences associated with grazed fuel beds. Mosaics of discontinuous fuels or disturbed patches often result from spot grazing by large herbivores, soil disturbance by small mammals, soil heterogeneity, or natural spatial heterogeneity of tallgrass prairie vegetation (Loucks and others 1985). Our research indicates that fuel parameters together with fire type are major factors associated with variation in fire behavior. This should enable us to understand the role of fire as an disturbance factor in the tallgrass prairie plant community.

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FIRE AND AGRICULTURAL ORIGINS: PRELIMINARY INVESTIGATIONS

Mark A. Blumler[1]

Abstract—tested the hypothesis that hunter-gatherers used fire to manipulate wild cereal stands, in a process leading to agriculture. In Israel, wild emmer (*Triticum dicoccoides),* barley (*Hordeum spontaneum*), and oats (*Avena sterilis*) grow in mixed stands, so efficient harvest is difficult. Wild cereal grains are differentially protected against fire by hull thickness and efficiency of self-burial. Wild oat diaspores drill deeper into soil than wild barley and emmer, except next to rocks, where wild emmer drills best. Wild barley has thin hulls that protect against charring less than the thick hulls of wild emmer and oats. I predicted that wild barley is susceptible to tire, and wild oats more tolerant than wild emmer except around rocks. Distribution and survival of wild cereal grains after arson fire supported these predictions. Wild barley occurred almost exclusively in unburned spots. The percentage of charred wild oat grains was lower than that of wild emmer in open soil, but not adjacent to rocks. The results suggest that people could have set fires to reduce the importance of wild barley, and in rocky areas to favor wild emmer, but it is doubtful whether they would have desired to do so.

The Agricultural Revolution was one of the major watersheds in human history and cultural evolution, and led to unprecedented, ongoing transformations of global ecosystems. The causes of this change in human economy continue to be debated (Adams 1983; Binford 1968; Blumlcr and Byrne 1991; Byrne 1987; Cohen 1977; Flanncry 1965, 1969, 1973; Harlan 1975, 1986; Henry 1989; Reed 1977; Rindos 1984; Sauer 1952). Available cvidcncc suggests that environment was at least as important as cultural/technological state: early agricultural centers were characterized by semi-arid climates with a long dry season, which favored the evolution *of annual* grasses and legumes with unusally large seeds, and gcophytcs (Blumler 1984, 1987, 1991b; Byrne 1987); most if not all of the first crop plants were derived from such species (Blumlcr 1987, 199lb; Byrne 1987). The Fertile Crescent is an area of special interest since cultivation may have begun there first, by 10,000 B.P. (Hillman and others 1989; Zohary and Hopf 1988), or perhaps several thousand years earlier (Kislcv and Bar-Yosef 1988; Unger-Hamilton 1989). Some scholars have suggested that the initiation of farming in this region was connected to the USC of fire as a vegetation management tool (Lewis 1977,; Navch 1974, 1984; Pullar *1977).* They proposed that fire was employed to increase and maintain the abundance of wild cereal grasses, and may even have caused the evolution of these unique monstrosities (fig. 1) in the first place.

Ethnographic and historical evidence demonstratcs that hunter-gatherers often manipulate vegetation with fire (Burrows 1991; Day 1953; Hallam *197.5, 1989;* Lewis 1973; Reynolds 1959; Shipek 1989; Stewart 1956). Control of fire certainly predates the Epipalcolithic, and may be of great age in the Old World (Naveh and Dan 1973; Sauer 1956). Regular burning of vegetation is well-attested in early historical times in Israel, Greece, and Rome (Liacos 1973; Naveh 1974). Thus, it is reasonable to assume that Late

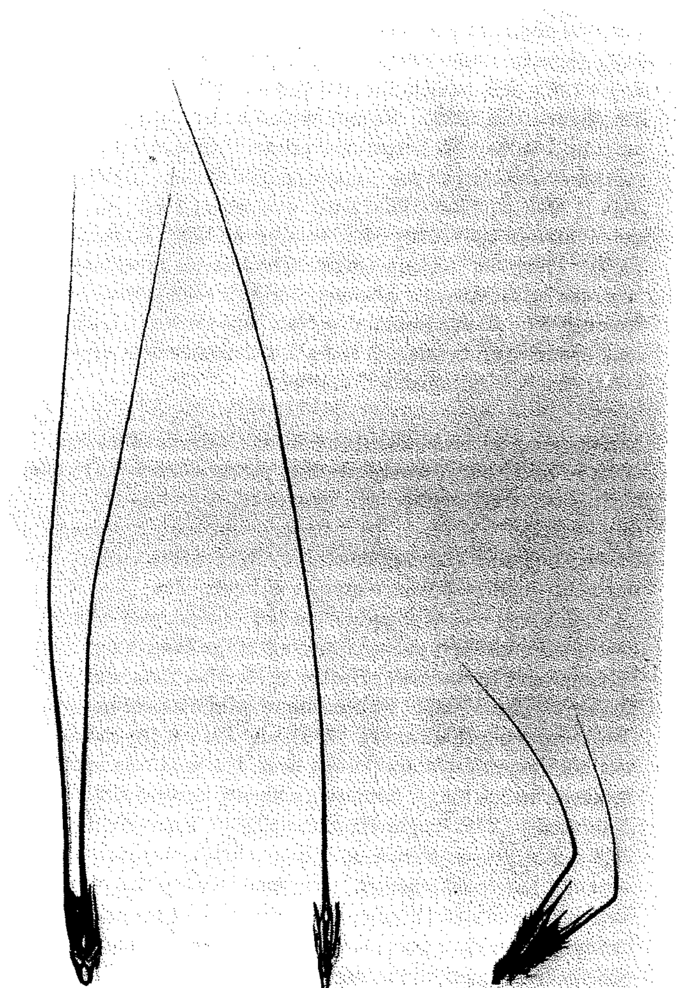

Figure 1.-Diaspores (from left to right) of wild emmer *(Triticum dicoccoides),* wild barley *(Hordeum spontaneum),* and wild oats (*Avena sterilis*). *(X* 2/3).

[1]Graduate Student, Department of Geography, University of California, Berkeley, CA.

Pleistocene peoples of the Near East would have set fires if the availability of wild cereals or other resources could have been enhanced by doing so. Noncthclcss, archaeologists and paleoecologists have been suspicious of the fire/domestication hypothesis, because archaeological/paleobotanical evidence offers no convincing support (Wright 1980). Furthermore, the study of Near Eastern fire ecology is in its infancy, and assertions about the response of wild cereals to tire have been pure speculation. The proponents of the fire/domestication hypothesis have generally assumed that the Fertile Crescent was naturally covered by dense woody vegetation, and that wild cereal stands could have formed only after the removal of this cover by disturbances such as fire. However, it is now well-established that steppic vegetation dominated the region during the Late Pleistocene, except possibly along the Levantine coast (Van Zeist 1969; Van Zeist and Bottema 1982), and that seedling establishment of woody species is extremely difficult on the fertile basaltic and terra rossa soils presently dominated by wild cereals (Berliner and others 1986; Blumler 1984, 1991b, c, d; Kaplan 1984; Litav and others 1963; Rabinovich-Vin and Orshan 1974; Rabinovitch-Vin 1983). Recent evidence also strongly suggests that the wild cereals arc primarily adapted to ungrazcd, undisturbed (i.e., unbumcd) conditions (Blumler 1984, 1991b, c; Litav 1965; Litav and others 1963; Naveh and Whittaker 1979; Noy-Meir and others 1989; Zohary 1969). Thus, the tire/domestication hypothesis in its original form can be dismissed _ although Naveh's (1984; Kutiel and Naveh 1987a, b) suggestion that Natufians on Mt. Carmcl used fire to open up maquis and allow establishment of wild cereal stands is reasonable if unproven.

In any case, the possibility that fire may have been used to favor wild cereals in certain specific circumstances, or to alter the mix of cereal grasses on a given site, is worthy of consideration. In Israel, for instance, wild emrner wheat, wild barley, and wild oats commonly form dense, mixed stands on good soils where grazing is light. The archaeological record suggests that wild emmer and wild barley were the first plants cultivated in the Near East (Blumler and Byrne 1991; Harlan 1975; Van Zeist and Bakker Heeres 1985).[2] Harvesting of wild oats seems to be time-consuming (Ladizinsky 1975), and the oat (*A. sativa*) was not domesticated until much later; but wild oats tend to dominate stands today, rendering efficient harvest difficult (Ladizinsky 1975; Unger-Hamilton 1989). Since the three wild cereal grasses mature at different times, they probably were not harvested together. Any manipulation that would have increased stand purity, especially of wild emmer or wild barley, should have been of benefit to the pre-agricultural peoples (Natufians) of the region.

While carrying out fieldwork in Israel during the 1987-8 rainy season, I undertook preliminary investigations into the effects of fire on the relative abundance of these three grasses. To this end, I considered diaspore characteristics that should affect fire tolerance, and tested my conclusions by measuring survival after fire. Ecological speculations arc rampant in the literature on agricultural origins, but experimental testing of ecological hypotheses is rare. This study was carried out in part to provide an illustration of the sort of research procedure that should prove fruitful in illuminating our presently rather sketchy understanding of the circumstances surrounding agricultural beginnings.

DIASPORE MORPHOLOGY AND FIRE

Several factors are likely to influence seed mortality during a bum. Grass fires arc typically fast-moving and not very hot, so seeds that are protected by a thick seed coat or other investing structures may escape with only minimal charring. During the passage of fire, a pronounced temperature gradient exists between the surface and deeper soil layers, so buried seeds should suffer much less mortality than those that lie on the surface or are caught up in the litter.

Wild cereal diaspore morphology is an adaptation that allows self-burial. I examined a number of sites early in the growing season, and found that depth of burial depends on microsite conditions and species (figs. 2 and 3).[3] Wild oats have hygroscopic awns, which cause burial, at approximately identical depth, under a wide range of conditions. Where there is no litter, wild emmer and barley tend to become oriented horizontally, which precludes self-burial except when diaspores are wedged up by rocks or soil cracks. Immediately adjacent to rock outcrops, wild emmer typically drills deeper than either wild barley or oats (in fact, it is occasionally found 15 or more centimeters beneath the surface).' Where there is abundant litter, wild barley diaspore rachis tips tend to weakly penetrate the soil surface, leaving the grain almost completely exposed, while wild emmer often remains suspended entirely above ground; nonetheless, seedling establishment of both species is excellent, presumably because litter shade reduces moisture stress. It may be no coincidence that wild emmer is found almost exclusively on hard limestone hills and basaltic plateaus (Harlan and Zohary 1966; Zohary 1969, pers. comm.), where rock cover is often so great that the seed rain from plants growing adjacent to rocks is spread throughout much of the open soil area, allowing rapid re-establishment away from rocks under favorable (i.e., high litter) conditions.

'Wild emmer is the progenitor of emmer (*T. dicoccum),* durum (*T. durum*), and most other tetraploid wheats, as well as bread wheat (*T. aestivum*); wild barley is the progenitor of all domesticated barleys (*H. vulgare*).

'Quantitative empirical data on drilling success in relation to microsite will be presented elsewhere (Blumler n.d.). Variability is great, of course; figures 2 and 3 are merely schematic diagrams illustrating the most characterisitc final positions of wild cereal diaepores under differing microsite conditions. Discussions of wild cereal self-burial in the literature (Aaronsohn 1910; Cook 1913; Zohary 1960, 1969; Zohary and Brick 1961) are generally in accord with my findings.

'In such cases, seedling emergence may be problematic

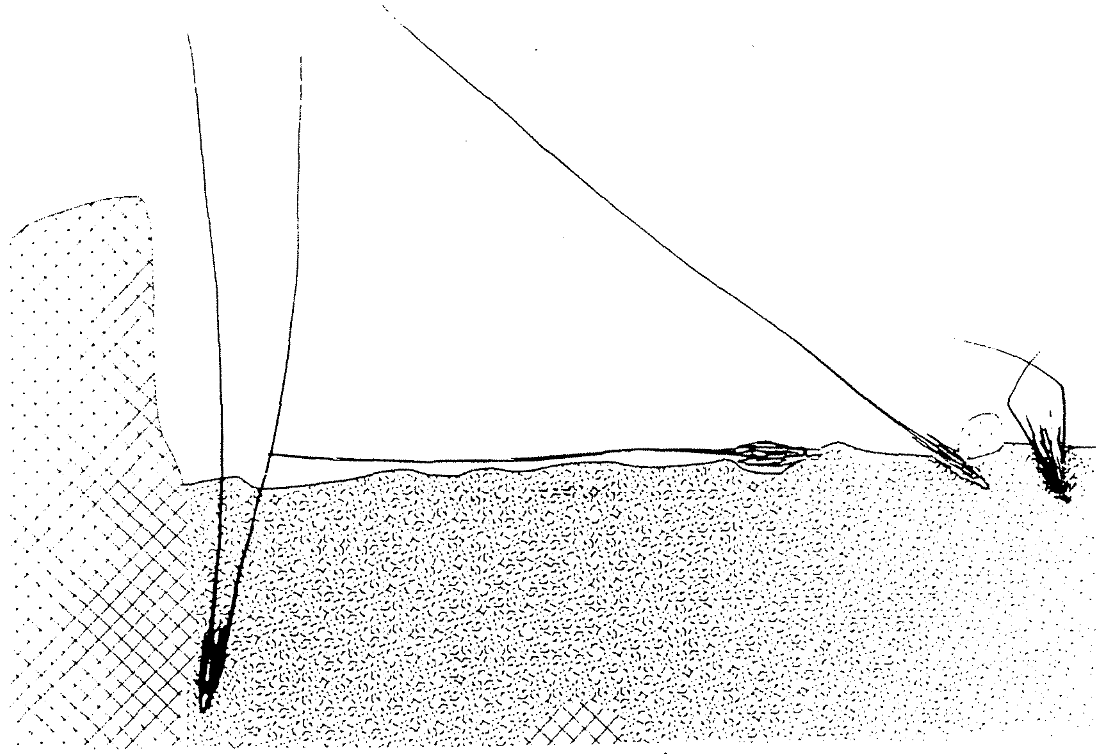

Figure Z.-Characteristic final position of wild cereal diasporcs in thc abscncc of plant litter (i.e., as a result of hcavy grazing or other disturbance). Wild emmcr and wild barley tend to lie prone, which prccludcs burial; whcn wcdgcd upwards by rocks, however, wild emmcr, in particular, can drill very far bcncath the soil surface (lcft). Wild oats burics itself wcll, cvcn in open soil (right).

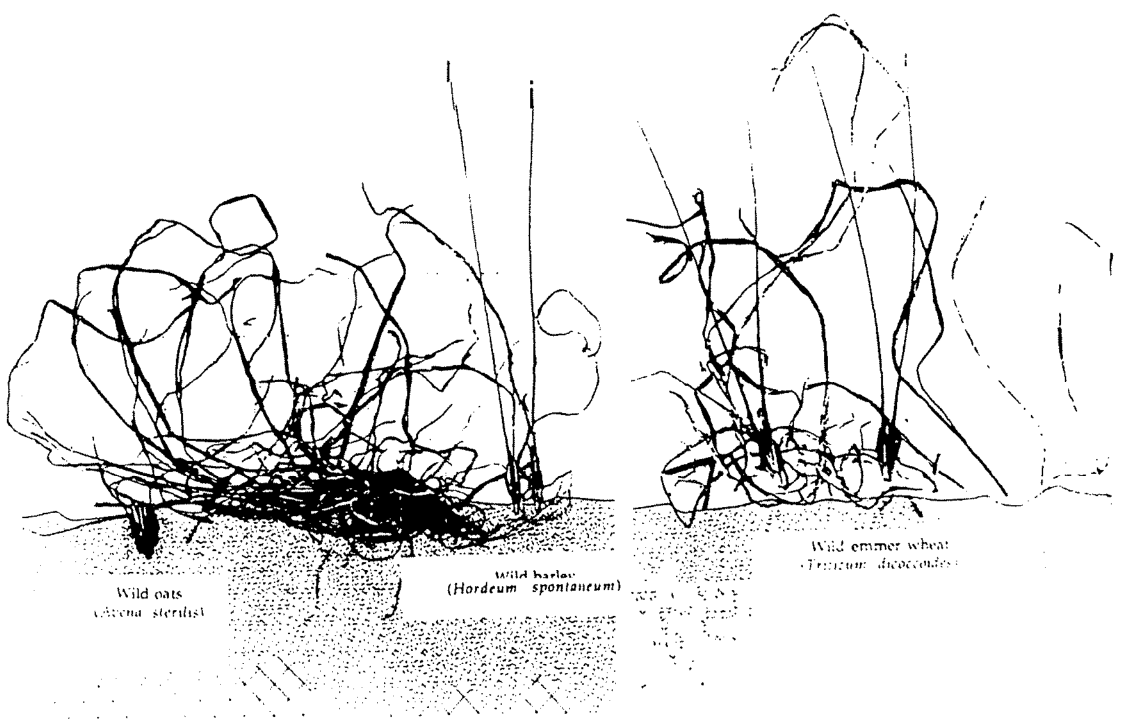

Figure 3.-Characteristic final position of wild cereal diasporcs whcre thcre has bccn an accumulation of litter (under rclativcly undisturbed conditions). Wild oats is about as succcssful at self-burial as it is under no-litter conditions; wild barlcy barcly pcnctrates the soil surface with its rachis tip; while wild emmcr typically remains suspended just above the soil surface.

Table 1. Characteristics presumably influencing resistance of wild cereal diaspores to charring and heat caused by fire.

	Hull Thickness	Self-Burial: Open Soil	Self-Burial: By Rocks	Seed Dormancy
wild emmer	thick	very poor	best	less than 50 percent
wild barley	thin	poor	good	almost none
wild oats	thick	good	good	50 percent or more

Wild barley has relatively thin hulls, and no seed bank (table 1); hence, it is probably more vulnerable to fire than wild emmer or wild oats, which enclose their seeds in thick husks and have a large pool of dormant seeds that tend to become buried during the growing season, if not before.[1] Hence, I predicted that wild barley is susceptible to fire, and wild oats more tolerant than wild emmer except around rocks.

MORTALITY DURING FIRE

Distribution and survival of wild cereal grains after arson fire supported these predictions. The study site was a Cenomanian limestone/dolomite plateau (Givat Ha-Kerem) in Jerusalem, covered by terra rossa (Danin and others 1983). Since 1948, grazing has been excluded almost completely (there was no grazing at all by domestic animals during 1987-8), and as a result, the site is dominated by wild cereals (as are many other outcrops of the same rock type around Jerusalem). In recent years, fires have been set annually on Givat Ha-Kerem by schoolchildren celebrating the end of term; because of the extremely rocky terrain, however, fires arc spotty, so that some patches remain unaffected. To determine vulnerability of wild cereal diaspores to fire, I roped off small (IO-27 dm^2) plots in the burned parts of Givat Ha-Kerem in March, 1988 (9 months after the fire, and long after the completion of germination), and determined percent mortality as the ratio of number of spikelets without seedlings to total number of spikelets. Random samples of spikelets that failed to produce seedlings revealed that all grains were discolored or charred, and probably inviable: germination of spikelets in these species is normally on the order of 90 percent or more (Anikster and others 1988; Golcnberg 1986; Blumler unpublished data). I sampled plots in open ground, as well as adjacent areas by rocks. Because of the large size and only partial burial of wild cereal diaspores in open areas, all spikelets could be easily located. However, determination of wild emmer mortality rates adjacent to rocks was more problematic, because it often buries itself completely there. Wild barley occurred almost exclusively in unburned spots, such as ant nests and rockpiles; I was unable to locate it in burned areas until anthesis, at which point it was too late to sample the previous year's diaspores. Hence, only the effects of fire on wild emmer and wild oats could be studied and compared. However, the strong preference of wild barley for unburned spots suggests that it is intolerant of fire. Unfortunately, I developed back problems and was forced to terminate the experiment after only a small number of plots had been examined. Nonetheless, I obtained statistically significant results.

The results are presented in table 2. In open areas, wild emmcr spikelet mortality was high, on the order of 60 percent. Wild oat mortality was less than that of wild emmer

Table 2. Scorching of wild cereal diaspores by an arson fire on Givat Ha-Kerem, Jerusalem, 1987

	Wild Emmer			Wild Oats		
Plot[a]	Scorched	Seedlings	Pct Mortality[b]	Scorched	Seedlings	Pct Mortality[b]
S1	164	98	62.6	12	4.5	21.1
S2	39	42	48.1	47	140	25.1
S3	112	17	86.8		0	100.0
S4	61	63	49.2	4	11	26.1
S5	29	28	50.9	13	102	11.3
	405	248	62.0	77	298	20.5
R1	16	15	51.6	2		66.7
R4	19	26	42.2	2	4	33.3

[a]Plots S1-S5 were located in open soil; plots R1 and R4 were located beside rocks, adjacent to S1 and S4, respectively.

[b]Percent mortality was calculated assuming that one and only one seedling arose from each viable diaspore. To the extent that seed predators may have removed diaspores, total mortality rates are likely to have been higher than calculated here.

[1]Wild emmer and wild oat diaspores typically contain a non-dormant grain and one or more dormant ones; the roots of the plant derived from the non-dormant grain tend to pull the diaspore down into the soil to some extent, thus increasing burial of dormant grains (Zohary pers. comm.).

at every open soil plot except S3, which contained only a single wild oat diaspore. If this plot is excluded because of the small wild oat sample size, wild emmer mortality was significantly greater than that of wild oats (t-test, $p < .01$). Most scorched diaspores lay on the surface or penetrated only slightly beneath it. Many surviving grains, on the other hand, were almost completely buried. Wild oats were rare adjacent to rocks, so comparison with wild emmcr in that microsite is problematic. There was no clear indication that the two species differed significantly in mortality around rocks. Wild emmcr survival was greater in plots R1 and R4 than in the adjacent open soil plots, but tests of statistical significance cannot be carried out on such limited data. Within R1 and R4, surviving wild emmcr diaspores were often completely buried, and immediately adjacent to a rock, whereas the destroyed diasporcs tended to bc a few ccntimctcrs away from the rocks, and not so well-buried.

DISCUSSION AND CONCLUSIONS

These preliminary results suggest that fire could have been employed to selectively reduce the importance of wild barley, and perhaps also to favor wild emmer in rocky areas, but that wild oats would generally benefit most. At Givat Ha-Kcrcm wild oats dominates most open soil areas, for instance, while wild emmer shares dominance in open soil at Givat Ram, a nearby unburned site. However, further multi-year studies are needed to verify these conclusions, and other aspects of wild cereal demography need to be studied, such as the effects of fire on reproductive output and predation. Wild emmcr seems to be a poor competitor (compared to wild barley and wild oats), so reduction in seedling density might allow it to establish larger, more productive individuals. Harvester ants (***Messor semirufus***) are the major seed predators at many wild cereal sites, such as Givat Ha-Kcrem, and they forage more efficiently where litter has been removed. Observations indicate that ants take wild barley relatively easily, perhaps because its single awn and elongate shape increase its maneuverability; wild oats and emmcr, on the other hand, have spreading awns that catch in litter, and harvesting rates of these two species may increase dramatically on a bare surface. In the absence of empirical data, one cannot rule out the possibility that in open areas wild emmer mortality from charring and heat might be balanced by wild oat mortality from predation, although this seems unlikely. Also, while the distribution of wild barley is suggestive, other explanations for its rarity on the Givat Ha-Kerem bum should be considered. It is possible, for instance, that wild barley requires relatively fertile conditions, such as are found on the harvester ant nests, which happen also to be seldom burned. However, data on species composition before and after fire at other Israeli sites (Olsvig-Whittaker and others n.d.; Blumler unpublished data; Naveh and Whittaker unpublished data) indicate that wild barley suffers dramatically during the first season after a bum.

There is no archaeological record of use of wild oats, and wild oats are less efficient to harvest than wild emmer or barley (Ladizinsky 1975). Hence, it is by no means certain that Epipaleolithic people would have found it worthwhile to burn wild cereal stands. Nonethclcss, they may have burned dense maquis on Mt. Carmel and other Levantine hills to encourage wild cereal establishment, as proposed by Naveh (1984; Kutiel and Navch 1987a, b).

Another possibility, which has not been considered in the agricultural origins literature, is that fire may have been used to favor wild legumes (specifically, the progenitors of lentils, peas, and chickpeas). These plants are seldom abundant today, and thus seem to be poor food resources (Blumlcr 1991a; Ladizinsky 1987; Zohaty and Hopf 1973). Yet they, too, were cultivated at an early date-possibly as early as or even earlier than the cereals (Kislev and Bar-Yosef 1988).[6] Fire often seems to favor legumes (e.g., Barry 1971; Burrows 1991; DeSelm and Clebsch 1991; Masters 1991; Parsons and Stohlgrcn 1989). Future research should be directed towards testing the hypothesis that burning could have markedly increased the abundance of edible pulses, as well as to refining our understanding of the effects of tire on wild cereal grasses

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[6]Interpretation is problematic because of the diffuculty in distinguishing wild from domesticated legumes in the archaeological record.

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FLORISTIC AND HISTORICAL EVIDENCE OF FIRE-MAINTAINED, GRASSY PINE-OAK BARRENS BEFORE SETTLEMENT IN SOUTHEASTERNKENTUCKY

J.J.N. Campbell[1], D.D. Taylor[2],
M.E. Medley[3], and A.C. Risk[4].

Abstract-Several rare plant species in Appalachian Kentucky have been found generally on sandy ridges of the southern Cliff Section in native grassy roadside vegetation or young brushy pine-oak (*Pinus-Quercus*) woods, and almost never in areas with less human disturbance. They include *Agalinis decemloba*, *Aster concolor*, *Castanea pumila*, *Cirsium carolinianum*, *Eryngium yuccifolium*, *Gymnopogon ambiguus*, *Helianthus atrorubens*, *Liatris squarrosa*, *Lilium philadelphicum*, *Oenothera perennis*, *Parthenium integrifolium*, *Phlox amoena*, *Polygala polygama*, *Rhynchosia tomentosa*, *Robinia hispida* var. *rosea*, *Sanicula marilandica* (var. *petiolulata*), *Schwalbea americana* (a candidate for federal protection) and *Sporobolus clandestinus*. Most are concentrated in the southeastern U.S.A., and several arc. typical of open pine or oak woods with frequent fire. Either these species have invaded roadsides and other disturbed areas after settlement, or they arc relicts from openings that were maintained by fire, Indians and large herbivores before settlement. The latter hypothesis is supported by the virtual absence of these species in recent clearings, suggesting low reproductive rates; some species have disappeared since 19.50. Also, there are historical indications that fire did maintain some open pins-oak barrens, together with an associated Federally Endangered animal--the red-cockaded woodpecker (*Picoides borealis*).

INTRODUCTION

During ongoing inventory of rare species in the Daniel Boone National Forest (DBNF) and other areas of Appalachian Kentucky (Palmer-Ball and others 1988, Campbell and others 1989, 1990, 1991), it has become clear that several rare plants are largely restricted to roadsides and other currently disturbed upland areas in the southern “Cliff Section” (Braun 1950). The purpose of this paper is to summarize the distributions of these species, and to present the hypothesis that most arc relicts from woodland openings maintained by fire, which became suppressed with the establishment of DBNF in 1930-40 (Martin 1990).

The Cliff Section is a highly dissectcd, largely forested region with exposures of sandstone and, at low elevations, limestone (fig. 1). To the west, it merges with the Highland Rim in the south, or with the Knobs in the north. To the cast, there is a transitional “Low Hills Belts", then the "Rugged Eastern Area" of the Appalachian Plateau, then the Cumberland Mountains (Braun 19.50). The boundary of DBNF approximates that of the Cliff Section, plus some extensions into the southern Rugged Eastern Area. The Cliff Section has a much greater density of globally and regionally rare plant spccics than elsewhere in Appalachian Kentucky, except for some parts of the Cumberland Mountains.

The rare species can be divided into groups based on their typical habitats. These arc rocky banks of larger streams, seeping streamheads on broader ridges, overhanging cliffs with rockhouses, flatter rock outcrops on clifftops and ridges, typical upland forest on moist to dry soil (with relatively few examples), and upland roadsides or disturbed woods. There is almost no overlap between these species groups, except for about five of the roadside group that have also been found on rocky riverbanks (see below). The “roadside” group mostly occurs in the southern half of the Cliff Section, especially in McCreary, Pulaski, Whitley and Laurel Counties (fig. 1). Most spccics are restricted to the southeastern U.S.A., and several are typical of open pine or oak woods with frequent fire. The term “barrens” *is* adopted in this paper for *the* putative fire-maintained, presettlement vcgctation. This term has similar meaning to “savanna”, which has been used more widely in the southeastern Coastal Plain for particularly flat and grassy woodland with greater seasonal changes in hydrology. Species' nomenclature generally follows Kartcsz and Kartesz (1980).

[1]The Nature Conservancy, 642 West Main Street, Lexington, KY 40508.

[2]Daniel Boone National Forest, Berea District, 1835 Big Hill Road, Berca, KY 40403

[3]Department of Biology, University of Louisville, Louisville, KY 40292.

[4]Department of Biology, Morehead State University, Morehead, KY 42653.

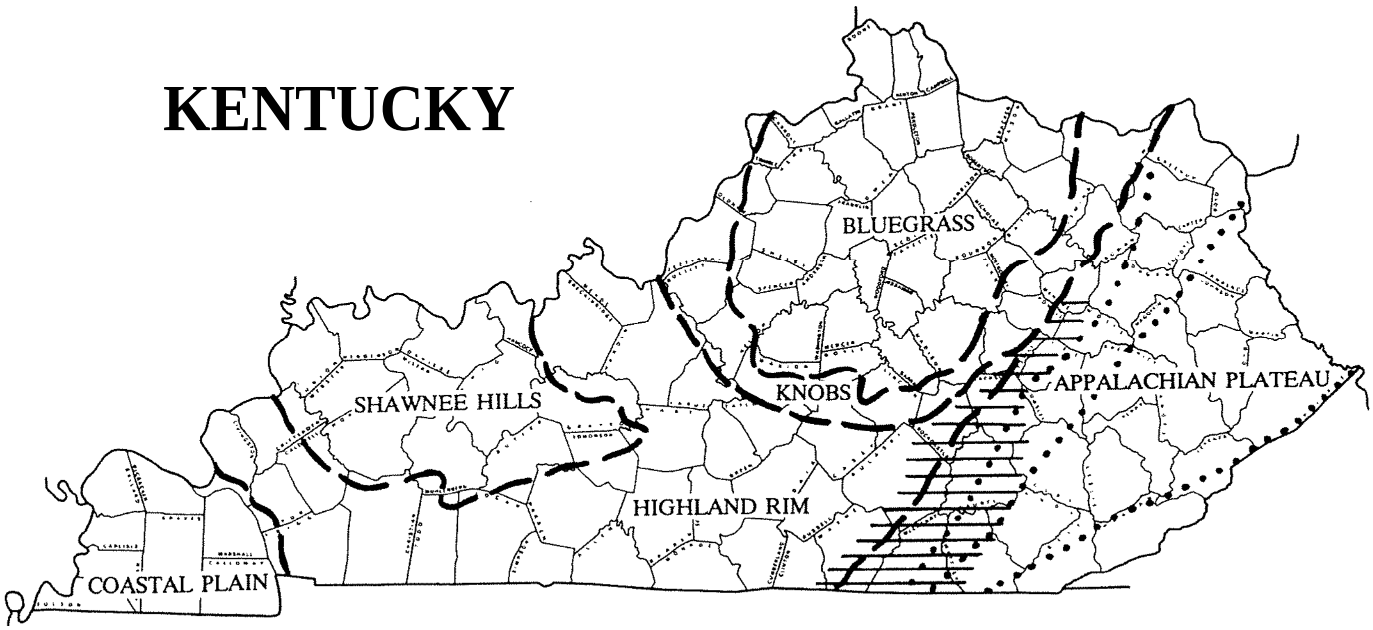

Figure 1. Map of Kentucky showing (a) major physiographic regions (dashed lines); (b) subsections (dottcd lines) of thc Appalachian Plateau and Mountains--from west to east, Cliff Section, Low Hills Belt, Rugged Eastern Area and Cumhcrland Mountains; and (c) the study area referred to in text (hatched)

SOURCES OF INFORMATION

Most of the data summarized below is in the database on rare species that the Kentucky State Nature Preserves Commission (KSNPC) has compiled during the past 15 years from all known publications on Kentucky plants, and from unpublished data shared by cooperating rcscarchers. The rare species list used by KSNPC is currently undcrgoing revision, and relevant unpublished data of the authors should be incorporated soon. Records from the Somerset and Stcarns Districts of DBNF, with which this paper is largely conccmcd, were increased 3-4 times during the 1987 and 1989 coopcrative inventories (see Introduction). Most of the earlier records were referred to by Rogers (1941) and Braun (1943, plus her collection labels). The inventories included searches along most public roads in the study areas, and much exploration of remote forested areas. Although transects were not quantitatively sampled, statements below that certain species appear largely restricted to roadsides arc based on intensive local exploration. At most open sites with rare species, the adjacent forest was explored to see if these species extended into the shade. For general information on the effects of fire in rccent history, D.D.T. interviewed several older USFS personnel and other residents familiar with the southern half of DBNF, especially Winnifer Freeman (Somerset), Clcmon Garrison (Mount Victory), Joe Planck (Somerset) and Ray Powell (McKee). Thc only other summary of fire-history in DBNF is the recent study of Martin (1990), which includes statistical details from USFS files.

NOTES ON RARE SPECIES OF ROADSIDES AND THICKETS

The list below includes all native species that generally meet two criteria.

(1) Within the Appalachian region of Kentucky, they are largely restricted to well-drained non-calcareous uplands of the Cliff Section (especially the southern half) and, in some cases, the Cumbcrland Mountains.

(2) Within this region, there are generally fewer than 10 records of each species (excepting *Helianthus atrorubens*, *Malus angustifolia* and *Phlox amoena)*, and most records are from grassy roadsides, brushy areas or open woods disturbed by man within the past IO-20 years.

In parentheses after each species: name is the number of Kentucky counties where it is known, followed by the approximate total of known sites in the state. Unless stated, most records are post-l 950.

Agalinis decemloba (2/3). In Kentucky, this southeastern (mostly Piedmont) species of dry open woods and edges is known from only three collections. These were made in 1927 (oak-pine woods), 1934 and 1987 (grassy roadside), all on dry, sandy ridges in the southern Cliff Section.

Asclepias amplexicaulis (1 1/35). This widespread eastern species of dry openings is scattered over southern Kentucky. Almost all Appalachian records are from roadsides on ridges in the southern half of the Cliff Section.

Aster concolor (4/12). In Kentucky, this southeastern species of dry sandy barrens and open woods is known mostly from the southern Cliff Section (plus two western sites). All post-1970 records are from upland roadsides, with only 1-20 plants, except for one site on Kentucky State Route (KSR) 751 with several hundred. Two of the four older (1940-50) records are from "dry" or "open grassy pine" woods.

Aureolaria pectinata (7/10). In Kentucky, this southeastern species of dry woods and openings is known from scattered southern counties. There is one Appalachian collection, made during 1939 in the southern Cliff Section on a "dry wooded bank of Bridge Fork Pond" [an artificial pond]. The closely related, or sometimes combined, northern species, A. *pedicularia* is known from grassy openings on Pine Mountain (Harlan Co.).

Carex gravida (13/20). This widespread mid-western species of open ground is known from several scattered areas of Kentucky (except the Bluegrass Region), mostly as the more southern var. *lunelliana*. In the Cliff Section, it is known only from disturbed woods, edges and roadsides, on sandy and calcareous soils.

Carex physorhytzca (2 14). This southeastern species of sandy open woods was recently discovered in Kentucky, from a barrens in the western Highland Rim (R. Cranfill, pers. comm.), and from roadsides and adjacent young, open *Pinus virginiana* woods in the southern Cliff Section.

Castanea pumila (7/10). In Kentucky, this southeastern species of dry, sandy thickets and disturbed woods is largely restricted to the Cumberland Mountains, but there are a few, mostly old, western records. There are only two verified Cliff Section records, both southern, from 1935 and 1989 (a suppressed individual on a small stream terrace). Johnson (1989) noted "its ability to recover from fire and other disturbances, through rapid suckering and sprouting from the remaining stem at or below the ground level." Near Jasper, Georgia, M.E.M. observed abundant suckers after clearcutting, in association with *Robinia hispida* varieties (see below). In addition to fire-suppression, the chestnut blight (*Endothia parasitica*) has probably reduced this species.

Cirsium carolinianum (6/15). This southeastern species, generally of dry sandy open woods and edges, has been recorded in scattered areas of Kentucky. Most sites are in the Cliff Section with half these in a 50 km^2 area along the Cumberland River, generally on roadsides, except for one in a more natural grassy pine-oak woods (table 1), and another at the edge of a small calcareous prairie. Only 1-20 plants have been found at each site.

Digitaria violascens (414). This southern, pantropical species of open pineland has been reported in scattered non-calcareous regions of Kentucky. The two Appalachian records are from dry sandy roadsides on Cliff Section ridges. Whether it is truly native to open pine woods in this region may be doubted given the weedy nature of this gnus.

Eryngium yuccifolium (> 20/ > 50). This southeastern and mid-western species of prairies and barrens is frequent in naturally open vegetation of western Kentucky, but there is only one Appalachian record, from the southern Cliff Section on "a moist flat of pine-oak barrens" (Rogers 1941).

Gymnopogon ambiguus (7112). **In** Kentucky, this southeastern species of dry, sandy openings and open pineland (especially fire-maintained *Pinus palustris* woods on the Coastal Plain) is known from scattered southern areas. There are only three Appalachian records, from "sandy shores, South Fork of Cumberland River" in 1935, and, in the 1980s, from an open grassy roadside in the southern Cliff Section and a seasonally wet field in the southern Rugged Eastern Area.

Helianthus atrorubens (6/ > 50). In Kentucky, this southeastern and Appalachian species, generally of dry open woods and edges, is known only from the southern Cliff Section and the transition to the Low Hills Belt. The sites arc mostly roadsides, and occasionally young open woods. It is locally dominant, with patches of several hundred plants, but only non-flowering plants occur in more shady areas.

Leiophyllum buxifolium (1/1). This species of Appalachian heath-balds, Coastal Plain sand-hills and pine-barrens, has been collected once in Kentucky, during 1939: "[a single individual] on top of dry [sandy] bank, Cumberland Falls, within park on S side of road going west, about 100-200 yards from park entrance" (McInteer 1940). The area is generally forested today, except for the roadsides. Another Appalachian heath-bald spccics, *Rhododendron minus,* still occurs in roadside woods near the park, but these may be planted. There is one other report of *R. minus* from Kentucky, on Pine Mountain (E. Carr, pers. comm.).

Table 1. vascular plants found on or near grassy roadsides with rare species Nomenclature generally follows Kartesz and Kartesz (1980); selected synonyms are in parentheses. Family arrangement follow Thorne (1961). + indicates species present; * indicates species locally abundant.

A-H: areas of ID-150 m^2 around patches of Aster concolor on KSR 751, from 1.5 km S of US 27 to 0.4 km N of railroad, Pulaski Co.

I: ca. 150 m^2 around patches of Aster concolor along dirt road, Bindsfield Ridge, 1.5 km SE of KSR 192, Pulaski Co.

J: ca. 100 m^2 around patches of Polygala polygama by Sand Hill Church on KSR 700, 8.5 km S of KSR 92, McCreary Co.

K: areas totaling ca. 50 m^2 around patches of Lilium philadelphicum on KSR 192, 1.15-2 km E of Craig's Creek Road, Laurel Co.

L: ca. 100 m^2 at "Bald Rock" on KSR 192, 1.7 km E of KSR 1193, Laurel Co.

M: ca. 3000 m^2 along KSR 700 and adjacent utility right-of-way, 1.5-3 km SW of Sand Hill Church, McCreary Co.

N: ca. 200 m^2 around Polygala polygama along dirt mad by Roaring Paunch Creek, 0.8 stream-km N of KY-TN state-line, McCreary Co..

O: ca. 300 m^2 around Sporobolus clandestinus and Phlox amoena along KSR 791, 1.3 km W of KSR 92. McCreary Co.

P: ca. 2000 m^2 around outcrops at Dobbs Hill on KSR 1363, 0.8-1.1 km W of Pleasant Bill Church, McCreary Co.

Q: ca. 5000 m^2 of pine-oak barrens (traversed by old road bed), 0.8 km NW of Barren Fork Cemetry, I.6 km SSE of Flat Rock, McCreary Co.

	A	B	C	D	E	F	C	H	I	J	K	L	M	N	O	P	Q
PTERIDOPHYTES																	
Pteridium aquilinum var. latiusculum				+	+									+			
Pellaea atropurpurea																	*
Asplenium platyneuron					+												+
Woodsia obtusa																	+
Polystichum acrostichoides					+							+					
GYMNOSPERMS																	
Pinus rigida								+				t					
Pinus virginiana	t	+	+	t	t	t		t			t		t			*	*
Pinus echinata				+	+	+				t	t		*		t		
Juniperus virginiana	+					t										*	t
DICOTELEDONS																	
Magnoliaceae																	
Liriodendron tulipifera				+	+							+		+			+
Annonaceae																	
Asimina triloba																	
Lauraceae																	
Sassafras albidum											+	+		+	+	+	
Ranunculaceae																	
Anemone virginiana												+					+
Aquifoliaceae																	
Ilex opaca																	
Clusiaceae																	
Hypericum (Ascyrum) hypericoides				+	+								+				+
Hypcricum gentianoides													+				+
Ericaceae																	
Oxydendron arboreum	+			+		+											
Gaylussacia brachycera																	+
Vaccinium stamineum (and neglectum)												+	+				
Vaccinium arboreum	+	+	+		+	+										+	+
Vaccinium vacillans	+				+						+	+					
Ebenaceae																	
Diospyros virginiana				+							+				t		t
Caryophyllaceae																	
E Cerastium glomeratum (viscosum)																	+
E Arenaria serpyllifolia																	+
E Dianthus armeria																	+
Silene virginica																*	+
E Silene antirrhina																	+
Pottulacaceae																	
Talinum teretifolium																	+
Ptiniulaceae																	
Lysimachia lanceolata												+					
Lysimachia quadrifolia																	
Polygonaceae																	
E Rumex acetosella																	

Table I. **(continued)**

	A	B	C	D	E	F	C	H	I	J	K	L	M	N	O	P	P
Geraniaceae																	
Geranium carolinianum																+	
Oxalidaceae																	
E *Oxalis fontana* ("europaea")																+	
Oxalis violacea																t	
Linaceae																	
Linum virginianum											+		+				
Polygalaceae																	
Polygala polygama										+			+				
Polygala senega var. *latifolia*													+				
Polygala curtissii																	
Polygala (*verticillata* var.) *ambigua*													+				
Celastraceae																	
Celastrus scandens																	
Euonymus americanus																·	
Violaceae																	
Viola pedata												t				t	
Viola hirsutula																+	
Viola cf. *emarginata*										t		t					
Viola tripartita var. *glaberrima*											t						
Viola rafinesquii																+	
Brassicaceae																	
E *Arabidopsis thaliana*																+	
E *Cardamine hirsuta*																	
E *Erophila verna* (*Draba v.*)																+	
Lepidium virginicum																	
Ulmaceae																	
Ulmus alata																+	*
Celtis tenuifolia																t	
Cistaceae																	
Lechea racemulosa																+	
Rhamnaceae																	
Rhamnus caroliniana							+								[illegible]	•	
Ceanothus americana													+		[illegible]		
Euphorbiaceae																	
Euphorbia corollata	t									t			t			+	
Anacardiaceae																	
Rhus (*Toxicodendron*) *radicans*											t				*	+	
Rhus glabra													+				
Rhus copallina		+	+	+	+			t	t	t			t			t	
Juglandaceae																	
Carya tomentosa									+						t		
Carya glabra													t				t
Carya pallida		?	?	+	?							t				t	
Aceraceae																	
Acer rubrum var. *r.*	+	+	+	+	+	+	+	+	t		t		*	+	+	+	
Fabaceae																	
Schrankia microphylla											t						
Cassia (*Chamaecrista*) *nictitans*									++				+t				
E *Lotus corniculatus*																t	
E *Trifolium agreste* (*procumbens*)																+	
E *Melilotus officinalis*																t	
Desmodium nudiflorum													·				
Desmodium ciliare						[illegible]					[illegible]						
Desmodium marilandicum	+				[illegible]								t			[illegible]	
Desmodium paniculatum (sensu stricto)										[illegible]			+			·	
*Desmodium glabellum** (not *humifusum*)							[illegible]		[illegible]		[illegible]		+				
Desmodium viridiflorum													t			[illegible]	
Desmodium laevigatum				+						t	t					[illegible]	
Lespedeza repens						+											
Lespedeza virginica		t	+													t	
Lespedeza intermedia		t		t	t				t								
Lespedeza intermedia x *virginica*						+											
Lespedeza hirta		+			t	t						+	+			t	
E *Lespedeza striata*													+			?	
E *Lespedeza cuneata*						t							t				
Stylosanthes biflora		+										t					
Tephrosia virginiana var. *v.*	ttt				+							t				+	
Clitoria mariana										t			t				

Table 1. (continued)

	A	B	C	D	E	F	C	H	I	J	H	L	M	N	O	P	Q
Amphicarpa bracteata var. b.											+						
Galactia volubilis					+				+	+			+			+	
Hamamelidaceae																	
Liquidambar styraciflua																+	
Fagaceae																	
Quercus alba	+	+	+							+	+		*				
Quercus stellata			+			+			+				+				*
Quercus montana ("prinus")	+					+					+		+			+	+
Puercus falcata			+		+	+										+	
Quercus marilandica					+	+	+									+	+
Quercus velutina	+		+		+	+	+		+		+				+	+	
Quercus coccinea		+			+				+	+	+		+			+	
Betulaceae																	
Ostrya virginiana																+	
Rosaceae																	
Fragaria virginiana var. v.					+	+									*	+	
Potentilla simplex var. s.										+	+						
Potentilla canadensis var. c.	+	+				+						+	+			+	
Rubus Flagellares (group)		+	+							+	+			+		+	
Rubus allegheniensis var. a.														+			
Rubus Argutae (group)					+				+	+				+			
Rosa Carolina																+	
Prunus serotina		+	+														
Amelanchier arborea var. a.												+				+	
Crassulaceae																	
E Sedum acre																*	
Onagraceae																	
Oenothera biennis					+											+	
E Oenothera laciniata																+	
Rubiaceae																	
Bedyotis purpurea (Houstonia lanceolata)										+			+			+	
Bedyotis caerulea (Houstonia C.)																+	
Galium pilosum var. p.					+					+	+					+	
Apocynaceae																	
Apocynum cannabinum											+						
Asclepias amplexicaulis										+			+				
Asclepias exalatata																?	
Asclepias variegata													+				
Asclepias verticillata																	+
Gentianaceae																	
Gentiana villosa														+			
Scrophulariaceae																	
Agalinis decemloba					+												
Pedicularis canadensis					+								+				
Ambrosia artemisifolia													+			+	
E Achillea millefolium																+	
E Chrysanthemum leucanthemum (L. vulgare)	+	+								+	+		+			+	
Senecio anonymus (smallii)		+				+		+	+	+					+	*	
Chrysopsis (Pityopsis) graminifolia		+		+	+			+	+	+			+		*	+	+
Chrysopsis mariana	t	t		+	+	+	+	+				+	+				
Solidago hispida																?	
Solidago erecta	+++				+		+		++			++				+	+
Solidago nemoralis	+++				++				++			+	*				
Solidago arguta var. a.									+				+	+			
Solidago odora	t	t		+		+	+	+	+	+					+	+	
Solidago rugosa													+				
Solidago gigantea						?											
Solidago altissima		t		+									+				
Solidago (Euthamia) graminifolia						+											
Aster undulatus		+			+	+					+				+	+	
Aster patens vw. patens	+	+	+		+	+	+		+	+			+	+		+	
Aster surculosus		+						+				+	+			+	*
Aster concolor	+	+	+	+	+	+	+	+	+								
Aster linariifolius		+		+	+										+	+	
Aster infirmus													+				
Aster umbellatus													+				
Aster paternus													+				
Aster solidagineus	+				+												
Aster pilosus var. pilosus		+	+			+						+				+	
Aster lateriflorus												+	+				

Table 1. (continued)

	A	B	C	D	E	F	G	H	I	J	W	L	M	N	O	P	Q
Aster dumosus var. coridifolies	+	+	+	+		+		+				+					
Erigeron annuus										+	+					+	
Erigeron strigosus													t			+	
Conyza canadensis var. pusilla												+				+	
Gnaphalium obtusifolium		+	+		+	t						+				+	
Antennaria plantaginifoiia		?				?	?				+		t			+	
Eupatorium fistuiosum				+	+								t				
Eupatorium album	+					t						+					
Eupatorium rotundifolium	t	t				t		t	t							t	
Eupatorium aromaticum		+				+		+		+	+						
Eupatorium rugosum var. r.			+														
Liatris squarrulosa					+	+			+								
Liatris microcephala																+	+
Cirsium muticum														+			
Cirsium carolinianum																	+
Cirsium discolor																+	
Elephantopus tomentosus													+				
Prenanthes serpentaria					?	?											
Lactuca canadensis																+	
Hieracium venosum						+					+					+	
Krigia virginica																+	
MONOCOTYLEDONS																	
Liliaceae																	
Lilium philadelphicum var. p.				?							+		+				
Uvularia perfoliata											?		+				
Aleris farinosa													+				
Smilax glauca	+	+			+				+	+		•		[illegible]		+	
E Verbascum thapsus																♦	
E Veronica arvensis																[illegible]	
Plantaginaceae																	
Plantago rugelii		+															
Plantago virginica																+	
E Plantago lanceolata																+	
Acanthaceae																	
Ruellia caroliniensis																+	
Lamiaceae																	
Prunella vulgaris var. lanceolata																	
Salvia lyrata													+			+	
E Satureja (Clinopodium) vulgaris												+					
Pycnanthemum pycnanthemoides var. p.																+	
E Mosla dianthera												+					
Polemoniaceae																	
Phlox amoena															*	*	
Solanaceae																	
Solanum carolinianum																+	
Convolvulaceae																	
Ipomaea pandurata													+				
Convolvulus (Calystegia) spithameus															+		
E Convolvulus (Calystegia) sepium var. s																?	
Campanulaceae																	
Lobelia puberula var. simulans	+		+			+		+			+		+	+			
Lobelia inflata												+					
Specularia (Triodanis) perfoliata																+	
Vitaceae																	
Vitis aestivalis										+			+			+	
Vitis vulpina										+						+	
Vitis rotundifolia													+		*	+	
Parthenocissus quinquefolia										+			♦			•	
Nyssaceae																	
Nyssa sylvatica var. s.	+					♦♦				•			[illegible]				
Cornaceae																	
Cornus florida			+		+		+	+	+		+		+		+		
Apiaceae																	
Sanicula marilandica var. petiolulata													[illegible]				
Sanicula canadensis											[illegible]						
E Daucus carota										t			[illegible]			t	
Caprifoliaceae																	
E Lonicera japonica																+	

Table 1. (continued)

		A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	P
	Asteraceae																	
	Helianthus atrorubens var. a.								?+					+				
	Angelica venenosa													+				
	Helianthus divaricatus					+					+			+				+
	Helianthus microcephalus		+			+					+	+		+		+		
	Helianthus hirsutus	+	+		+	+				+			+					
	Verbesina (Actinomeris) alternifolia														+			
	Verbesina occidentalis													+			+	
	Rudbeckia fulgida var. fulgida					+							+					
	Rudbeckia triloba var. t.	+															*	
	Coreopsis major	+	+	+	+	+	+	+	+	+	+	+	+				+	+
	Parthenium integrifolium var. i.										+			*				+
	Smilax bona-nox		+															
	Smilax rotundifolia				+			+				+		+	+			
	Dioscoreaceae																	
E	Dioscorea batatas													+				
	Juncaceae																	
	Luzula echinata																+	
	Cyperaceae																	
	Cyperus ovularis															+		
	C. gravida															+	+	
	C. artitecta (and C. physorhynca)															t	t	
	Carex umbellata (tonsa)																t	
	Carex nigro-marginata																t	
	Carex hirsutella (complanata var. h.)													t			t	
	Carex caroliniana													.				
	Carex suanii												8					
	Poaceae																	
	Stipa (Piptochaetium) avenacea										+		⊠	⊠		*	+	*
	Danthonia spicata		+										•	⊠	+		+	*
	Danthonia sericea																t	t
	Aristida dichotoma					+												
	Aristida longespica	+																
	Aristida purpurascens var. virgata		+															
E	Bromus japonicus																	
E	Poa compressa																	
E	Poa pratensis																+	
E	Festuca elatior (sensu lato)													+				
E	Festuca (Vulpia) octoflora																+	
E	Holcus lanatus																+	
E	Dactylis glomerata																	
	Elymus glabriflorus												+					
	Gymnopogon ambiguus	+				+												
	Eragrostis spectabilis															+		
	Sporobolus clandestinus															+	*	
	Erianthus alopecuroides					+								+				
	Andropogon (Schizochyrium) scoparius	*	+	*	*	*	+	+	t		t		+	*		+	*	+
	Andropogon gerardii	*		+	*													
	Andropogon virginicus var. v.					+	+			+	+		+		+			
	Andropogon ternarius					t	t									+	+	
	Sorghastrum nutans	*		+	*	+	+			t								
	Panicum flexile						t						+					
	Panicum anceps		+	*	+	+				t						*	+	
	Panicum (Dichanthelium) boscii	t	t						t					+			+	*
	Panicum (D.) commutatum														+		+	
	Panicum (D.) ravenelii													+		?		
	Panicum (D.) polyanthes												+		+			
	Panicum (D.) sphaerocarpon													+				
	Panicum (D.) laxiflorum										+		+	+	*		+	
	Panicum (D.) lindheimeri												+					
	Panicum (D.) acuminatum (sensu lato)					+			+				+	+	+		+	
	Panicum (D.) microcarpon										+							
	Panicum (D.) dichotomum (sensu stricto)	+				+	+						+	*			?	+
	Panicum (D.) depauperatum																+	
E?	Setaria geniculata																	

Lespedeza capitata (or hybrids) (>10/ > 20). In Kentucky, this widespread eastern species of dry openings (often sandy pincland) is scattered in western regions. However, there arc only three Appalachian records, all from the Cliff Section during 1935-40 (Rogers 1941, Braun 1943). Braun's plants were identified as *L. simulata*, which has been interpreted as a hybrid between *L. capitata* and ***L. virginica*** or ***L. intermedia***. Also, it was found during 1989 in a wet bottomland meadow half a mile south of the KY-TN state-line.

Liatris squarrosa (> 20/ > SO). In Kentucky, this widespread southeastern species of dry openings is frequent in southern and western regions, but there are only two Appalachian records. Both are from relatively undissected ridges on the eastern side of the southern Cliff Section, in 1937 (dry open woods) and 1989 (dirt roadside). *Liatris* species that are more widespread in the Cliff Section also occur on the roadsides, especially *L. squarrulosa*, less often *L. spicata*, occasionally *L. aspera*, and **on** rocky sites ***L. microcephalu.***

Lilium philadelphicum (9/21). In Kentucky, this species of dry to damp, acid openings, thickets and pine barrens is known only along the Cliff Section, as the largely Appalachian var. *philadelphicum*. Most records are from roadsides on ridges, but one is from the edge of a calcareous prairie, and a 1940 record is from dry pine woods. It was locally common (Rogers 1941) but several populations have disappeared in the past 10-30 years. Currently, most sites have only l-5 plants; none exceed 20. In addition to fire-suppression, digging for ornament may have contributed to its decline.

Malus angustifolia* (61 >25)**. This southeastern species of open woods and thickets is reported from scattered non-calcareous areas of southern Kentucky, mostly in the southern Cliff Section. There may be some intermediates with the more northern ***M. coronaria (especially var. *lancifolia)*. Most sites have only 1-1 0 trees and are on dry ridges along roads and in young woods *of* ***Pinus virginiana*** or pine-oak. One population has at least 50 trees (with much *Crataegus* spp. and *Prunus americana).* Less often, it has **been** found on rocky riverbanks, or on bottomland thickets extending into the Rugged Eastern Area.

Melampyrum lineare (3/3). In Kentucky, this northern species of dry to damp brushy grassland and open woods is known from a few records in the Cumberland Mountains, as var. *latifolium,* and in the Cliff Section, as ***var. americanurn.*** The latter variety is currently known only along the 75 m paved trail to Sky Bridge, with 400-500 plants at the edge of dry woods dominated by *Pinus rigida*, *Quercus* spp., *Gaylussacia baccata* and *Vaccinium vacillans*. An annual species, it often increases in woods after fire or logging (Swan 1970; Scheiner and Tecri 1981; Abrams and Dickmann 1984; Gibson and Good 1987).

Muhlenbergia torreyana (i/l). This southeastern species of "pine-barrens and meadows" is a candidate for federal protection. There is only one obscure Kentucky record (Hitchcock and Chase 1950), presumably based on a collection in the southern Cliff Section or the adjacent Highland Rim. It was formerly known from the oak-barrens region of Tennessee, in the transition from Highland Rim to Applachian Plateau (Svenson 1941).

Oenothera perennis (3/3). In Kentucky, this north-central species of wet, or occasionally (in the south) dry, natural openings is known from only three southern records. The only Appalachian record, dated 1935, is from the southern Cliff Section, in "dry soil, open woods" along a ridge road, ***close*** to *Schwalbea americana* (Braun 1943 and collections). The only post-1960 record in Tennessee is from a physiographically similar roadside (Patrick and others 1983).

Orbexilum pedunculatum **var.** *pedunculatum* (*Psoralea psoralioides* **var.** ***p.)*** (4/1 0). In Kentucky, this southeastern variety of dry openings has been found in a few southern counties. The only Appalachian records are from the southern Cliff Section, either on ridgetop roadsides, or on open rocky riverbanks.

Panicum aciculare (415). In Kentucky, this southeastern (generally Coastal Plain) species of sandy pine woods is known from a few southwestern sites (as var. *aciculare*), and from two sites in the southern Cliff Section (as var. *angustifolium*) on ridges in dry, open, grassy pine woods near a road and a clifftop. As ***"P. angustifolium"***, this species was reported to increase greatly with frequent prescribed burning by DeSelm and others (1973). Some other *Panicum* spp. may have similar distributions and responses (e.g., *P. ravenellii*)

Parthenium integrifolium (> 20/ > 50). This mid-western and east-central species of dry openings is not rare in western Kentucky. However, the only Appalachian records arc about 15 sites in the southernmost Cliff Section, mostly on ridgetop roadsides with only l-10 plants. At least 20 non-flowering plants were found in a more shady barrens (table 1).

Paspalum setaceum **var.** *longepedunculatum* (4/4). In Kentucky, this southeastern taxon of sandy openings with pine is known from a few open ridgetop sites in the southern Cliff Section, and as a railroad waif in Jefferson County.

Phlox amoena (7/ > 2.5). *In* Kentucky, this southeastern species of dry openings is known from the southern Cliff Section and the adjacent Highland Rim. It is locally frequent (with 100-1000 plants) along roads and adjacent forest edges, generally on sandy soils and occasionally above limestone. Only one site has frequent plants in more natural vegetation: the rather open, grassy, stunted *Pinus virginiana* woods on the sandstone outcrops *of* Dobbs Hill (table 1).

***Polygala polygama* (116).** In Kentucky, this northern and Coastal Plain species of dry, sandy openings is known only from the southernmost Cliff Section. Most sites are upland roadsides (with 10-50 plants), but a 1935 record is from "pine-oak" woods. It is a short-lived perennial that often increases after fire (Abrams and Dickmann 1984; Niering and Dreyer 1989).

Rhynchosia tomentosa (3/3). In Kentucky, this southeastern species of dry, sandy openings is known from only three records. The only Appalachian collection, dated 1949, is from the "edge of cut-over woods, 4 miles east of Cumberland Falls" (probably along KSR 92). Also, it was found in 1989 about 2 km south of the KY-TN state-line, on Big Island in the Big South Fork.

Robiniu ***hispida*** var. ***rosea*** **[=** ***R. boyntonii*]** (4/10). In Kentucky, this Appalachian taxon is known only from the Cumberland Mountains (with other varieties) and the southern Cliff Section, mostly in a 10 km^2 area around Day Ridge, McCreary Co. All sites are on relatively narrow sandstone ridges or knobs in dry pine or oak woods, especially young stands, thickets and edges. It occurs at low density in patches up to 30 m^2, with flowering observed only in the open.

Sanicula marilandica (1/2). In Kentucky, this north-central (to Rocky Mt.) species is known from only two localities, each with less than 10 plants, in the southern Cliff Section. They were found in edges and burned thickets along roads on rather broad ridges between the Cumberland River and the Big South Fork. The plants are var. *petiolulata*, which typically occurs in "dry sandy pineland" of the southern Atlantic Coastal Plain (Fernald 1950).

Schwalbea americana (112). This species is a candidate for federal protection that is known from sandy, acid, damp to dry soil in open pine or oak barrens on the Atlantic Coastal Plain, plus a few old collections from Tennessee (including the "oak-barrens" of the Higland Rim-Cliff Section transition) and Kentucky. The Kentucky collections were from "dry sandy soil on knobs and sandstone plateau margins" in the southern Cliff Section, "with *Cleistes*" at one site (Braun 1937b, 1943). This species appears restricted to fire-maintained vegetation (S. Orzell, pers. comm.). Musselman and Mann (1977) noted: "particularly vigorous growth of *Schwalbea* was evident after early spring fire at the Horry Co. [SC] site. In such years, seed production was abundant." It is parasitic on a wide range of woody plants.

Sporobolus clandestinus (7/8). In Kentucky, this widespread eastern species of dry openings is known from scattered southern regions. The only Appalachian records are from the southern Cliff Section, on roadsides adjacent to sandstone outcrops, and on some limestone clifftops. It is locally dominant, with patches up to 300 m^2.

Tephrosia spicata (217). In Kentucky, this southeastern species of sandy openings is known only from the southern Cliff Section. Most records are from open rocky banks of the Cumberland River. Two others are collections dated 1941 and 1980 from disturbed areas on ridges near Barthell (McCreary Co.).

Viola fimbriatula **[=** ***V. sagittata*** var. ***ovata*]** (3/3). In Kentucky, this north-central species of disturbed woods (especially on mineral soil) is known from a few Cliff Section records. The only post-1950 record is from McCreary Co., along an old eroded roadside, with at least 30 plants.

NOTES ON ASSOCIATED VEGETATION

Some of the roadsides with rare species have a relatively high diversity of native species, and a low frequency of exotics. Table 1 lists the ca. 300 vascular species found at good examples of such vegetation and some nearby grassy woods. The most abundant species include several warm-season (C4) grasses, with *Andropogon scopurius* the most frequent dominant. The only typical native cool-season (C3) grass is *Stipa avenacea*, which is locally dominant in young pine woods adjacent to the roads. Other frequent species include composites, especially *Coreopsis major*, *Helianthus* spp., *Chrysopsis* spp., *Solidago* spp., *Aster* spp. and *Eupatorium* spp., and legumes, especially *Lespedeza* spp. and *Desmodium* spp. About 10 percent of the species present are exotics, but most of these were recorded only at the Dobbs Hill site, which is the only site adjacent to houses. The only exotic found at more than *2-3* sites is *Chrysanthemum leucanthemum* (= *L. vulgare*).

One of the most extensive native grassy areas, with several rare species (especially Aster *concolor),* is along 3 km of KSR 751 between Burnside and Keno (Pulaski Co.). In addition to the typical dominants--Andropogon *scoparius, A. gerardii* and *Sorghastrum nutans,* frequent species here include *Tephrosia virginiana, Lobelia puberula, Helianthus hirsutus, Coreopsis major, Senecio anonymus, Chrysopsis mariana, C. graminifolia, Solidago erecta, S. nemoralis, S. odora, Aster patens, A. concolor, A. dumosus, Gnaphalirrm obtusifolium, Eupatoriron rotundifolium, E. aromaticum, Panicum anceps* and *Andropogon virginicus. Adjacent* forest is dominated by *Pinus* spp., *Quercus* spp. and *Acer rubrum*.

Typically the soils are hapludults with fine sandy or silty loam texture, A horizon pH of 4.5-5, and a depth of SO-150 cm to the sandstone or shale. On shallower hapludults or dystrochrepts near sandstone outcrops, the vegetation generally lacks taller species such as *Andropogon gerardii, Sorghastrum nutans, Helianthus atrorubens* and *Eupatorium* spp. An unusual variant with patches of *Sporobolus clandestinus* was found on some rocky sites, especially Dobbs Hill. In addition to abundant *Pinus virginiana* at this site, the trees included much *Juniperus virginiana,* which, together with some of the other frequent species (especially *Ulmus alata, Celtis tenuifolia, Rhamnus caroliniana, Phlox amoena, Rudbeckia triloba, Pellaea atropurpurea* and *Woodsia obtusa*), may indicate more base-rich soils (following Campbell 1987). *S. clandestinus* itself is also frequent on some limestone sites.

Apart from these roadside remnants, there is little information on the barrens or open forest that may have existed when annual burning was a common practice before DBNF was established. However, on drier ridges in the southern Cliff Section, Braun (1950, p. 102) notcd: "Instead of this pint-heath or pine-oak-heath community, some of the promontaries arc occupied by open pine woods (the three species of pine) with a grassy layer of *Andropogon scoparius* (little blucstcm), *A. glomeratus* (broom-sedge), and *Sorghastrum nutans* (Indian grass), in which arc a few scattcred forbs. Fires have modified most (perhaps all) of these pine summits, although the abundance of large *Cladonia* (lichen) mats is an indication that there has been *no* fire for many years."

Similar vegetation may have extended onto relatively moist sites, where droughts still occurred often enough to spread fires. The only direct information about such woods comes from Rogers (1941). He noted the following plants in "a moist flat of pine-oak barrens" along the road to Bauer: *Salix humilis* (vars. *humilis* and *microphylla), Hypericum punctatum, Eryngium yuccifolium**, *Liatris scariosa* [probably *L. squarrulosa**] and *L. spicata**; and he noted *Helianthus atrorubens** in "pine-oak barrens at the Tennessee State Line." Also near the Bauer Road, he noted several species typical of openings or edges, all in "woods" unless noted: *Andropogon gerardii* ("common"), *Robinia hispida**, *Lespedeza virginica, L. capitata**, *Polygala verticillata, Oxypolis* rigidior, *Angelica villosa, Cuscuta campestris, Solidago* caesia, *Aster patens* ("var. *phlogifolius*") and *A. solidagineus*; *Pycnanthemum pycnanthemoides, Helianthus hirsutus* and *Coreopsis major* var. *stellata* (all "dry woods"); *Anemone virginiana* ("dry pine-oak woods"); *Lobelia puberula* ("wet woods"); *Lilium philadelphicum** ("common along road"), *Coreopsis tripteris* var. *deamii* ("by the road"); *Hypericum frondosum* [*prolificum*?] ("low, moist, shaley soil in open thicket"). In *1987, Andropogon gerardii* is still common along the road to Bauer, but of the rarer species (shown by *), only *Helianthus atrorubens* was encountered.

Except for some of the roadsides, there are virtually no areas where a diverse native barrens vegetation remains. A few woodland-pastures today may bear some structural resemblance to prcscttlement barrens, and such areas were frequently burned by residents before the modem era of fire-suppression. However, grazing has been intensive, and exotic plants have often replaced the native flora in such pastures. None of the rare plants listed above have been found in actively pastured areas. A few dry, wooded areas near clifftops have an open grassy aspect, with occasional fires, but these have generally become too shady for most of the rare species noted here.

NOTES ON FIRE HISTORY

Archaeological evidence shows that, for at least 10,000 years before 1650, Indians lived in many parts of Appalachian Kentucky (e.g., Cowan 1985, Ison 1990). It is likely that they used fires extensively for managing game animals and clearing garden plots, especially on slopes near rockhouses. Lightning fires are relatively infrequent in DBNF, with only 10-15 per 1000 km^2 each year (Martin 1990), and they are probably not repeated often enough in the same locations to create open grassy vegetation. However, the role of Indians versus lightning in causing prescttlement fires must remain an open question.

There was almost no landscape description in the pioneer literature from the southern Appalachian Plateau in Kentucky and the adjacent Highland Rim. A few accounts suggest areas disturbed by fire, Indians or buffalo *(Bison bison).* Walker (1749) described an area in Jackson County where "The woods have been burnt some years past, and are now very thick, the only timber being almost all kill'd", and an area in Morgan County with "the only fresh burnt woods we have seen." He noted Indian trails and buffalo in several places. Near Pincville, he initially named Clear Creek as "Clover Creek", noting that "Clover and hop vines are plenty there"; the clover was probably *Trifolium stoloniferum*, which was associated with buffalo in Kentucky (Campbell and others 1988). Walker (1824), recounting his travels in 1775, noted "twenty miles, entirely covered with dead brush" in the Rockcastle and Laurel County area. This statement suggests the results of a large fire (see also McHargue 1941). Arnow (1960) noted descriptions of pioneers in the Cumbcrland River drainage that suggested "park-like" forests "with so little undergrowth a traveler could see a deer for 1.50 paces. There were, too, along the creeks and rivers, treeless glades and valleys, sometimes filled with cane...or only high grass..." Edwards (1970) described Wayne County (mostly in the eastern Highland Rim) during about 1775: "Three-fourths of the county was covered with virgin forests; the lowlands contained some cane, or tall grass as they preferred to call it...Price's Meadows [initially called the Big Meadow], near the mouth of Meadow Creek, contained very high grass. Corn could be planted without the forests being cleared."

Interviews with older residents provide a general historical view of the southern Cliff Section. Until DBNF was established in 1930-40, intentional fires were widespread, except perhaps for a few decades before 1910 when the Kentucky Landsharers Association had control over much land and restricted burning. Annual fires occurred in much of the area during 1910- 1930. They were generally set in February and March to promote grass and forb growth for cattle. Also, hogs ran in the forest, with about 0.5-I per km^2, and many became feral. In some years, a second set of fircs were set in October or November "to keep the woods open". Fires were generally started along roadsides on ridges and allowed to bum without control, unless property was threatened. In general, ridgetop forests contained much *Quercus coccinea* (ca. 50-60 cm dbh), *Q. velutina* and *Pinus echinata*, with scattered *Q. alba* (to 100 cm dbh) and *Liriodendron*. Most woody understory on ridges was removed, except for scattered Quercus spp. and *Liriodendron*, creating some savanna-like areas. The ground cover of blueberries and other low ericaccous shrubs, grasses and forbs was much thicker than today. Pink ladies' slipper orchids (*Cypripedium acaule*) were more frequent, but yellow ones (*C. pubescens*) were reduced by fire. Composites were more frequent, though concentrated along roads. Birds were generally more numerous, though wild turkey (*Meleagris gallopavo*), like deer (*Odocoileus virginianus*), had been much reduced by hunting.

By some accounts, fire would generally stop near the top of east and north slopes, but it would creep down west and south slopes, creating a scrub forest with such species as *Pinus rigida*, *Quercus marilandica* and *Kabnia latifolia*. However, by other accounts, the fire would often be blown onto cast slopes by prevailing winds, and it would seldom move down west and south slopes. Accounts agree that north slopes seldom burned and often had thick understories of *Acer saccharum* and *A. rubrum* below canopies of *Liriodendron* and *Quercus* spp.

Acquisition of land in DBNF by USFS began about 1933, bringing with it suppression of fire. Burning for forage generally stopped about 1945, though arson increased after 1970. All accounts agree that pine is more common today than 40-60 years ago. Abandoned fields and open woods grew back with much pine and *Liriodendron*. However, soils on and near ridgetops were often so worn-out that only scrub trees, mostly pines and oaks, grew back, and were called- "barrens". Fire was not generally set in this scrubby vegetation, which did not bum well. Remaining barrens of this type have much lichen (Cladonia) today, suggesting fire exclusion.

DISCUSSION

The restriction of several rare plants in southeastern Kentucky to roadsides and similar disturbed sites might seem paradoxical, because such artificial habitats arc generally considered to be dominated by common weeds and grasses. Two general hypotheses may explain this phenomenon: (a) these species have invaded the region along roads and other disturbed ground after settlement and forest-clearance; or (b) they arc relicts from natural openings that were maintained largely by fire, with old stable roadsides and adjacent areas offering them a continually open refuge.

The following two arguments favor the latter hypothesis (b), involving fire.

(1) These species generally do not appear invasive or weedy within this region, except perhaps a few of the more frequent ones (also *Digitaria violascens* and *Paspalum setaceum var. longepedunculatum*). Most have never been found in tree-fall gaps, clear-cuts, cropland, pastures, old-fields, artificial wildlife-openings or railroad rights-of-way. Moreover, some of them appear to have declined or disappeared in recent decades: *Aureolaria pectinata*, *Castanea pumila*, *Eryngium yuccifolium*, *Leiophyllum buxifolium*, *Lespedeza capitata*, *Lilium philadelphicum*, *Muhlenbergia torreyana*, *Oenothera perennis*, *Rhynchosia tomentosa* and *Schwalbea americana*. It seems most unlikely that the rarest species, especially those with disjunct records 100 miles or more further south (*Muhlenbergia torreyana*, *Schwalbea americana*) dispersed into Kentucky in the 200 years since settlement.

(2) As noted above, there is considerable evidence that fire has played an important role in the upland forests of this region within the past 100-200 years, before the modem era of fire-suppression. It is possible that death of large trees due to other factors in the presettlement forest created temporary gaps suitable for some of these species. However, rapid dispersal into such gaps would still be required, and, as already noted, these species generally have not dispersed into newly created openings.

Further support for the "fire hypothesis" comes from evidence in other southeastern regions. Even in the Appalachians, fire, mostly set by Indians, was probably a widespread factor maintaining open vegetation before European settlement (Devivo 1990), and early settlers continued frequent burning (Pyne 1982, Otto 1983). On the Coastal Plain, there is evidence of widespread prehistoric, anthropogenic fire (Myers and Peroni 1983). and several of the rare species noted above are typical of fire-maintained vegetation in addition to rights-of-way (S. Orzell, Florida Natural Areas Inventory, pers. comm.). Experimental use of fire in the Southeast has confirmed that barrens or savanna vegetation can be restored and maintained by decades of annual burning (Komarek 1974; Kulhavy and Connor 1986; DeSelm and Clebsch 1990).

One of the closest areas to southeastern Kentucky where extensive fire-maintained areas existed before settlement, and where substantial pieces still survive, is the "oak-barrens" region centered on Coffee County, Tennessee (Svenson 1941; Patrick 1979; DeSelm 1989; DeSelm and Clebsch 1990). The open grassy vegetation there is typically found in relatively flat areas, locally with fragipan soils, on the Appalachian Plateau and its residuum overlying the eastern Highland Rim. Almost all the rare species noted above in southeastern Kentucky occur in that region, plus several rat-c spcoics of seasonal wetlands. Some species have no records in between, but there are a few well-known barrens sites with rare species on the Appalachian Plateau in northeast Tennessee (Patrick 1979; DeSelm 1989, and unpublished).

Other circumstantial evidence concerns the habitat of the red-cockaded woodpecker ***(Picoides borealis),*** a Federally Endangered Species. This species has declined drastically in Kentucky within the past 50-100 years, and only 10-l 5 birds are currently known (S. Phillips, pers. comm.). Optimal habitat for this southeastern species appears to be dry, open forest with large pine trees at least 75-100 years old. Given the admixture of hardwoods in DBNF, it is estimated that 400 ha may be required for a stable colony. In Kentucky, logging of large pines has probably been the major cause of the species' decline, rather than understory encroachment, and the birds may be more tolerant of closed forest than those on the Coastal Plain (P. Kalisz, pers. comm.).

Much of the older pine today, including most trees used by the woodpeckers, grew up during the period of frequent burning for woodland-pastures. During the last century (from County Court Deed Books; and Barton 1919), about 5-10 percent of the southern Cliff Section forest was composed of pine, mostly *Pinus echinata*. This percentage is probably much higher that which would exist without any fire. Without fire, current patterns of succession suggest that pine would be largely confined to the driest ridges and clifftops, where, despite extensive recent searches, signs of the red-cockaded woodpecker remain extremely rare. Therefore, before settlement, it seems likely that this species was largely dependent on fires to regenerate extensive areas of pine, especially the relatively fire-tolerant *Pinus echinata* (Martin 1990).

Although this paper focuses on the rare species of moderately dry soils in open habitats, several other uncommon or rare species in this region of Kentucky may have benefited from fire. Some of these are restricted to thin soil around rock outcrops with little or no woody cover, especially ***Arenaria*** *glabra, Crotonopsis* ***elliptica, Oenothera*** *linifolia* and *Talinum teretifolium*. Fires may have increased the openness of such places. Some more widespread species can persist in the shade of relatively undisturbed pine-oak forests, but clearly do better in the open. Such species persist mostly along trails and logging roads through the forest, but they are locally frequent in small clearings and burned areas. They include *Cleistes* ***divaricata*** (see also Komarek 1974; Gregg 1989), ***Danthonia compressa*** (see also Lindsay and Bratton 1979), *Isotria verticillata* (see also Baldwin and Wieboldt 1969) and *Porteranthus trifoliatus*. Such species are probably too widespread, well-dispersed and persistent in shade to be good indicators of prescttlement barrens, though they may well have occurred in relatively moist or shady variants of such vegetation.

The "fire hypothesis" may also be extended to some uncommon or rare species of seasonally wet, flat ground in thin-canopied forest, thickets, small natural openings or adjacent old-fields. In Kentucky, some are largely restricted to strmmheads in the southern Cliff Section: *Carex* ***joorii,*** *Calamagrostis* ***cinnoides,*** *Calopogon tuberosus, Gratiola* ***pilosa, Lobelia*** *nuttalii, Platanthera cristata,* ***P. integrilabia*** and ***Verноniu*** *noveboracensis*. Others are mostly in broader valleys adjacent to, and in a few cases within, the Cliff Section, mostly in fill-sun: ***Bartonia*** *virginica, Drosera brevifolia, Eryngium* ***prostratum,*** *Gratiola viscidula, Gymnopogon brevifolius, Hypericum canadense, Hypericum* ***crux-andrewsii*** ***(Ascyrum stuns), Platanthera*** *lacera,* ***P.*** *ciliaris,* ***Polygala cruciata, Sabatia catnpanulata,*** *Stenanthium gramineum* ***var. micranthum, Trichostema setaceum*** and *Xyris torta*. Although the wetness of these sites is probably sufficient to maintain small openings, it is likely that fires formerly increased the openness. Forest succession appears to have eliminated some of these species from some sites, and excessive mowing from others (Campbell and others 1989, 1990). They generally have southeastern ranges, especially on the Coastal Plain (see also Braun 1937a,b), where several occur typically in wet, open pine barrens or savanna, where annuals fires promote unusually high diversity (Komarek 1974; Folsom 1979; Walker and Peet 1983).

In more rugged areas of Appalachian Kentucky cast of the Cliff Section, the general lack of rare species suggesting a fire history might be attributed to the general lack of extensive broad, flat ridges where fire might have frequently spread before settlement. However, the endemic *Silphium wasiotensis* (similar to *S. mohrii* of the "oak-barrens" in Tennessee and elsewhere) is restricted to young woods and roadsides on lower slopes, often in areas that have burned (Campbell and Medley 1990). Also, on Pine Mountain, there are small grassy openings with a few rare species that may have been maintained by tire: *Aureolaria pedicularia* (see also *A. pectinata* above), *Baptisia tinctoria* (see also Niering and Dreyer 1989, in relation to fire), *Danthonia compressa* and *Robinia hispida* var. *kelseyi* (see also var. *rosea* above).

In contrast, on more calcareous soils at or just beyond the western margin of the Cliff Section (and in cases indicated by * below, rarely on richer soils in the Rugged Eastern Area), there are several uncommon or rare species of roadsides or other openings that may indicate a tire-history. Some of these species still occur in relatively natural glades, grassland or brushy woods with occasional fire. They include *Apocynum medium* (or *A. androsaemifolium*), *Castilleja coccinea**, *Echinacea purpurea*, *Lathyrus venosus* var. *intonsus**, *Gentiana alba*, *Orbexilum onobrychis** (*Psoralea o.*), *Phaseolus polystachios**, *Polygala senega* var. *senega*, *Salvia urticifolia*, *Silene regia* (Rogers 1941), *Silphium terebinthinaceum* var. *brauniae*, *Solidago ridiga*, *S. speciosa* var. *speciosa** and *Veronicastrum virginicum**. For individual notes, see Campbell and others (1989, 1990; Palmer-Ball and others 1988).

In conclusion, although no definitive statement can be made based concerning the relationship of these rare species to tire within Kentucky, it is likely that fire was a major factor maintaining them on the presettlcment landscape. The exact nature of their barrens habitat will perhaps never be known, but it is likely that large areas were dominated by a relatively open canopy of pines (especially *Pinus echinata*), with some oaks, and much grass (especially Andropogoneae and *Stipa avenacea*). Although the evidence is circumstantial, biological interests, especially in the federally listed species, warrant serious attention to the following suggestions.

(1) It should be recognized that most of these rare species are probably relicts of a natural community that is virtually extirpated within Kentucky.

(2) A search should be made for similar vegetation remaining elsewhere, which might provide clues about ecological factors.

(3) The roadsides and other rights-of-way where these species survive should be managed to maintain their populations.

(4) Attempts should be made to reconstruct the original pine-oak barrens using fire, starting in areas adjacent to the roadsides with these species.

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LODGEPOLE PINE ARTHROPOD LITTER COMMUNITY STRUCTURE ONE YEAR AFTER THE 1988 YELLOWSTONE FIRES

Tim A. Christiansen, Robert J. Lavigne, and Jeffrey A. Lockwood'

Abstract-Litter arthropod data was collected every 10 days from nine intensively burned forest stands, five lightly burned stands, and nine unburned forest stands. For burned forest stands (n=540 samples, there were decreases in insect density (87 percent), noninsect density (67 Percent), noninsect taxa (63 percent), and noninsect diversity (20 percent).

Burned stands with greater densities of tree seedlings had significantly ($P < 0.05$) lower arthropod densities. Those with greater densities of standing dead trees had significantly higher arthropod densities and lower diversities. Those with greater densities of litter had significantly higher arthropod densities and lower diversities.

INTRODUCTION

Remarks by E.O. Wilson (1987) at the opening of the invertebrate exhibit of the National Zoological Park in Washington, DC, states the importance of invertebrates to ecosystems. He remarked "if invertebrates were to disappear, I doubt that the human species could last more than a few months. Most of the fishes, amphibians, birds, and mammals would crash to extinction about the same time. Next would go the bulk of the flowering plants and with them the physical structure of the majority of the forests and other terrestrial habitats of the world. The earth would rot within a few decades the world would return to the state of a billion years ago, composed primarily of bacteria, algae, and a few other very simple multicellular plants." A researcher in forest resources, K.J. Stoszek (1988), noted "insects are among nature's most prominent agents of influence. Almost every process in forest ecosystems (for example, nutrient cycling), each developmental phase of forest stands, and every life stage of dominate and subordinate species of forest vegetation are subject to direct or indirect influences of feeding by insects. Without insects, current patterns of plant reproduction, growth, and death would not exist."

Arthropod communities located in unburned, lightly burned, and intensively burned forest stands were studied 1 year after the 1988 fires. The objectives of the study were (1) to determine the effects of fire on habitat structure, (2) to determine the effects of tire on litter arthropod diversity, density, richness and species evenness, (3) to correlate habitat factors (i.e., density of standing dead trees, herbaceous cover, seedling and sapling density, number of fallen trees, and litter biomass with arthropod ecological parameters, and (4) discuss management procedures for conservation of arthropod communities.

'University of Wyoming, Department of Plant, Soil and Insect Sciences, Laramie, WY 82071.

METHODS AND MATEFUALS

Yellowstone National Park (YNP) occupies 8995 km^2 in the northwestern comer of Wyoming with small areas located in neighboring Idaho and Montana. Elevations range from 1500 m to over 3400 m. Present climatic patterns produce generally long, cold winters and short, cold summers. Annual precipitation ranges from 75 mm to 200 mm (Houston 1982).

Forested areas occupy 79 percent of YNP. Lodgepole pine (Pinus contorta) comprises 81 percent of the forested areas at elevations of 2300 m to 2600 m in which we have research sites (Houston 1982).

Nine randomly chosen unburned forest stands of at least 5 ha were paired with nine intensively burned forest sites and five lightly burned forest stands. Lodgepole pine stands were considered intensively burned if (1) all the trees lacked branches, (2) there was very little ground litter biomass, and (3) fallen trees were burned to some degree. Lightly burned forest stands produced as halo fire stands around intense fires, had a soil litter layer, fallen trees which were singed, and trees with branches and needles burned and brown but still intact.

Arthropods were collected during July to mid-September, 1989. Litter was collected from five 0.5 m^2 quadrates every 20 m (the initial starting point was randomly chosen each sampling period) along two of the three transects (the transects were randomly chosen before each sampling period) every 10 days in each forest site. Each litter sample collected for arthropod extraction was stored in a zip-lock plastic bag for not more than 12 hours before processing. These samples were then placed in Berlese funnels for 24 hours. Arthropods extracted from litter were stored in 70 percent ETOH.

Density of both live and standing dead trees, seedling density, fallen trees, and percent herbaceous cover were determined by making counts within a l-m swath along each transect on each site. Litter samples, which were collected for biomass weight, were placed into paper bags. Litter samples were oven dried for 24 hours at 25 °C and weighed to the nearest 0.01 gram.

Ecological parameters were of arthropod and annelid density, species richness, species evenness, and diversity. Density was based on the number of individuals per quadrate, species richness was based on numbers of individual species (Southwood 1978); evenness and diversity (Shannon-Weaver using the natural log) were analyzed using a program developed by Kotila (1986). Simple linear regression (STATGRAF) was used to determine biotic correlations at the $P < 0.05$ level of significance. Student's t-tests was used to identify statistical differences ($P < 0.05$) between ecological parameters for unburned, lightly burned and intensively burned stands.

RESULTS

Forest Arthropod Community

Undisturbed lodgepole pine forest stands (trees > 100 years) contained higher biotic variables than fire disturbed lodgepole pine stands (table 1). Litter biomass was decreased 19 percent in lightly burned stands and 62 percent in intensively burned pine stands. Downed trees decreased 24 percent in light bums and 30 percent in intensively burned pine stands. The percentage of herbaceous cover decreased 96 percent in light bums and 86 percent in intensively burned forest stands.

Litter mites were the dominate arthropod fauna in both density and species richness (table 2). Insect richness declined 63 percent in lightly burned mature lodgepole pine stands and 67 percent in intensively burned stands of that type (table 3). Insect community density was affected even more than richness with a 92 percent loss in light bums and an 82 percent dcchne in intensively burned stands. Community diversity declined more in light burns (66 percent) than in more intensively burned sites (40 percent).

Noninscct richness declined in both lightly burned stands (71 percent) and intensively burned stands (66 percent) (table 3). Community density declined 89 percent in light bums but only 67 percent in intensive bums. Noninsect diversity declined most in light bums (65 percent) and less (32 percent) in intensive bums.

Table 1. Biotic variables for unburned, lightly burned, and intensively burned lodgepole pine stands

Variable	Fire disturbance None	Light fire	Intense fire
Litter biomass ($g/1m^2$)	153.20a[1,2]	123.60a	57.801,
Trees with needtes >1.82m ht. ($no./100m^2$)	42.82a	45.20a	0.00b
Tree seedlings <15.24cm ht. ($no./100m^2$)	24.42a	7.80b	17.64a
Trees with needles >15.24cm ht. and <1.82m ht.	40.50a	0.00b	0.00b
Standing dead trees no. needles and > 1.0m ht.	12.09a	14.20a	33.08b
Logs	38.11a	29.00a	26.73b
Herbaceous cover (percent)	50.19a	1.90b	7.24b

[1]Means followed by different letters differ at the $P<0.05$ level of significance according to Student's t-test.

[2]n=27 transects.

Table 2. Major arthropod groupings (percent) in unburned, lightly burned, and intensively burned lodgepole pine stands

Arthropod group	Fire disturbance None	Light fire	Intensive fire
Density			
Mites			
Oribatids	42[1]	15	38
Others	21	48	47
Insects			
Collembola	24	31	5
Others	13	8	10
Species			
Mites			
Oribatids	16	23	17
Others	38	23	37
Insects			
Collembola	25	31	30
Others	23	23	16

[1]n=540 samples.

Table 3. Ecological parameters (avg/m^2) for litter arthropods in unburned, Lightly burned, and intensively burned Lodgepole pine stands

Parameter	Fire disturbance None	Light fire	intensive fire
	Insects		
Richness	18.80a[1,2]	7.00b	6.10b
Density	154.70a	13.00b	19.40b
Evenness	.82a	.97b	.87a
Diversity	2.39a	.82b	1.43c
	Noninsects		
Richness	27.80a	a.00b	9.40b
Density	222.70a	25.00b	74.10c
Evenness	.76a	.78a	.75a
Diversity	2.52a	.87b	1.70a

'Means followed by a different Letter differ at the P<0.05 level of significance according to Student's t-test.

[2]n=540 samples.

Factors influencing litter arthropod ecological parameters in unburned, lightly burned, and intensively burned forest.

The following are biotic variables which have been correlated (P < 0.05) with litter arthropod ecological variables.

Unburned forest stands.

Diversity was negatively correlated with tree seedlings ($f = 0.91$).

Diversity was positively correlated with trees over 1.84m in height ($r^2=0.66$).

Diversity was negatively correlated with standing dead trees ($r^2=0.66$).

Density was positively correlated with logs ($r^2=0.66$).

Lightly and intensively burned forest **stands.**

Density was negatively correlated with tree seedlings ($r^2=0.66$).

Discussion. Biodiversity conservation is currently an important and intensively researched topic. Temperate regions should not be given any less attention than tropical regions. Temperate systems may not have the highly diverse fauna as found in the tropics, but temperate systems are important to world-wide biodivcrsity (Piclou 1979). Management decisions which may affect temperate forest arthropod communities cannot be based on research conducted in the tropics.

What is the goal of biodiversity conservation? Why should we study arthropod diversity and community structure? The goal may be to maintain a system by prescribed bums or the goal may be to allow system succession by naturally caused fire. The goals are determined by forest and national park resource managers. A number of studies indicate that natural disturbances are critical in maintaining species diversity (Horn 1974; Levins 1968; Tilman 1982).

E.O. Wison's address states the importance of understanding arthropod communities. Arthropod community structure is changed by habitat structure manipulation (Christiansen and others 1989; Schowalter 1985).

Forest Arthropod Community Structure

Habitat structure.

Habitat structure is important for arthropod community structure. One theory of preservation and conservation practices is that natural systems should be left alone and not cleaned except by natural phenomenon (Franklin 1988). Prescribed fire is one approach that is used to modify forest habitat structure. The degree of fire disturbance most certainly affects various forest components. Comparsons of unburned, lightly burned, and intensively burned lodgepole pine stands in Yellowstone National Park lead to the following conclusions.

If litter biomass and survival of older trees are important to conservation practices for the Yellowstone region, than light bums are a good strategy. However, intensively burned stands contained more tree seedlings, standing dead trees, and herbaceous cover than did lightly burned stands. Thus, intensive burns provide more potential resources, at least in the short term, for arthropod biodivcrsity than lightly burned pine stands provide.

The greatest loss of litter arthropod diversity in lodgepolc pine stands occurred in lightly burned stands. Lightly burned pine stands also had lower arthropod community densities than unburned or intensively burned stands had. These results are interesting since the largest litter biomass loss occurred in intensively burned stands. It is possible that light bums disrupt trophic webs enough to eliminate many arthropod's food resources but do not disrupt niches enough to make invader species competitive. lntensive bums drastically decreased litter biomass, which may have disrupted niche and food resources to such a degree that invader arthropod species can compete. Disturbance may benefit species diversity by opening habitats to fugitive species that ephemerally invade disturbed habitats (Conncll 1978; Sprugal 1985).

Influence of habitat on arthropod ecological parameters. Litter arthropod diversity in unburned and burned lodgepole pine stands was lower in stands with higher tree seedling densities. It may bc that stands with higher than average seedling densities contained lower densities of mature trees. Thus, habitats, in both unburned and burned stands might have been more open than usual and might have had lower litter arthropod diversity for that reason. Many arthropods, such as Collcmbola (springtails) and many fitter mites, arc sensitive to moisture differences which could be affected by more open habitats. A study by Pontailler (1979) described moisture fluctuation due to tree thinning and establishment of forest gaps. A second possibility is that pine seedlings have not yet produced enough litter to support litter fauna. Both of these explanations are supported by the finding that higher than average arthropod diversities occurred in dense stands of mature lodgepole pines. These stands had closed canopies and greater litter biomass than found in dense stands of tree seedlings. Studies by Schowalter and others (1981) and Seastedlt and Crossley (1981) showed that many arthropod species became more abundant as debris increased, and that numbers of insect species that inhabit leaf litter increased enclosed-tree-canopy sites.

Lower arthropod diversity in unburned pine stands was correlated with greater numbers of standing dead trees. The occurrence of lower arthropod diversity in older stands may be inconsistent with the view that old-growth forests support high arthropod diversity (Franklin 1988). Older stands contained more fallen trees than did younger stands. A positive correlation existed bctwccn higher arthropod community density and grcatcr numbers of logs. This correlation indicates that old-growth pine stands support a few high density litter arthropod species.

Litter arthropod community density correlated negatively with pine seedlings. Higher pine seedling densities were found in intensively burned stands, which also had lower litter biomass. It is biologically significant that lower arthropod density would be correlated with reduced litter biomass; reduced litter biomass means reduced food and habitat resources for litter-inhabiting arthropods. Increasing densities of standing dead trees were corrclatcd with higher arthropod densities but lower diversity.

Arthropod density and diversity were low on burned sites with large numbers of logs. Lightly burned pine stands, which contained more litter biomass than intensively burned stands, contained higher arthropod community densities and lower diversity. This implies either that a few species were able to adapt and multiply in burned stands or that invader arthropod species entered the stands from nearby unburned pine stands.

Conclusions About Arthropod Diversity and Conservation

Habitat loss is one of the major factors in diversity reduction (Pimm and Gilpin 1989). The present study showed that litter arthropod diversity was lower in burned forest habitats than in unburned stands. However, species evenness increased in disturbed stands. Species evenness is an index describing the distribution of species in a community. Thus, an increase in species evenness suggests that competition is among more species than just those which compose the majority of the community. Chesson (1985) states that competing species that cannot. coexist in a constant environment may cocxist in the presence of environmental variation.

If the immediate management goal of burning is to maintain high litter arthropod diversity, either for biodiversity conservation or ecosystem functions, then high intensive bums are the suggested control method. Long-term management may be a different matter for diversity. Mature unburned lodgepole pine stands support greater diversity than found in very young (i.e., seedlings) pine stands. However, litter arthropod diversity in mature forests with high densities of standing dead trees is not as great as litter arthropod diversity in somewhat younger forest stands. These same older forests support greater densities of fewer litter arthropod species, however.

Results of our study indicate the complexity of conservation and management of litter arthropods in lodgepole pine forests. Our research has only provided preliminary data. There is clearly a need for more habitat and arthropod community structure interaction research on an ecosystem level if forest management goals arc to be achieved.

ACKNOWLEDGMENTS

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SOME THOUGHTS ON PRESCRIBED NATURAL FIRES

Jack D. Cohen*

Abstract-Wildland tire is a significant component of nearly all North American ecosystems. High intensity, stand-replacement tires are normal in certain ecosystems, especially in the northern Rocky Mountains. Wilderness fire managers are obligated to let tire operate as a natural influence to the extent that this is possible. Where wilderness areas incorporate stand-replacement-type tire ecosystems, ecologically significant prescribed natural fires must reach stand-replacement fire intensities. However, because weather forecasting capabilities are limited, fire managers are unable to predict whether prescribed natural tires will escape prescribed boundaries. Moreover, the effectiveness of suppression actions decreases as wilderness tires increase in size. Thus, fire managers face the dilemma of managing for natural tire influences on ecosystems, with the consequence of increasing the potential for escaped fue situations.

Typically, thunderstorms develop over the northern Rocky Mountains in late spring and early summer. The following hypothetical situation begins on June 29, with lightning strikes peppering a broad area of the Intermountain region of the Northwestern United States.

A large wilderness area in the northern Rocky Mountains has a prescribed natural fire plan under which a few fires are allowed to bum within its boundaries. These fires are prescribed so that natural fire will continue to be a significant ecological influence in the wilderness area. Investigations have determined that this ecosystem normally experiences stand-replacement fires. Thus, to be ecologically significant, the prescription permits some high intensity burning, i.e., crown tires.

The fire managers use criteria based on the National Fire Danger Rating System's Energy Release Component (ERC) to decide whether or not to suppress lightning ignitions. However, using the ERC has had its uncertainties. Last season, the spring and early summer values were well above normal. All fires were suppressed. But the July and August weather had turned rainy and cool, and ERC's were below normal.

In the current season, the ERC's have closely followed normal values. The 30-day forecast predicts normal temperatures and precipitation for July. On July 1, a reported lightning fire is designated as a prescribed natural fire.

However, by July 11, there is a distinct trend toward hot, dry, weather conditions. From the end of July to August 5, the ERC's are consistently and increasingly above normal. The 30-day forecast for August calls for above-normal temperatures and below-normal precipitation. Although no new natural fires are allowed to bum, the July 1 fire continues. Even with the hot, dry conditions, the burned area is less than 10 acres (4 ha) as of August 5, well within the prescribed limits for size and proximity to boundaries. At this point, the prescribed natural fire is not yet an ecologically significant event.

On August 5, the National Weather Service forecasts the possibility that a dry cold front will move through the area in 3 to 5 days. The forecast does not change the designation of the prescribed natural fire. On August 8 and 11, two dry cold fronts produce strong winds. As of August 13, after the cold fronts pass, the fire perimeter contains over 8,000 acres (3,200 ha). Numerous spot tires and crowning occur. Within a period of 5 days, the fire has become ecologically significant.

The fire managers in this scenario have executed the policy of allowing fire to assume a more natural role in the wilderness and have accomplished an ecologically significant fire. But now they must deal with the uncertainty of the remainder of the fire season and thus the possibility that their management fire will escape predetermined boundaries. If undertaken at this time, an effective suppression action must be capable of containing an active 8,000-acre fire.

The Yellowstone Fires of 1988 represent one possible result of the implementation of a Park Service (U.S. Department of Interior) and Forest Service (U.S. Department of Agriculture) policy that attempts to return historic fire occurrence to designated areas. Research has established that fire is a significant component of most North American ecosystems (Amo and Brown 1989; Wright and Bailey 1982). The policy that allowed some tires to bum in the Greater Yellowstone area reflects management's desire to maintain processes vital to the ecosystem's existence.

An effective natural fire policy provides for the occurrence of ecologically significant fires. That is, the policy prescribes the occurrence of periodic fires that achieve a range of intensities over a large enough area so that tire will continue to be a significant ecosystem process. Normal ranges of ecologically significant fire frequencies and intensities vary

'Research Physical Scientist, Southeastern Forest Experiment Station, Forest Service, U.S. Department of Agriculture, Dry Branch, GA

among ecosystems. The spectrum ranges from ecosystems with frequent tires of low intensity to those with infrequent fires of high intensity (Bacon and Dell 1985). Much of the Greater Yellowstone area as well as other wilderness areas in North America have ecosystems where ecologically significant fires are of the infrequent, high-intensity type that result in the replacement of all surface vegetation in a portion of the burned area (Brown 1989; Heinselman 1985).

A problem arises when a natural fire program that requires high-intensity fires is implemented. Wilderness areas have administrative boundaries that separate the wilderness landscape from landscapes where uncontrolled high-intensity tires are undesirable. Much of the concern during and after the 1988 wilderness fires (the Yellowstone Complex and the Canyon Creek Fire in the Scapegoat Wilderness) has related to natural fires crossing wilderness boundaries and threatening or destroying outside values. The wilderness fire manager's goal is to let tire operate as a natural process and at the same time contain it within prescribed boundaries. But this goal can create dilemmas. The following discussion examines, in terms of scale characteristics, the various elements that contribute to this potential fire management dilemma. Although this discussion may relate to the initial bum-or-suppress decision, it does not specifically address that decision. Rather, this discussion focuses on the limitations of managing an ongoing prescribed natural tire.

THE DILEMMA

A natural prescribed fire may bum for several months. Due to the limits of weather predictability, a fire manager cannot predict fire behavior on the basis of extended-range weather forecasts. Thus, it is possible that any prescribed natural fire will exceed its prescription. There are ecosystems in which fires must be large and intense if they arc to be ecologically significant -- and such tires have the potential to out-scale fire suppression capabilities. By the time a fire manager realizes a fire will exceed its prescribed limits, suppression efforts may not be effective. Thus, managing for natural fire processes in wilderness areas also enhances the potential for escape.

ELEMENTS OF THE DILEMMA

The basis for the wilderness fire management dilemma can bc found in the response of fire behavior to the weather, limitations of weather predictability, and a limited fire suppression capability.

Wildland Fire

The conditions associated with fast-spreading, high-intensity tires (e.g., the 1988 Yellowstone Fires) are drought and high winds. Drought conditions promote drying in vegetative fuels, both dead and living, thus making the fuels more flammable. High windspeeds increase spread rates, which increases intensities and spot fire ignitions. Although drought conditions are commonly referenced in discussions of severe fire situations, drought alone is not sufficient to produce large, high-intensity tires. High windspeeds are required to drive fire to extreme behavior. Thus, given sufficient fuel loadings, severe fire situations depend on two different aspects of the weather.

Weather

Atmospheric phenomena can be generally characterized by distinct time scales. Dutton (1976) describes the temporal characteristics of several weather features as follows:

Atmospheric Dhenomena	Time scale
Planetary waves	1 yr- 1 mo
Synoptic systems	1 wk . 1 day
Mesoscale features	1 day . 1 hr

Trends in weather variables such as average monthly temperature and precipitation are related to the planetary scale, whereas, a specific day's temperatures and precipitation are related to synoptic and smaller scales. Drought conditions arc associated with planetary waves, and high winds are associated with synoptic systems and mesoscale features. Thus, weather conditions operating on two different atmospheric scales contribute to the conditions that produce severe fires. In general, severe fire behavior potential develops over a month or more as fuels become drier (drought), but has an episodic time scale of one week to one hour (high winds).

Weather Forecasting

The ability to forecast the weather depends on the atmosphere having the characteristic of predictability (Lorenz 1968). There arc indications that the atmosphere behaves in highly nonlinear ways, and that this limits weather predictability (Lorcnz 1963, 1969; Gleick 1987; Tennekcs 1988). In a mathematical modeling context (which is largely how weather forecasting is done), this non-linearity results in a loss of connectivity over time. That is, the state of the atmosphere at a given time (the initial conditions) loses its predictable relation with the state of the atmosphere at some later time.

I think the general conclusion can be drawn that weather conditions cannot be specifically predicted over time periods longer than their associated atmospheric time scales. That is, a forecast of weather variables associated with the mesoscale to synoptic time scale (e.g., specific precipitation or wind events) does not apply beyond about 3 days. Forecasts covering several weeks to several months, which predict general trends in weather variables (e.g., departures of mean temperatures and precipitation amounts from normal) are associated with planetary time scales. Extended-range forecasts that provide likelihoods of shorter time scale weather conditions are not an exception. in this case, the statistical characteristics associated with a planetary scale situation are described rather than a forecast of specific deterministic information about a smaller time scale condition.

Effective Fire Suppression

To be cffective, a fire supprcssion action must be scalcd to match a firc's spread and intensity. A fire suppression action must be capablc of constructing a quantity of firc line comparable to the spread rates and fire growth, and the fire line must bc sufficiently wide to prevent crossing caused by flames and fircbrands. A firc supprcssion action can bc ineffective because insufficient resources arc committed to it or because the fire overpowers a maximum practical suppression effort.

Managing for ecologically significant, high-intensity fircs requires that these management fires reach large sizes relative to fire sizes normally controlled as wildfires. To further complicate matters, weathcr forecasting limitations prevcnt the long term prediction of a fire's eventual size and intensity. Thus, an effective suppression force must be capable of constructing enough firc line to contain portions of or all of a management firc that could be potentially of high-intensity and extend over an area of scveral thousand acres. Howcvcr, the larger a fire is, the less cffcctivc is a suppression action. That is, the fire's growth and/or intensity is more likely to out-scale suppression efforts. Commonly, after wildfires become large, suppression is not cffcctivc until a sufficient weather or fuel change occurs, causing a fire to return to a scale where suppression is effective. In the case of the 1988 Greater Yellowstone Fires and the Canyon Creek Fire, a sufficient weather change (to cool and damp) did not occur until mid-September.

CONCLUSION

Large, high-intensity fires are a natural occurrence in some ecosystems. Where these ecosystems occur in wilderness areas, fire managers arc obligated to maintain natural processes for the existence of the ecosystem. Prescribed natural fires are a reflection of this obligation.

Because a prescribed natural fire can bum for an extended period, specific weather conditions cannot be selected. The fire burns under whatever conditions occur. But, for an ecologically significant fire, the weather must accommodate a high-intensity fire for some period of time. If, however, severe burning conditions are too persistent, the fire can exceed prescribed limits.

The fire manager does not have extended-range forecast information at the scale of specific fire weather conditions. This is due to the lack of predictability of the atmosphere at the scalc responsible for high wind speeds. Thus, the eventual state of the prescribed natural fire cannot be predicted.

Fire suppression actions required to contain a prcscribcd natural fire within designated boundaries may not succeed. The achievement of an ecologically significant (large size, high intensity) wilderness fire reduces the likelihood of effective fire suppression, should suppression actions become necessary. Thus, the maintenance of fire as a natural process can lead to wilderness fires that escape prescribed boundaries to become costly wildfires. This is the essence of the prcscribcd natural fire dilemma.

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USE OF THE 1990 CENSUS TO DEFINE WILDLAND URBAN INTERFACE PROBLEMS

James B. Davis'

Abstract-Predicting the movement of people into rural wildlands previously has been limited to studies of population and housing growth in counties or other large geographical areas. In these studies, the areas of high tire danger that contain dispersed rural housing cannot be distinguished from the areas less vulnerable to wildfire (small towns and adjacent urban areas) because the data and the analysis procedures associated with the *1980 census* does did *not* give sufficient information about rural and wildland areas. Analysts studying rural demographics supplement census data with information From such sources as local tax assessors' records or building permit files.

INTRODUCTION

If we are going to effectively manage the wildland urban interface fire problem we need to know where people live, work and play within the interface area. Wc also must know something about their knowledge and attitudcs toward the environment and its mnnagcmcnt and protection (Davis 1990; Irwin 1987, 1988). We need to know where people obtain their knowledge and how thcy formulate their ideas and attitudes--a rapidly developing ficld called psychographics. If WC know what our customers want and what benefits &hey perceive, we can kc more effcctive in communicating with them.

We can help develop a firesafc community by influencing the location of housing within fire-prone areas and help regulate the design of homes and other structures in those locations most likely to bum. The intcrrclationship between the factors that result in a choice of a building site and the factors that matter in fire spread and suppression, such as vegetation type, slope class, and aspect, access and proximity to water and roads nced to be understood. Reasonable estimates can be made of housing to be built five or more years in the future whcn these factors arc included in population projection modcls (Bradshaw 1987). These estimates can be mapped and overlaid on fire risk and hazard maps to allow a fire manager to display to local policy and planning officials detailed information on the areas likely to bc threatened by future wildfires and the homes and population that will be at risk unless mitigating measures are taken. The ability to display this information will enable fire managers to be proactive rather than reactive in their contacts with public leaders.

PROBLEMS

Rural Growth

Many foresters are surprised that they must cope with the most rapidly changing and dynamic segment of our nation's population. Although the increase in rural population has slowed somewhat since the 1970's when rural counties were growing three times as fast as the urban counties, population growth in many of the Nation's forest and range counties continues to exceed urban population growth and will probably continue to do so past the turn of the century (Long 1983; Rice 1987).

California, for example, has traditionally doubled its population every 20 years since statehood. However, it will not double its 1970 population again until at least 2020, a period of 50 years. Yet, the population of I.5 of its counties--all forested with the exception of one--is continuing to double in 20 years or less--tEe areas that are increasing in population most rapidly are those most prone to wildfires.

Problems Beyond Local Control

Another problem is that rural area population dynamics are influenced by socioeconomic factors well beyond the borders of the area involved. California has long appealed to Americans who move for one reason or another. By the late 1960's, however, California gained migrants from fewer states than previously, and it began to send migrants to Oregon, Washington, and Nevada, as well as to Oklahoma and Virginia (Hcrbcrs 1986). Between 1975 and 1980, California had a net loss of 420,000 people in migration exchanges with its ten western migration partners. But this loss was offset by a net gain of 534,000 people from the rest of the U.S., chiefly from the Northeast and Midwest because of the decline of the iron and automobile industries and because young professionals were being attracted to California's aerospace, computer and other high-tech industries, resulting in a total gain of 114,000 to California's population.

In the late 1970's Oregon residents sported bumper stickers asking Californians to visit but not to stay. By the mid 1980's such fears were allayed because Oregon began exporting people to California due to the decline in the woods products industry and rising unemployment in the Northwest (Sweeney 1979).

This continually changing economic situation has made population growth projections into fire prone areas difficult.

'Research Forester, Fire Planning and Economics Research, Forest Fire Laboratory, USDA Forest Service, Riverside, CA

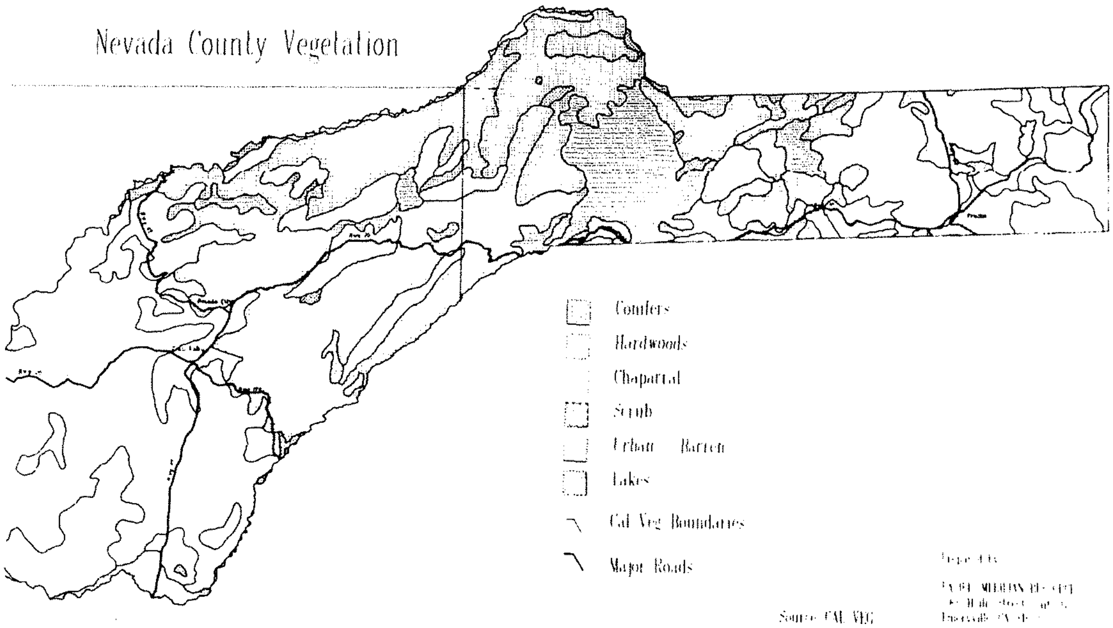

Figure 1--Broad categories of vegetation found in Nevada County. The vegetation changes from mostly grass, chaparral, and hardwoods at the lower elevations in the western part of the county, to heavy stands of conifers in National Forests covering the higher elevations in the east. Major highways are indicated on the map as well.

Limitations on Population Growth Estimation

For foresters, the 1980 census has not been helpful because of the poor level of resolution in wildland areas; the tracts are very large areas in most instances and often include diverse demographic characteristics within a tract. For example, the twelve tracts in Nevada County, California range from thinly inhabited National Forest Land to urbanized residential areas (Fig. 1).

Analysis Models Are Limited

While knowing "what is there now" is difficult, it is only part of our battle. We need to know "what will be there in the future." The census information does the local planner little good unless it can be interpreted for his or her needs in both a temporal and spatial manner. This is a particularly difficult problem in the wildland urban interface because there have been few predictive models. Although such models exist for urban areas--the projections needed for the construction of a shopping center, for example--we know of no case in which they have been used to predict the location and number of households at risk from wildland fire. Population analysis in rural areas has usually been concentrated on estimating the movement of population to urban areas as farm and lumber industries decline, or in predicting the broad overall change in a county level population.

Extensive literature exists on the population change of particular rural counties, and permits extrapolation of this information to many potential rural growth situations (California Department of Forestry and Fire Protection 1988). However, virtually no micro-level studies have been done to understand where people in rural areas choose to live (Lindhult and others 1988). Much of the rural demographic research--if it has been done at all--has been in the northeastern United States where counties are generally small and relatively homogeneous. Counties in the western United States, on the other hand, are large, heterogeneous, and require a much more rigorous analysis.

Regional development models are similarly underdeveloped outside of metropolitan areas. Although they have been used to establish the regional growth within urban areas, they are less adequate for rural areas for which data and economic conditions are less well understood (Beforf and others 1988). The interrelation between economic conditions and housing development has been posited in the literature, and evidence in rural areas indicate that people often commute long distances in order to take new jobs. Economic conditions go hand in hand with changes in the housing supply, but little is known about how economic growth affects the distribution of housing in wildland interface areas which often include a high number of retired persons.

RESEARCH ON WILDLAND DEMOGRAPHICS

The Riverside Forest Fire Laboratory, in cooperation with the University of California's Institute of Governmental Studies in Berkeley, is making an effort to solve the problem of wildland urban interface demographics. Dr. Ted Bradshaw is the principal investigator from the University for the project.

The cooperative effort is attacking the following three questions and is using Nevada County, California, as a field laboratory:

1. Can we identify reliable sources of demographic data for the wildlands.

2. Can we develop models to define and better understand the movement and eventual settlement of people in our wildland areas?

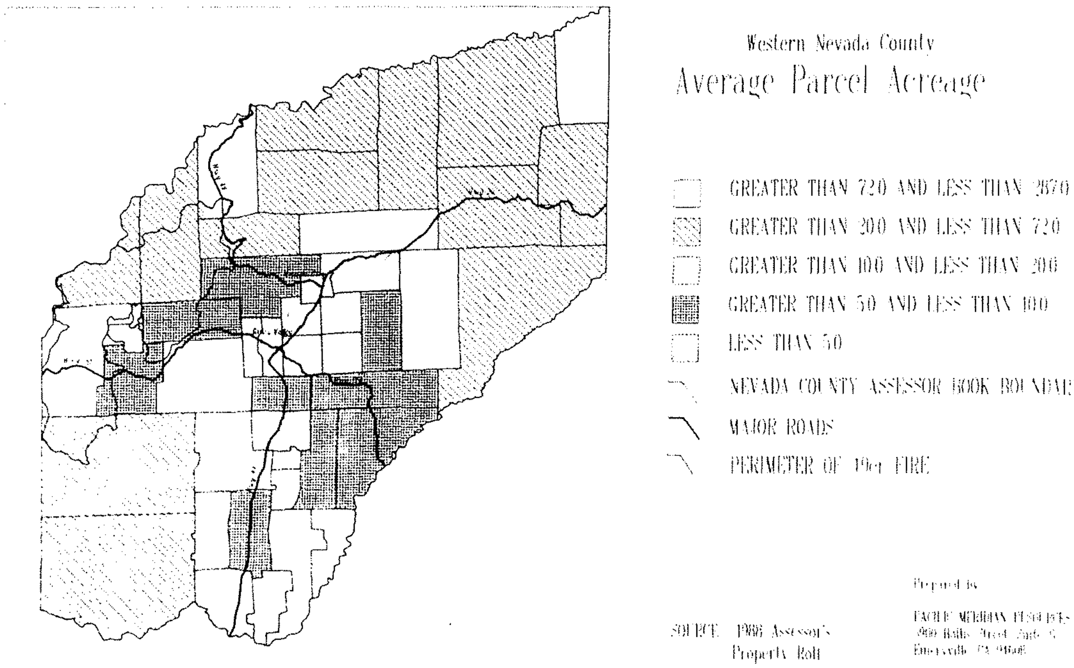

Figure 2--Patterns of population from the 1980 census. These data demonstrate the capacity of GIS to translate data on total population into density per acre. Current population densities arc significantly higher due to an average annual county population growth of 6 percent since the census.

3. What must we do to take advantage of the much higher resolution data that will be available from the 1990 census and the commercially available data and analysis software that will spin off from it?

Identification of Data Sources

The data we are using in our research come from various sources with different geographical boundaries:

- The vegetation data are from a statewide species mapping effort called "CAL VEG" based on land and aerial data.

- Fire severity zones in Nevada County are based on a series of maps prepared by the California Department of Forestry and Fire protection and determined from topographical, climatological, and fuel considerations (Phillips 1983).

- Census data from the 1980 census arc given by enumeration district (Fig. 2). In selected areas we are examining the existing pattern of settlement by using census data, current updates, and aerial photos, when possible, and are seeking methods to estimate the accuracy of the statistical data. A major source of information has been county tax assessor's records. We have found that data on building permits arc a key factor in determining patterns of growth since 1980.

- Property rolls contain information on the size, use, and value of property in the county. Thcsc data arc shown for geographical areas defined by the county assessors' books.

Current research has enabled us to go from book to page level--a degree of resolution that normally will include 50 or fewer households. Also obtained from the assessors' records arc data on the per acre value of improvements. The areas with the highest values usually arc associated with residential construction and much of it is located in areas of high fire hazard.

Using assessors' data on average parcel size, trends in dcvciopmcnt arc easy to identify. Further analysis will show the characteristics of these parcels with regard to tire dangers, roads, and physical amenities.

Our rcscarch is extending the field of investigation to include groupings much smaller and more specific than the usual national or regional aggregates. We arc constrained by neither political nor administrative boundaries such as cities, villages, or natural regions, but our rcscarch is allowing us to study levels of human categories that arc not territorially well delincd (for example wildland urban rcsidcnts).

Development of Models

While current population and attitudinal information should be useful to foresters and fire managers, our long-range objective is to develop predictive models. Wc arc conducting analyses to estimate parameters of various models that include growth as well as attitude toward forest land and its management and protection. The attitude and growth are related to factors such as vegetation type, slope, aspect, attractive physical features, proximity to urban settlements, employment, subdivisions, infrastructure, roads, etc. We will determine whether our models accurately estimate growth at reasonable levels of confidence by comparing our model determinations with patterns that have occurred over the past 5-10 years and with current building permit issuance and opinion surveys. We will select the most descriptive model and refine it as needed.

How do we take advantage of the 1990 Census?

Although we are making headway with non-census data, the 1990 census data, when they become available in 1992 or 1993, promise to create a "desktop computer revolution." Along with benchmark demographic data, the census includes a survey of housing and housing units. For our purposes the census of housing will be very important because it describes the location and demographic characteristics of the people living in each housing unit. It also details ownership, condition. and value of the property (Kirchner and Thomas 1989).

The 1990 census data will be available on four census computer "summary tape files" (STFs):

- STF- I and STF-2 will contain data on household type, race, sex, age, marital status, and detailed information on the residence obtained from the "short" census questionnaire sent to every home in the country. This information for the first time will provide good resolution in rural areas and will be traceable to the equivalent of a city block.

- STF-3 and STF-4 will contain the same basic data as the first two summary files, plus the information from the "long" census questionnaire. The long form will be answered by a 17 percent sample of households. This form will contain demographic information that fire planners may need, including income, educational background, migration, language, type and place of employment and housing information such as availability of 3 telephone.

In fact, this high level of resolution has created somewhat of a problem to the Census Bureau in maintainig confidentiality. In rural areas it might be possible to identify the source of some data--the income of a single ranch family for example- -and the Bureau has had to incorporate methods to screen out such information.

One objective of our analysis will be to determine whether the detailed 17 percent survey will give us all of the demographic information we need in very sparsely populated areas, or whether we will still have to depend to some degree on other sources such 3s building permits and assessors' records. Much of our research will be aimed at correlating information that we can obtain from census records with factors that cause people to move into the interface area.

Micro Computers and Laser Discs

Although the 1990 census data will be available in several forms from hard copy reports to computer tapes, the most exciting improvement for computer-wise foresters will be that the information will eventually be available on laser read-only memory compact discs known as CD-ROMs, reflecting a decade of changing computer technology. By putting census data on laser discs, the Census Bureau will make great quantities of information available to the individual with a good personal computer and the computer capability to use the information. Compact discs have enormous potential because each 4-S/8-inch disc can store as much information as three computer tapes or 1,500 floppy disks. An expensive mainframe computer is not required to process information contained on a compact disc. However, one problem may be "data overkill." There is likely to be so much information that determining what information to use and how to use it efficiently will be difficult.

With the addition of a laser disc reader--available to almost cvury forestry or fire management headquarters office for less than $1000--a microcomputer can become a desktop information system capable of printing STFs on demand.

However, despite the obvious advantages of compact discs, the Census Bureau is not releasing them as the basic medium for distributing 1990 census data because as yet, there is no standardization in disc technology. Until there is standardization as well as user-friendly software, much computer skill will be needed to use this new technology. To help users get started, the Census Bureau is making three CD-ROMS--Test Discs 1 and 2, and the 198.5 American Housing Survey--available now. The discs sell for $125 each and can be ordered from the Bureau's Customer Service Office.

TIGER Files

A recent innovation, that may prove very valuable for model development and testing and for understanding wildland urban interface population dynamics, is the automated mapping system known as TIGER (Topologically Integrated Geographic Encoding and Referencing). This system has enabled the Census Bureau, working with the U.S. Geological

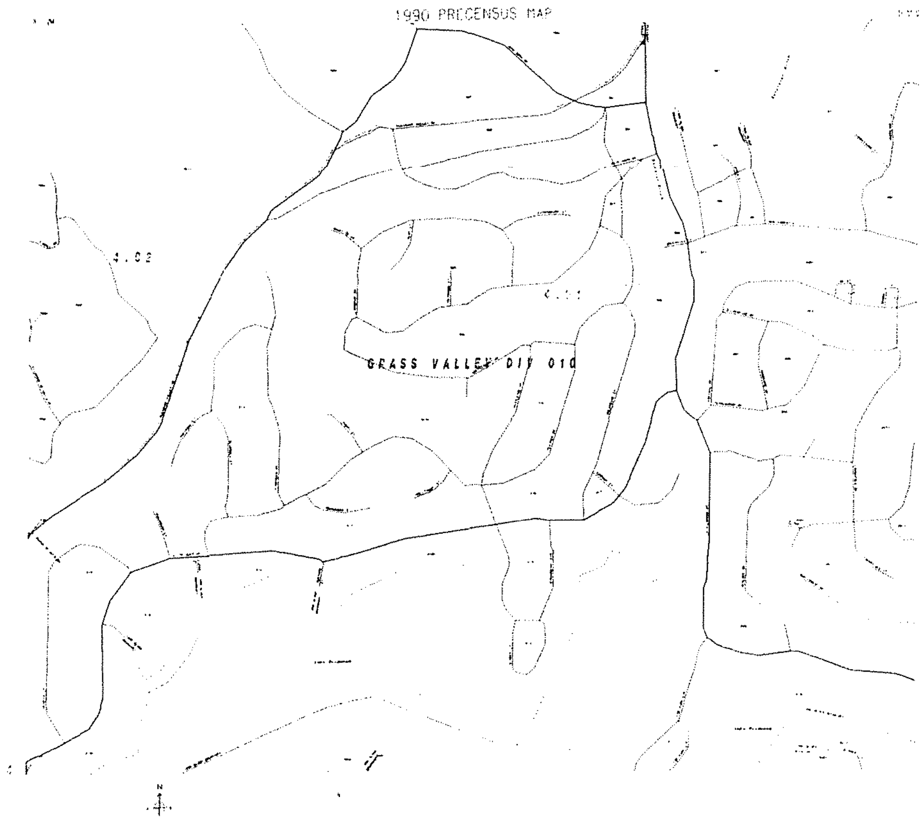

Figure 3--Section of preliminary map printed from the TIGER files. Map scale is about 4 inches to the mile. For many locations TIGER is capable of generating the most detailed and up-to-date maps available.

Survey, to develop computerized maps covering the entire United States (U.S. Department of Commerce 1985). TIGER is essentially a digital street map of the country (Fig. 3). The TIGER process uses geographical information system (GIS) technology that translates the intersection of boundaries of one type of information--census related information, for example--with information from another geographic feature.

The Bureau's preliminary plans envision TIGER boundary files for counties, census tracts, block numbering areas, and county subdivision. The road systems are so complete that forestry agencies should take a good look at them from the standpoint of updating their own transportation systems. The TIGER files currently are available only on magnetic tape, but the Bureau is looking at the possibility of releasing TIGER on CD-ROM as well.

As of now, TIGER files contain only geographical information--individual streets and other features digitally coded by latitude and longitude. They will not contain any 1990 census data. Several software companies are planning to combine the TIGER files with 1990 census data on compact discs.

Geographical Information System Technology

Desktop demographic systems become even more powerful when linked to geocoding and mapping software--geographical information systems (GIS). GIS technology and the proposed census data systems are virtually made for each other. Geographical information systems analysis can overlay many features about an area's population and urban development with data about the physical characteristics of the area (Thompson 1989). A GIS also provides a set of tools necessary to model and understand the flow of people, resources and commodities into and through the interface--essentially a depiction of the infrastructure.

CONCLUSION

The ability to assign a latitude and longitude to in-house records will be a fast effective link between census information and our wildland urban hazard reduction and fire prevention efforts. GIS technology will allow land and fire managers to superimpose population forecasts and trends, fire behavior factors, and even past fire occurrence records, enabling projections of fire problems years before they actually occur.

Although this paper has been oriented to the wildland urban interface fire problem, the potential for demographic research is much greater. The dynamics of populations and their attitude toward wildlands and their management affect all phases of forestry. We expect that many of the concepts and models that we are developing will apply equally to other forestry problems from wildlife management to watershed management.

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CLIMATE, FIRE, AND LATE QUATERNARY VEGETATION CHANGE IN THE CENTRAL SIERRA NEVADA

Eric G. Edlund and Roger Byrne[1]

Abstract-Fossil charcoal provides a record of significant changes in the importance of fire in the Central Sierra Nevada over the past 15,000 years. Changes in fire regime appear to be related to regional shifts in climate. During the late Pleistocene (ca. 12.5—10 ka), minimal sedimentary charcoal influx is correlated with fossil pollen and macrofossil indicators of a moist climate, probably with deeper spring snowpack than the present. In the early Holocene (10—7 ka), macrofossils indicate a shift from white and lodgepole pines to more xeric ponderosa pine-dominated forest. Charcoal influx climbs rapidly to maximum values in this zone, in conjunction with increases in fir, oak, and dwarf mistletoe pollen, along with bracken fern spores. Charcoal declines to modem values between about 7-3 ka, by which time the modem mixed conifer forest became established.

Changes in the abundance of bracken, dwarf mistletoe, oak and ponderosa pine can be strongly correlated with charcoal influx. The late-Pleistocene interval of minimum charcoal influx is a period in which dense forest surrounded the lake, indicating that fire frequency was not directly a function of fuel availability. Increasing summer drought in the early Holocene made tire an important factor in vegetation change. The zone of rapid increase in charcoal ahundancc, beginning 10,000 years ago, is associated with abrupt changes in vegetation, including the first appearance of ponderosa pines and firs following dcglaciation.

INTRODUCTION

Concern over the potential impacts of climate change on natural ecosystems has demonstrated a need for long-term studies of vegetation-climate-fire relationships. Recent workers (Overpeck and others 1990; Clark 1988a) have suggested that prolonged warm-dry climatic intervals may lead to increases in fire frequency and intensity. The relationship is not a linear one, however; a shift to a warmer, drier climate could eventually reduce fire intensities as a function of decreased biomass available for burning.

The composition of forests in the Sierra Nevada has been strongly influenced by fire. Before twentieth-century fire suppression, fire frequencies in mixed conifer forests averaged about 7-10 years (Wagcncr 1961; Kilgorc 1973). Studics of Sicrran ponderosa (Weaver 1968), red fir, and sequoia-mixed conifer forests (Kilgore 1973) have demonstrated the extent to which the dominant montane tree species are adapted to periodic firc. The role of fire in higher elevation forests, where mountain hemlock and lodgepole pine dominate today, is less clearly understood (Rundel and others 1988). Before the twentieth century, natural fires in the Sierra Nevada are believed to have been of generally mild intensity and limited extent.

Computer modclling of forest responses to climate change (Overpeck and others 1990) has indicated that an increase in the rate of ecological disturbance accompanying potential CO_2-induced climatic changes would produce greater changes in stand composition than would climate changes alone. Such impacts are of concern in modern forest management, particularly since palcoccological work has tied fire to climate changes on time scales of hundreds of years or less. Working on lake sediments from northwestern Minnesota, Clark (1988a) found high charcoal abundance from 1400-1600 A.D., a period of warm, dry climate in the area. Fire frequency during this interval is estimated at 44 years, compared to 85-90 years during the subsequent “Little Ice Age” of the 17th—19th centuries.

The role of climate in determining fire regimes may have been even more important during the major climatic shifts which have occurred over thousands of years since the last major ice age. Good evidence for a relationship between climate and fire frequency has been uncovered in midwestem North America. Early work by Waddington (1969) documented an increase in charcoal influx at Rutz Lake, Minnesota from 8-4,000 years ago, corresponding to a shift from oak to prairie vegetation. In southern Wisconsin, Winklcr and others (1986) recorded increased charcoal 6,500—3,500 yr. B.P., at a time of lowered lake levels and a shift from mixed mesophytic forest to oak savanna.

Paleoecological work in the Sierra Nevada provides a chronology of postglacial climate change inferred from shifts in vegetation (see fig. 1 for locations discussed below). Late Plcistoccnc pollen and macrofossil records show evidence of colder, drier conditions, with sagebrush (*Artemisia*) and juniper important components of the vegetation (Adam 1967; Batchelder 1980; Cole 1983; Davis and others 1985; Davis and Moratto 1988). At some sites, pine and fir forests developed bctween 12,500—10,000 years ago, probably responding to soil dcvclopmcnt and a wetter climate. In the

[1]Dcpartmcnt of Geography, University of California, Berkeley, CA 94720.

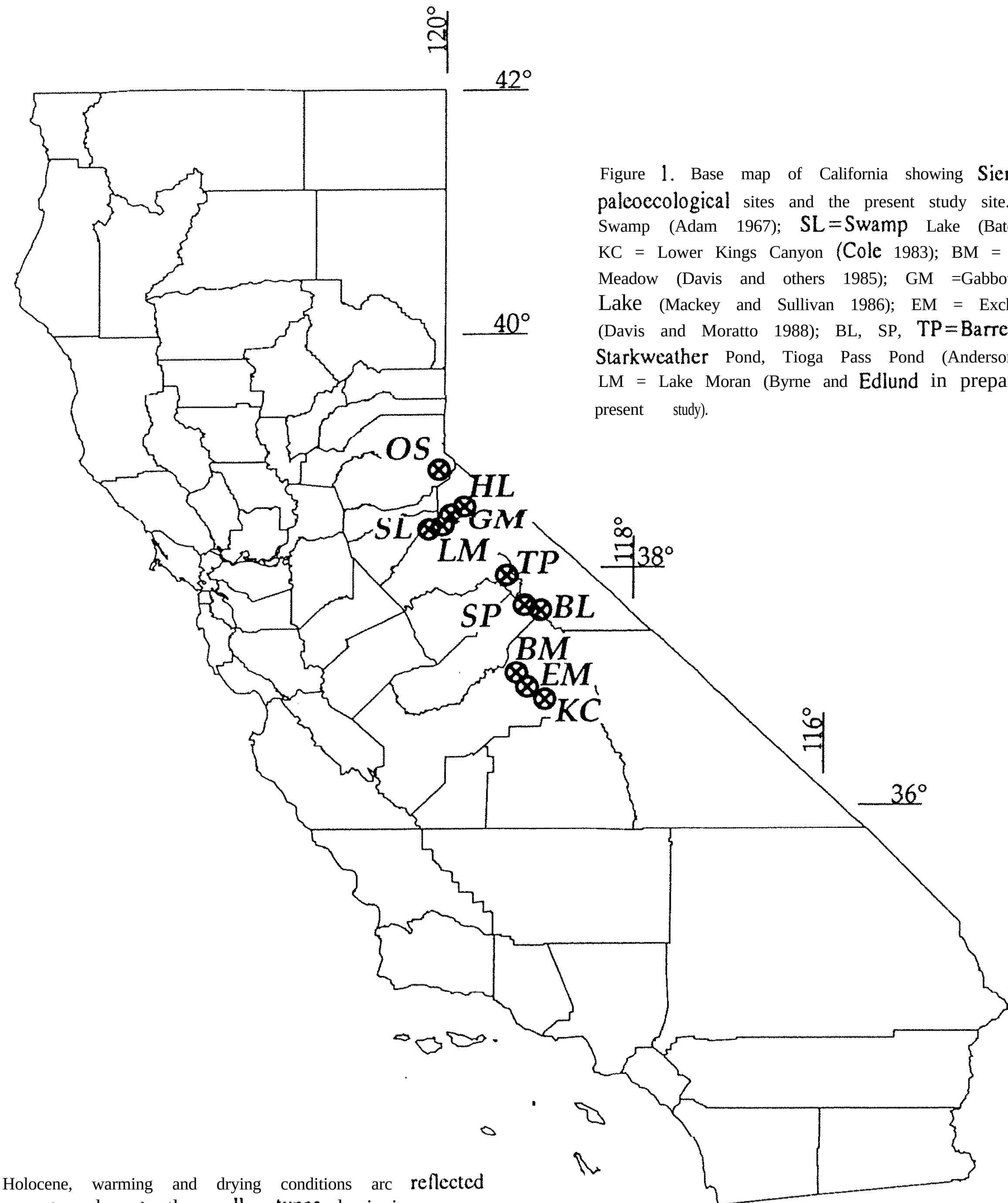

Figure 1. Base map of California showing Sierran paleoecological sites and the present study site. OS =Osgood Swamp (Adam 1967); SL=Swamp Lake (Batchelder 1980); KC = Lower Kings Canyon (Cole 1983); BM = Balsam Meadow (Davis and others 1985); GM =Gabbot Meadow Lake (Mackey and Sullivan 1986); EM = Exchequer Meadow (Davis and Moratto 1988); BL, SP, TP=Barrett Lake, Starkweather Pond, Tioga Pass Pond (Anderson 1990); LM = Lake Moran (Byrne and Edlund in preparation, and present study).

early Holocene, warming and drying conditions arc reflected in increases in oak and other pollen types, beginning ca. 10–9,000 yr. B.P., and lasting until at least 6,500–5,000 yr. B.P. (Mackey and Sullivan 1986; Byrne 1988; Davis and Moratto 1988; Anderson 1990). High elevation sites record increased effective precipitation beginning about 6,000 yr. B.P. (Anderson 1990). At some of the lower lake sites, warn-climate indicators persist until ca. 4,000–3,000 yr. B.P., when fir increased in response to the onset of Neoglacial cooling (Adam 1967).

The early Holocene xerothcrmic interval has been widely recognized in western North America. Mathcwes (1985) summarized work in British Columbia documenting xerothermic conditions 10–7,000 yr. B.P., following an interval of cool moist climate in the late Pleistocene (12-10 ka). He argued that douglas-fir, alder, and bracken fcm, which reach maximum levels in pollen records over this interval, are fire-adapted species which responded to increased fire frequency along with climatic warming.

In the Sierra Nevada, the existing evidence for changes in the role of tire during postglacial time is quite limited. At Exchequer Meadow (Davis and Moratto 1988), sedimentary charcoal reaches maximum abundance in deposits dated approximately 8,000–4,000 yr. B.P. At nearby Balsam Meadow (Davis and others 1985), macroscopic charcoal appears only after ca. 7,000 yr. B.P.

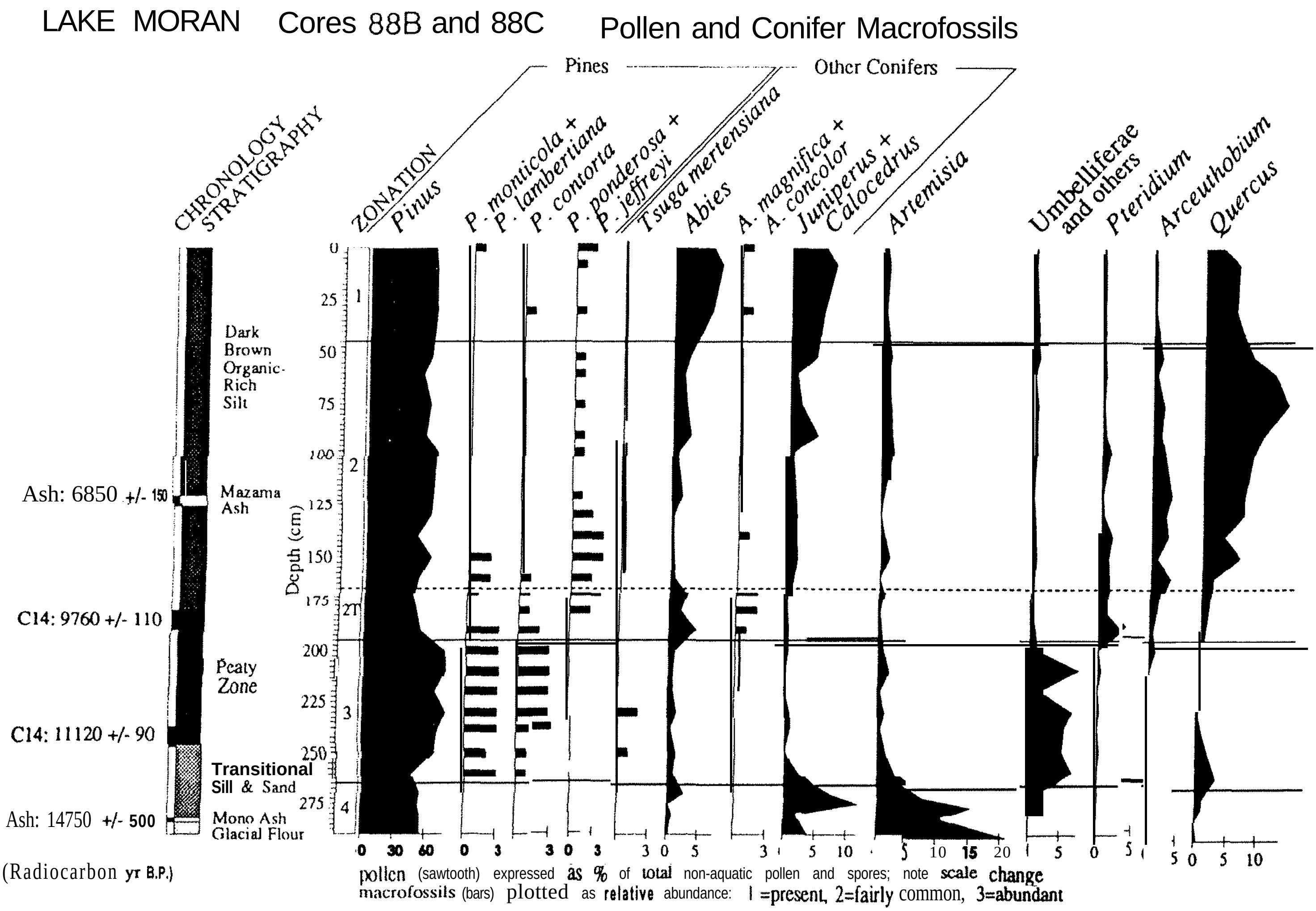

Figure 2. Selected pollen and macrofossils from Moran cores 88B and C. Sawtoothed pollen curves, labeled with genus or family name, indicate abundance as a percentage of total non-aquatic pollen grains and spores counted. Macrofossil bars, labeled by species, indicate relative abundance (see text). Zonation is by the authors. Radiocarbon dates were obtained from Beta Analytic, and volcanic ash layers were identified by Andrei Sarna-Wojcicki, U.S.G.S.

METHODS

The lake sediment samples analyzed for this project were taken in October, 1988, using a standard Livingstone piston corer with 2" diameter barrel. Two cores, 88B and C, were taken within 2 meters of one another, and correlated by depth and stratigraphy. Cores were transported intact to the U.C. Berkeley Pollen Lab. Core B was used for macrofossil analysis, while core C was subsampled at 10-20cm intervals for pollen and microscopic charcoal analysis. ^{14}C dates were obtained on two ten-centimeter segments of core 88C. Two volcanic ash layers present in the cores were identified by Andrei Sarna-Wojcicki at the United States Geological Survey in Menlo Park.

Extraction and preparation of pollen samples followed standard procedures as described by Faegri and Iversen (1975). Each pollen and charcoal sample underwent the same preparation, in order to eliminate differential effects of chemical treatments on the samples (Clark 1984). Pollen concentrations were calculated based on the ratios of *Lycopodium* control grains counted at each level. The curves of taxon abundance in Figure 2 are plotted as percentage of total non-aquatic pollen and spores counted; a total of at least 300 grains was identified at each level in the core. The diagrams were compiled using CALPALYN (Bauer and Orvis 1990).

Core 88B was sampled in measured segments of 5 or 10cm. Macrofossil sampling was based on standard procedures described by Birks (1980). Identification of pine needles was accomplished by comparing external morphology and thin sections with reference material and with Harlow's (1947) photographic key. For each sample, we calculated the total length of needle remains of each taxon. For Figure 2, length values were classified on a scale from 1, "present," with only one or two fragments per sample, to 3, "abundant," with total needle length exceeding 200mm per sample.

Microscopic charcoal was analyzed using 400x magnification and an ocular grid with squares 19.8 μm on a side. All charcoal fragments larger than one-half of a grid square were assigned to the appropriate size class, and the total area of charcoal was calculated. Calculated charcoal concentration

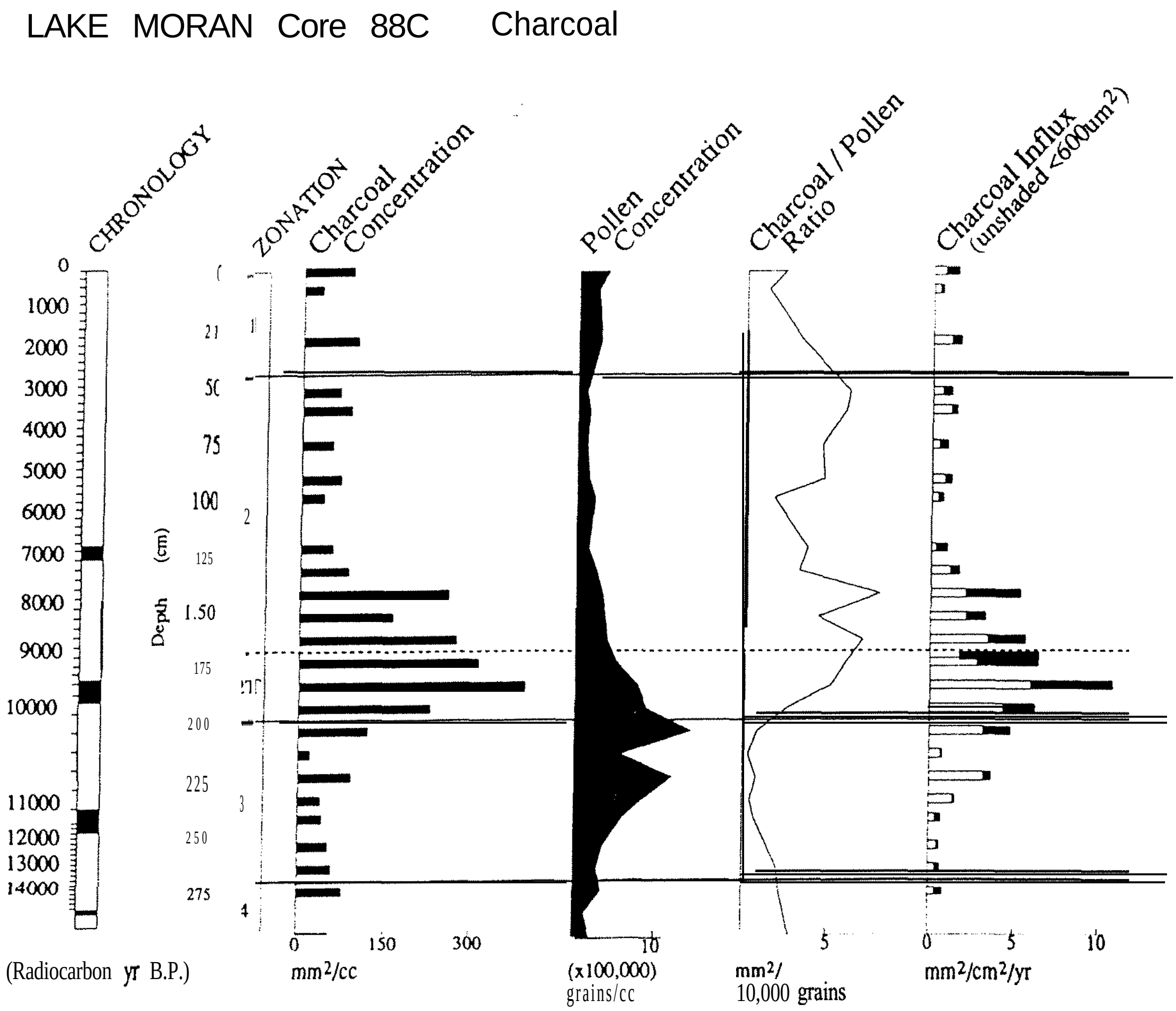

Figure 3. Charcoal and pollen indices for Moran core 88C. Sample depths and zonation are the same as in Figure 2 Calculated charcoal influx is divided into the share of fragments smaller (unshaded) and larger than $600\mu m^2$.

and influx to the lakebed are based on the ratio of counted charcoal to counted *Lycopodium* control spores (fig. 3). Sedimentation is estimated at a linear rate between radiocarbon and ash dates. Influx is not estimated for the glacial flour sample below the lowest tephra date. To control for variation in charcoal influx due to sedimentation processes, the ratio of charcoal to pollen was calculated for each sample (Cwynar 1978).

Charcoal Taphonomy

Questions of interpretation of sedimentary charcoal have been discussed in detail by Patterson and others (1987) and Clark (1988b). Charcoal in lake sediments ranges in size from fine dust, ≤ 2 micrometers in diameter, to macroscopic fragments centimeters in length. Like dust, small particles may travel long distances once entrained. Charcoal may reach high altitudes in the convective plume which rises from a fire. More intense tires produce higher plumes, resulting in longer-distance transport of all size classes of charcoal. The smallest sizes of charcoal may reflect a subcontinental source (Clark 1988b). As a result, even lakes in areas of 20th century fire suppression contain high levels of charcoal in recent sediments (e.g., Lake of the Clouds, MN, Swain 1973). Conversely, local tires, recorded as fire scars on trees, may go unrepresented in lake sediments if the plume convects most charcoal beyond the lake basin (Patterson and others 1987).

Lakes with small watersheds can accurately record local fires (Anderson and others 1986). Lake Moran is a small lake with no inlet stream, and a drainage basin of about 12 hectares. In this setting, it may be expected that larger microscopic charcoal fragments in the lake sediments originated from nearby fires, while the smallest fragments record events within a larger region. Figure 3 breaks microscopic charcoal influx into small fragments, $<600\mu m^2$ in area, and larger pieces, which ranged up to $>14,500\mu m^2$. We assume that the fires which produced the larger charcoal fragments probably occurred within 5-10 km of the lake (cf. Clark 1988b).

VEGETATION HISTORY AND THE RECORD OF FIRES AT LAKE MORAN

The Mono Craters and Mazama ash layers and radiocarbon dates provide a chronology for the Lake Moran sediments. The lake was exposed by ice retreat some 15,000 years ago This represents an early date for Tioga (late-Wisconsin) dcglaciation in the Sierra Nevada, confirming Batchelder's (1980) report from nearby Swamp Lake.

The earliest pollen assemblages (zone 4 on figure 2) reveal an open vegetation of sagebrush (*Artemisia*), juniper, and pines. This environment must have been effectively drier than the present study area, perhaps similar in appearance to higher subalpine environments today. No identifiable macrofossils are present in these sediments. Sedimentation rates were slow following the initial formation of the basin, and the calculated annual charcoal influxes arc among the lowest in the 'core. Some large charcoal fragments (> 2.500 μm^2 in area) are present, but it is uncertain whether these fragments blew into the lake from nearby fires, or were simply redeposited by the melting of the nearby glacier.

In late-Pleistocene zone 3, spanning ca. 12,500—10,000 yr. B.P., pine needles and high percentages of pine pollen indicate the establishment of a closed-canopy forest throughout much of the area (Figure 2). This forest signal is accompanied by increases in taxa normally associated with meadows, including members of the Umbelliferae, Liliaccac, Onagraccae, Malvaceae, and Ranunculaccac. (These taxa are grouped as "Umbellifcrae and others" in Figure 2). The presence of mountain hemlock (*Tsuga mertensiana*), white pines (*Pinus monticola* and *P. lambertiana*), and lodgepole pine (*P. contorta* ssp. murrayana) indicate a moister climate than that found in the Sierra Nevada today. The meadow taxa may have become established on sites too wet for tree growth. During this time, deep snowpacks may have persisted late into the summer, damping the effects of California's summer drought season. Charcoal concentration is generally lower in this interval than anywhere else in the core (Figure 3). The ratio of charcoal to pollen is consistently low, and larger charcoal fragments (> $600 \mu m^2$) arc virtually absent. The evidence suggests that fires rarely burned the dense forest which surrounded the lake.

The Pleistocene/Holocene transition (subzone 2T) is marked by rapid increases in all measures of charcoal abundance (Figure 3). Charcoal concentration and influx reach maximum values here, at levels 5-10 times greater than in modern or late-Pleistocene scdimcnts. Lodgepole and white pines wcrc beginning to be replaced by yellow pines (P. *ponderosa* and/or *P. jeffreyi*) (Figure 2). During this transitional period, persisting less than 1000 years, firs (both *Abies magnifica* and *A. concolor*) becamc important constituents of the Moran forest.

The pollen record for zone 2 (Figure 2) shows a small relative decrease in pines, with increases in oaks and bracken fern (*Pteridium*). The evidence reveals a more open forest, with warmer summers allowing an increase in the relative importance of oaks. Dwarf mistletoe (*Arceuthobium*) pollen increases in this interval, perhaps indicating that conifers were under increasing ecological stress. Charcoal influx remains high until ca. 7,500 yr. B.P., dropping off to near-modem levels just above the Mazama ash layer (Figure 3).

Interestingly, both the charcoal/pollen ratio curve and the oak percentage curve (fig. 2) show continued high values through the middle Holocene (7,000—3,000 yr. B.P.). Since there is no evidence for changes in the lake's sedimentation regime, wc rely on the consistently low charcoal influx values to infer a decrease in the intensity of fires during this interval, compared to the early Holocene; however, the oak, bracken and sagebrush suggest that the forest remained drier and more open than it is today. By 3,000 yr. B.P., Neoglacial cooling and/or increasing moisture allowed fir, lodgepole, and sugar pine to reoccupy the lake margin. Fire has remained less important than it was in the early Holocene, although modem charcoal influx exceeds late-Pleistocene minimum values.

The important implication of the high charcoal values is that the early Holocene was a period of more extensive and more intense fires than either the late Pleistocene or the late Holocene. Indeed, it seems likely that an increase in the importance of fire was the mechanism by which the changing postglacial climate produced dramatic shifts in vegetation. The source of the early Holocene charcoal may well have been the dense late-Pleistocene forest, which began to burn under a more xcric climatic regime.

Temporal changes in several pollen and macrofossil types show a strong correlation with the charcoal signal. Bracken is highly correlated with total charcoal influx, as is fir to a somewhat lesser extent. The latter relationship is puzzling but important; fir is not normally considered a fire-adapted species, particularly compared to its associates in the Sierran montane forest. Red fir (*Abies magnifica*), the first species to appear in the macrofossil record, may have been able to effectively colonize fire-cleared patches, or it may have become established on soil fertilized by increased nutrient cycling under more frequent fires. In zone 2, increases in pondcrosa pine, oak and dwarf mistletoe lag behind charcoal influx, but generally the curves for these taxa parallel the changes in the charcoal/pollen ratio. Umbellifcrae and Cupressaceae pollen arc negatively correlated with charcoal, as are lodgepole (*Pinus contorta*) and white pines (P. *lambertiana* and *P. monticola*).

CONCLUSIONS

Our results suggest that Sicrran fire regimes have changed as a function of climate. In the Sierra Nevada, fire frequency and intensity are controlled by California's strongly seasonal precipitation regime. Today, summer drought makes fires increasingly likely in September and October, before the first winter rains. The Lake Moran record shows that from 12,000 to 10,000 years ago, summer drought was less pronounced than today, probably as a result of late-spring snowstorms and/or snowpack persisting into the summer. At that time, warm summers coupled with more abundant moisture led to the development of a dense mixed conifer forest, comprising several specks which no longer grow together in the Sierra Nevada. Fire was less important as an ecological factor in this late-Pleistocene forest than in the Holocene.

At 10,000 yr. B.P., in association with a rapid increase in fossil charcoal influx, the local vcgctation changed abruptly. Red fir and pondcrosa pine first appeared at this time. Conversely, western white pine disappeared from the site, and lodgepole and sugar pine began a more gradual decline. Bracken fern became much more important about 10,000 years ago, while oak and dwarf mistletoe pollen increased more gradually, reaching maximum pollen percentages between 9,000—3,000 yr. B.P. We infer rapid environmental changes beginning at the end of the Pleistocene. The Lake Moran record demonstrates the importance of fire as a determinant of vegetation during this climatically significant period.

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FIRE-HERBICIDE SYSTEMS FOR MANIPULATING JUNIPER

D.M. Engle and J.F. Stritzke[1]

Abstract-Fire exclusion results in extensive encroachment of fire-intolerant junipcrs, specifically eastern redcedar (Juniperus virginiana) and ashe juniper (J. ashei) into tallgrass prairies and other grasslands and hardwood forests of the central US. Control of both juniper species is possible with fire because they do not sprout from roots and so they are killed by intense tires that scorch the crown. However, low-intensity fires on sites with dense stands of junipers do not scorch crowns of larger juniper trees. One objective of our studies was to determine the effect of various paraquat treatments on juniper foliage water content, a primary factor affecting flammability of juniper crowns. A second objective was to determine if paraqoat pretreatment would increase crown scorch from broadcast tires in tallgrass prairie. We evaluated leaf water content of eastern redcedar treated individually with two rates (0.3 or 1.1 kg/ha) of paraquat, in two carriers (water, oil-in-water emulsion), and at two volumes (47 or 188 l/ha) of carrier. The oil-in-water emulsion carrier reduced leaf water content more consistently than the other carriers, so we used the oil-in-water emulsion carrier in a study of paraquat applied aerially in early August. Rate ranged from 0.3 to 3.4 kg/ha and included two volumes (47 or 94 l/ha). All aerial applications of paraquat reduced juniper leaf water content to 50 percent or less three weeks after treatment compared to 100 percent water in untreated junipers. Leaf water content in the late summer dry season will normally decline to about 80 percent, a level too moist for ignition of juniper foliage. Combining paraquat with burning almost doubled the crown scorch of large trees over either treatment alone and increased kill of large trees to more than SO percent compared to no trees killed with the burning-only or paraquat-only treatments.

INTRODUCTION

Tallgrass prairie and other grasslands of North American arc regarded as fire-tolerant systems which evolved with fire as a part of the natural disturbance *regime* (Anderson 1982). Protection from fire *results* in extensive encroachment of fire-intolerant woody species, including eastern redcedar and ashe juniper into tallgrass prairies as well as into other grasslands and hardwood forests of the central U.S. (Arend 19.50; Bragg and Hulbert 1976, Wright 1978). Juniper encroachment into these ecosystems has increased exponentially in recent years, modifying the Physiognomy of these ecosystems and reducing their value as rangelands (Wright and Bailey 1980; Snook 1985).

Tallgrass Prairies that become dominated by juniper are similar to other ecosystems that were previously grasslands or savannahs but now have successional processes driven by woody vcgctation. Upon reaching a transitional threshold Promoted by reduced fire frequency and intensity, new successional processes prevent reversion to grassland from overstory dominance by woody species, and fire is no longer an effective agent in reversing succession to grassland (Archer 1989; Bryant and others 1983; Walker and others 1981). Drastic anthropogenic modification (i.e., herbicides or mechanical manipulation) of the woody vegetation is necessary to convert the plant community to dominance by herbaccous Plants (Archer 1989; Engle 1987).

Fire kills both species of juniper if fine fuel loading is sufficient to produce an intense fire that completely scorches the crown because neither species sprouts *from roots or stems* after topkill (Owensby and others 1973; Wink and Wright 1973). However, tree mortality decreases as tree size increases so fire intensity must increase to scorch the crown of taller trees (Bryant and others 1983; Dalrymple 1969; Engle and others 1988). Fire intensity and tree mortality are reduced further in dense stands of large trees because junipers reduce the production of fine fuel so that fires in these stands are of tow intensity or perhaps fires fail to carry at all (Bryant and others 1983; Engle and others 1987).

Junipers arc often controlled mechanically or by herbicides, but mechanical and herbicide methods of juniper control are generally either too expensive or are ineffective on large trees (Scifres 1980; Stritzke 198.5). Small trees can be controlled individually with some soil-applied herbicides and paraquat applied in hot weather can result in considcrabtc damage to trees (Engle and others 1988). Integration of several brush control treatments into a single set of treatments, i.e., integrated brush management, is one way to deal effectively with brush (Scifrcs 1980). Paraquat applied to individual trees in the summer has increased juniper crown damage from broadcast bums the following spring with light line fuel loading (Engle and others 1988). A combination of broadcast application of paraquat followed by a prescribed bum has bccn suggested as an integrated method to control severe infestations of juniper (Engle and others 1988). We

[1]Professors of Range Science and Weed Science, respectively, Oklahoma State University, Stillwater, OK.

conducted two studies, each with a separate objective: 1) to determine the effect of various paraquat treatments on juniper foliage water content, a primary factor affecting flammability of juniper crowns (Bunting and others 1983), and 2) to determine if aerial application of paraquat will reduce foliage water content and increase crown scorch from broadcast fires in tallgrass prairie.

METHODS

Study 1 was conducted on two sites approximately 15 km southwest of Stillwater, OK on the Oklahoma Agricultural Experiment Station's Agronomy Research Range. Shallow prairie was the primary range site of one location and red clay prairie was the primary range site of the other location. About 2800 kg/ha of fine fuel arc produced on both sites in a normal year. Herbaceous understory was dominated by tallgrasses and eastern redcedar canopy cover was less than 5 percent.

Paraquat was foliar applied to individual eastern redcedar trees on August 17-18, 1988 with a compressed-air hand sprayer using a T-3 conejet nozzle to simulate aerial application. Treatments were in a factorial arrangement of paraquat (0.3 or 1 .1 kg/ha), carrier (water or oil-in-water emulsion), and volume of carrier (47 or 188 l/ha). The design was completely randomized with ten replications on each of two sites located approximately 5 km apart. Eastcm redcedar foliage was sampled at weekly intervals (August 24, September 1, and September 8) following treatment, weighed in the field, and dried in a forced-air oven to determine foliage water content, which is expressed on the basis of dry weight.

Study 2 was conducted in Johnston County, OK, approximately 30 km northeast of Ardmorc, OK. The study area is located on a loamy prairie range site normally producing about 3900 kg/ha of forage in the absence of juniper interference. Ashe juniper, with canopy cover of approximately 25 percent, was the overstory woody dominant The under-story was a mixture of tallgrasses and midgrasses. Paraquat was applied aerially in the oil-in-water emulsion carrier to ashe juniper on August 9, 1989. Herbicide treatments included no herbicide treatment and paraquat applied at rates ranging from 0.3 to 3.4 kg/ha. Paraquat rate treatments were nested within two volumes (47 or 94 l/ha) of the carrier. Plots were 0.1 ha (30 X 30 m). The design was a randomized complete block with four blocks. Foliage was sampled three weeks after paraquat treatment, weighed in the field, and dried in a forced-air oven to determine foliage water content, which is expressed on the basis of dry weight.

Two blocks were burned with a headfire on September 1, 1989. At the time of the bum, air temperature was 38°C, relative humidity was 40%, average wind velocity was 8 km/h, and fine fuel loading within the juniper stand was visually estimated at 1500 kg/ha. Crown damage to trees and tree kill were determined in all treatment plots two months after the bum. Visual estimates of crown damage and tree kill were conducted on three size classes based on tree height: small (0.8 to 1.5 m), medium (1.5 to 2.5 m), and large (2.5 to 5.0 m).

We subjected the data from both studies to analysis of variance. Leaf water data from study 1 and study 2 were analyzed as repeated measures in time (Winer 1971). Means were separated by LSD subject to a protected F-test at the 95% probability level as suggested by Carmer and others (1989).

RESULTS

Study 1

Study site interacted ($P < 0.0001$) with treatment and sampling date so data from each study site were analyzed separately. No treatment effects were significant one week after paraquat application, but by two weeks after treatment, paraquat rate interacted with both carrier and volume of carrier ($P < 0.0224$ and $P < 0.0182$, respectively) at Site 2 (fig. 1). Water content of foliage with all treatments increased the second week after treatment, which we attributed to a change in available soil water in response to 20 millimeters of precipitation on August 28 between the first and second week after treatment. By the third week after treatment, leaf water had dropped drastically in trees in all trcatmcnts, with some below 50 percent leaf water. Paraquat treatment rate, volume, and carrier interacted at study Site 1 and 2 on the third week after treatment ($P < 0.0163$ and $P < 0.0002$, respectively). Foliage water content was lower in trees treated with the 1.1 kg/ha rate of paraquat and results were more consistent with the oil-in-water carrier (fig. 1).

Study 2

Leaf water content did not differ ($P > 0.1288$) between the two volumes of carrier on either sampling date so we averaged the rate data over the two volumes. Leaf water content was less in foliage of treated trees than in untreated trees two weeks after paraquat treatment and declined to 50 percent or less by three weeks after treatment with all rates of paraquat ($P < 0.0001$) (fig. 2). Although increasing rate of paraquat was not additive, all rates of paraquat desiccated ashe juniper foliage to the extent necessary to increase flammability by three weeks after treatment (Bunting and others 1983). Although juniper leaf water was higher in 1989 than in normal years (Engle and others 1988), leaf water content in the late summer dry season will normally decline only to about 80 percent, a level too moist for ignition of juniper foliage.

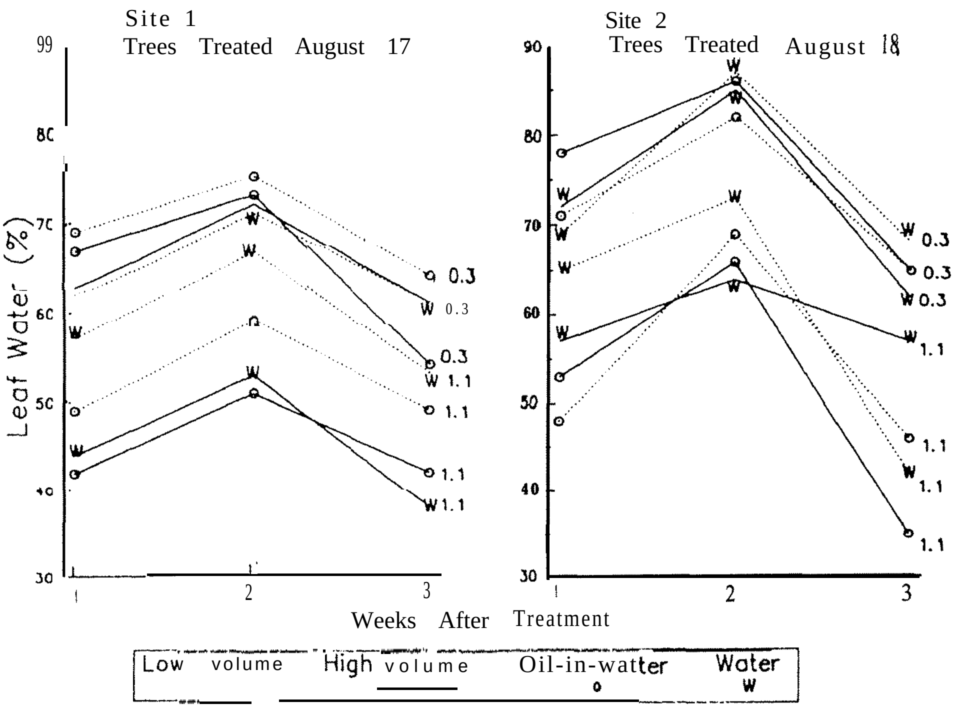

Figure 1.- Leaf water (%) after paraquat application at Site 1 and Site 2. Paraquat rate (0.3 or 1.1) is in kg/ha. Low volume of carrier is 47 l/ha and high volume is 188 l/ha. Values arc means of 10 trees. LSD,,,= 13 at Site 1 and LSD,,,=23 at Site 2 on week 3. Foliage of untreated trees was 80% water at both study sites on September 8.

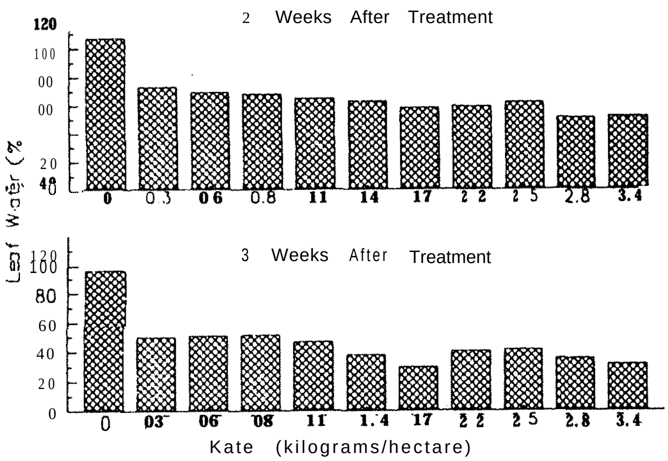

Figure 2.- Leaf water (%) two weeks and three weeks after paraquat was aerially applied on August 9, 1989. Valued art: means of 8 trees, averaged over volume of carrier ($LSD_{0.05}$ = 10 on week 2 and $LSD_{0.05}$ = 11 on week 3).

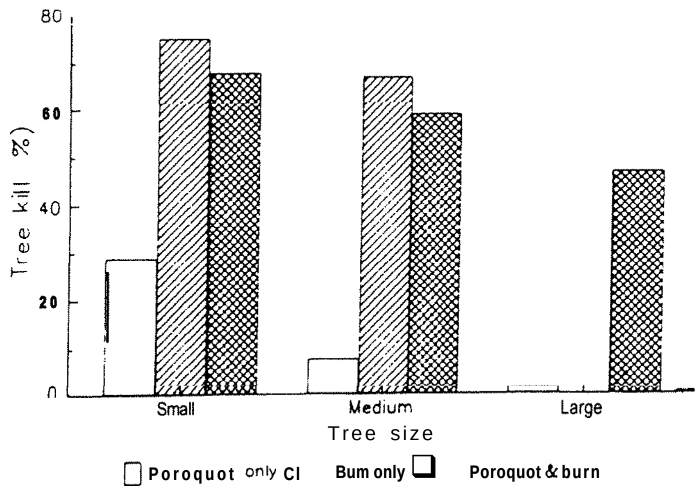

Figure 3.- Crown damage (%) two months after burning. Values for paraquat only treatments are averaged over rate Treatments were not different (P > 0.0604) for small and medium trees, but treatments were different (P < 0.03 19) for large trees (LSD,,,, =27).

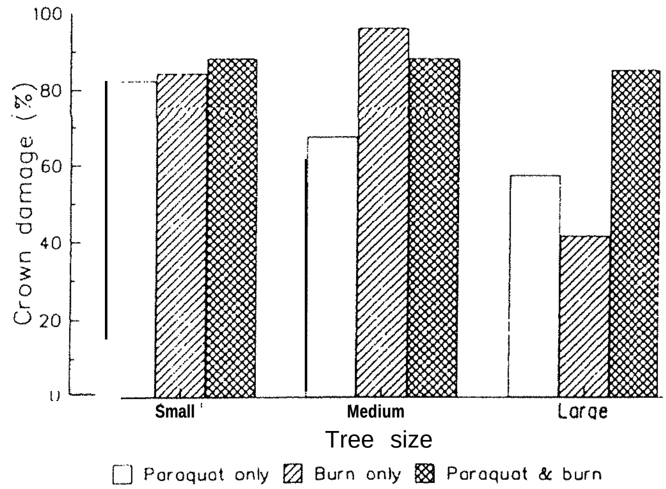

Figure 4.- Tree kill (%) two months after burning. Values for paraquat only treatments are averaged over rate. Treatments were not different (P > 0.303 1) for small trees, but treatments were different (P<0.0392) for medium and large trees (LSD $_{0.05}$ =48 and 3 1, respectively).

The amount of crown damage to trees was not affected by either carrier volume or paraquat rate within the paraquat plus bum treatment for any size of tree (P>0. 1247). Howcvcr, crown damage and tree kill of medium and large trees differed (P < 0.0604) among the three treatments (paraquat only, bum only, or paraquat plus bum) (fig. 3 and 4). Crown damage to trees from fire alone and paraquat alone was similar to the results of previous studies (Engle and others 1987). The effects of paraquat and fire on large trees were approximately additive in respect to crown damage which exceeded 80 percent in the paraquat plus bum treatment plots (fig. 3). Paraquat and burning appear to have a synergistic effect in killing large trees in that almost no trees were killed by the single treatment of either paraquat or burning but half of large trees were killed by combining the two treatments (fig. 4).

DISCUSSION

Paraquat applied in hot weather by hand to individual trees (study 1) or applied aerially in a broadcast spray (study 2) was effective in reducing juniper foliage water content to below the critical point of 60 percent water (Bryant and others 1983; Bunting and others 1983; H.A. Wright, pers. comm.). Desiccation of juniper foliage by paraquat applied aerially almost doubled the crown scorch and increased the kill of large trees from 0 to 50 percent. The results of this study arc in agreement with previous work in which desiccation of juniper foliage by treating individual trees with paraquat compensated partially for light fine fuel loading in cool-season fires the spring after summer paraquat application (Engle and others 1988).

We believe it is possible to use paraquat as a desiccant to promote crown fires in closed-canopied stands of juniper. Previous attempts to ignite crown fires have been unsuccessful in dense stands of ashe juniper in Texas (Bryant and others 1983) and in pinyon (Pinus cdulis) and juniper woodlands in Nevada (Bruner and Klebenow 1979) possibly because of high foliage water content, gaps in the tree canopy, and cool fire-weather conditions. Bryant and others (1983) evaluated igniting windrows of recently dozed ashe juniper to produce an intense fire with flames in contact with standing trees to produce a crown fire in dense stands of ashe juniper, but no sustained crown fire resulted. However, six standing trees were killed for every dozed tree by the windrow fire thereby reducing the overall cost of mechanical treatment of the juniper stand. Bruner and Klebenow (1979) were unable to obtain crown tires in closed stands (i.e., no understory) of pinyon-juniper and concluded that crown fires are possible only when burned under hazardous conditions.

Our research indicates an integrated approach using paraquat and tire can be used to reduce overstories of large junipers for restoring tallgrass prairie dominated by junipers. Further research is needed to determine if crown fires can be ignited from paraquat-desiccated strips in dense stands of junipers using aerial ignition with a helitorch.

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ELASTICITIES ASSIST TARGETING OF ARSON PREVENTION PROGRAMS

R.A. Kluender arnd L.C. Thompson'

Abstract-Elasticities (percentage change in one factor divided by percentage change in another factor) were calculated to demonstrate the effect that reducing the number of arson fires in Arkansas counties had on area burned. Elasticities are employed by economists and managers to determine which factors yield the greatest returns per unit of effort expended. Hypothetical reductions in area burned and average wildfire size were determined by randomly decreasing arson wildfires. Results showed that as arson rates increased above SO percent, disproportionately greater reductions in area burned accrued from reducing arson. Accordingly, counties with high elasticities for area burned should he the first targets for arson reduction campaigns. Elasticities for average fire size showed weak responsiveness to arson reductions. When the primary objective of a prevention program is reducing area burned, elasticities for area burned can provide another tool for wildfire prevention specialists to use in appraising where scarce resources can be best utilized.

INTRODUCTION

Achieving effective wildfire prevention and suppression programs requires proper analysis of available data and correct interpretation of results, which supports the generation and implementation of effective policy. Because of the tremendous task of acquiring, entering and extracting meaning from wildfire data, detailed analysis is commonly not performed. Instead, management targets (typically calculated statistics) or goals are used to gauge the yearly progression of control programs. Generally, these management targets are presented in a standardized form (as an example, on a "per thousand protected hectares" basis) because they provide a quick gauge across county and regional boundaries and can be used across state boundaries to weigh the success of innovative programs.

In Arkansas, state lands protected from wildfire by the Arkansas Forestry Commission (AFC) include all privately owned forest and pasture lands but not areas within incorporated town and city borders, row-crop lands, federal ownerships (such as national forest lands) and other public ownerships. The Associate State Forester for Protection in Arkansas has set four wildfire management targets for county and state level programs. They are: 1) less than 1.5 hectares per thousand protected hectares (TPH) burned per year; 2) not more than 0.37 fires per TPH per year; 3) an average fire size less than 4 hectares and; 4) less than 40 percent arson fires. The most important of these goals is the first, to keep burned area as low as possible. Counties below any particular target are considered within compliance relative to their wildfire prevention or suppression goals.

Factors such as weather, attitudes and prevention and suppression efforts all play a part in determining the final yearly toll to wildfires. However, increasing rates of arson (Arkansas Forestry Commission 1984-1989) have aroused concern. These trends were first reported by Kluender et al. (1988, 1989). Perhaps the most important findings of these studies were that local residents caused 70 percent of the arson tires and that arson fires had an average size twice that of other causes (8.4 vs. 4.2 hectares). Additionally, these studies indicated that while general state-wide trends were important, they did not provide the detailed information required to formulate county-level fire prevention and suppression plans. Preferably, prevention and suppression programs should be designed for local conditions to better target problems and reduce wildfire losses. Kluender et al. (1990) subsequently looked at county-level wildfire patterns and found considerable variability among Arkansas' 75 counties for arson rates and area burned. The data showed that of the 35 counties that exceeded the AFC target of 40 percent arson rate, 27 counties also exceeded the target for area burned; and, of the 39 counties that exceeded the target for area burned, 28 counties also exceeded the target for arson rate. Of the 48 counties that exceeded either target, 28 counties simultaneously exceeded both targets. So, the link between higher arson rates and higher area burned is well established among counties.

Wise management dictates that limited budget dollars be disbursed in the most effective way. Frequently, in wildfire prevention campaigns, managers may wonder whether money is being spent in the right place or on the right program. Numerous appraisal methods have been used by various agencies from time to time. Benefit-cost ratios express some measured benefit against the cost of obtaining it. Measures of cost to protect a known "value at risk" adopt an actuarial approach to the same problem. These measures, however, are static, cross-sectional statements of expected benefit for given expenditure. A more sophisticated concept is the use of elasticities to identify the percentage change of a dependent variable (like hectares burned) for a percentage change in an

'Associate Professor Forest Economics and Associate Professor Forest Protection, Department of Forest Resources, Arkansas Agricultural Experiment Station, Monticello, AR 71655.

independent variable (like arson rate); thus, elasticities measure responsiveness to change. Elasticities are used by economists and policy makers to show how much change in a given factor to expect for a given change in a driving or causal variable (Pindyck and Rubinfeld 1981). Generally, those independent variables that produce the greatest changes in the dependent variable (highest elasticities) are the best choices for policy manipulation.

Two factors point to the need to reduce the total number of arson tires in the South. First, arson is, in most southern states, the greatest single cause of wildfires (USDA Forest Service 1984). Second, arson tires tend to be larger than those from other causes. This paper demonstrates the use of elasticities as a measure of responsiveness to arson prevention based on hypothetical reductions in total area burned and average fire size. Our objective was to describe a tool that wildfire managers might use to help them select targets for arson prevention programs.

METHODS

We acquired the records of all reported wildfires on lands protected by the Arkansas Forestry Commission (AFC) for the period January 1983 through December 1988 (Arkansas Forestry Commission unpublished data). These data included records developed from Individual Fire Reports (AFC Form 24 10. 1) tilled out by suppression personnel immediately after a fire was investigated. Variables chosen for inclusion in this study were year, county, cause (for example, arson or debris burning) and hectares burned per fire. The data set included reports of 16,047 tires. A second data set was obtained from the AFC that contained total hectares and protected area per county. The data sets were sorted by county and merged. The number of fires per TPH, area burned per year per TPH, average fire size, and percentage arson tires for each county were calculated.

Because we (and the AFC) were interested in evaluating the effects of reducing arson fires in counties with high arson rates (by AFC definition, high includes those that exceeded the AFC management target of 40 percent arson rate), counties with an arson rate greater than 40 percent were retained in the analysis. Thirty-five of Arkansas' 75 counties (47 percent) remained in the active data set.

To simulate an effective prevention program that reduced arson rate to the AFC target, individual arson fires were randomly eliminated from each county data set until arson fires comprised 40 percent or less of the total fires. After randomly reducing arson fires to 40 percent, average tire size, area burned per TPH and number of fires per TPH were recalculated for each county. Elasticities for area burned per TPH (E_{AREA}), and average tire size (E_{AVSIZE}) were calculated for each county. For example, elasticity of area burned was calculated by:

$$E_{AREA} = \frac{(\Delta AREA\ /\ AREA)}{(\Delta ARSON\ /\ ARSON)}$$

Where:

$\Delta AREA$ = Change in area burned after reducing arson rate
AREA = Area burned before reducing arson rate
$\Delta ARSON$ = Change in percentage arson tires
ARSON = Percentage arson fires before reducing arson rate.

Elasticity of average fire size was calculated in a similar manner.

Three replicates of the random reductions in arson tires for each county were created and the calculations for E_{AREA} and E_{AVSIZE} performed for each county in each replicate. An ANOVA was performed on the E_{AREA} and E_{AVSIZE} data sets to determine if differences existed between replicates. To establish relationships, E_{AREA} and E_{AVSIZE} were regressed against the percentage of arson tires in each county before the reduction to 40 percent. Regression analysis was also used to ascertain what contribution the pre-reduction arson rate and average fire size of each county made to E,,.

A standard statistical package, SPSS (Norusis, 1988), was used to perform the initial data analysis and data sorting. The Quattro Pro spreadsheet (Borland International 1989) was used to calculate the elasticities, and SYSTAT (Wilkinson 1988) was used in the final comparison of pre- and post-reduction conditions and in the regression analysis. Statistical significance was accepted at the α = 0.05 level.

RESULTS AND DISCUSSION

The ANOVA showed no differences among the replicates for either E_{AREA} ($F_{2,102}$ = 0.085, p = 0.919) or E_{AVSIZE} ($F_{2,102}$ = 0.050, p = 0.951). Therefore, we used the mean value for each county's elasticities in all further analyses.

Elasticities for area burned per TPH (E_{AREA}) with respect to arson rate were greater than 1 .O (unity elasticity) for 23 of 35 counties; these counties were considered responsive to reductions in arson fires (Figure 1). When this elasticity was regressed against arson rate the linear function was:

$$E_{ARM} = 0.388 + 0.013 \times \text{ARSON RATE}$$

Both the constant and the slope were different from zero. While considerable variation was present in the data, general trends were obvious. The slope shows that the higher the initial level of arson tires, the greater will be the response of area burned to reductions in arson levels. Additionally, the best-tit line (R^2 = 0.435) rose above unitary elasticity at an arson rate of 49 percent. Accordingly, we reason that area burned per TPH would typically be responsive to changes when the arson rate in a county exceeds 49 percent, or 50 percent in round numbers.

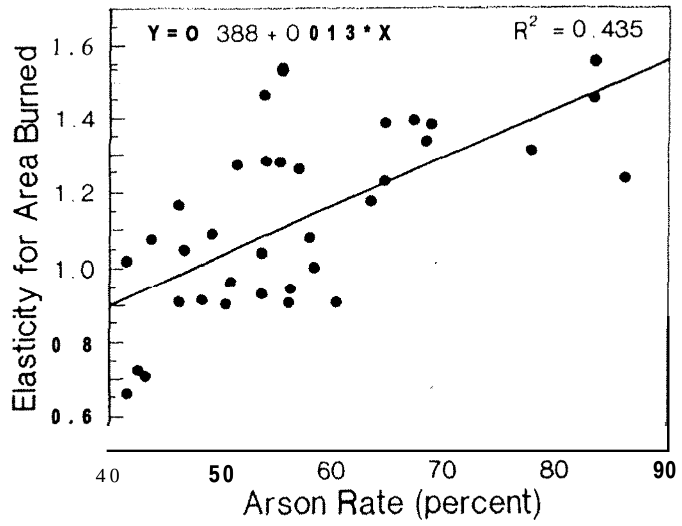

Figure 1. Elasticity for wildfire area burned compared with arson rate for 36 of 75 counties in Arkansas that exceeded the wildfire management target of 40 percent arson.

Elasticities for average fire size (E_{AVSIZE}) with respect to arson rate were ail below unity and, hence, considered unresponsive. Although average fire size decreased when arson fires were eliminated, the reduction was relatively small when expressed as a percentage. Hence, E_{AVSIZE} was typically low. When this elasticity was regressed against arson rate neither the constant nor the slope were different from zero.

Finally, we regressed the elasticities of area burned as a dependent variable against arson rate and average fire size The response surface was a quadratic function:

E_{AREA} = 0.187 + 0.014 x ARSON RATE
+ 0.019 x AVERAGE FIRE SIZE +
0.001 x (ARSON RATE)(AVERAGE SIZE).

However, only arson rate was different from zero; this surface had an R^2 of 0.549. Therefore, we conclude that arson rate alone, which had an R^2 of 0.435, is the best predictor for estimating E_{AREA}.

This analysis establishes that when the primary objective of a prevention program is reducing area burned, a good tool for choosing targets for the prevention program is the elasticity for area burned. For best results, ordinal ranking of counties should logically proceed from those with the highest to lowest elasticities. The best choice among counties with equal elasticities should be made by selecting the county with the largest average fire size.

We have shown that for Arkansas counties with high arson rates, disproportionately greater reductions in area burned can be expected when the number of arson fires is decreased. This is important because keeping burned area as low as possible is the most important goal of the AFC. Calculating and using elasticities for area burned will aid the efficient targeting of monies and other efforts for arson prevention programs. In areas where arson is not the primary cause of wildfires, perhaps other causes could be investigated in a similar manner.

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LONG-TERM IMPACTS OF FIRE ON COASTAL PLAIN PINE SOILS

William H. McKee, Jr.'

Abstract-Repeated burning of pine forests over long periods may have pronounced effects on the maintenance of soil fertility and soil development. Analyses of soils from four long-term prescribed burning studies in the Atlantic and Gulf Coastal Plain indicate that burning has had no effect on the total carbon and nitrogen level in the surface mineral soil. Winter burning increased the retention of nitrogen in the mineral soil over time. Changes in the carbon/nitrogen ratio in the forest floor with burning suggest that at least part of the increase in nitrogen in the mineral soil was due to pyrolysis of the litter. Available phosphorus was consistently increased in the surface 5 cm of soil by prescribed burning; however, the effect is less apparent on total phosphorus reflecting the low mobility of the nutrient. Concentrations of exchangeable bases in the surface soil increased with the frequency of burning. It is postulated that without burning, immobilization of calcium in the forest floor can lead in time to a magnesium:calcium imbalance and alteration of the soil formation processes.

INTRODUCTION

A concern about repeated burning is that it may reduce the "tilth" and productivity of soils in the long-term. Studying long-term effects of tire in the South is difficult, however, because burning has been part of the ecology of most fire sites there. Fire affects soil properties but measuring the cumulative effects on soil development takes many years and many fires. Data from some long-term burning studies in the Southeastern Coastal Plain offer clues about how fire influences soil forming processes.

Soil properties have been monitored in a number of Coastal Plain prescribed burning studies (McKee 1982, Ralston and others 1982, and McKee and Lewis 1983). In this paper I have combined the findings and updated the measurements for four major studies to develop indications of how burning may alter soil chemical properties and influence soil development.

MATERIALS AND METHODS

Study Areas

The four prescribed burning studies represent a wide range of soil textures, drainage classes, topographic positions, and understory vegetation. Brief descriptions of the four areas arc as follows:

Alabama. This study is near Brewton, Alabama, on the upper Coastal Plain. Soils are classed as coarse loamy siliceous thcrmic (Typic Paleudults), complexed with fine loamy siliceous thermic (Typic Palcudults), loamy siliceous thermic (Grossarenic Palcudults) and loamy skeletal siliceous thermic (Typic Hapludults). Overstory vegetation consists of 60- to 70-year-old longleaf pine (Pinus palustris Mill.). e index (age 50) ranges from 19 to 24 m, and understory vegetation consists of grasses, forbs, and small woody sprouts.

'Soil Scientist, USDA Forest Service, Southeastern Forest Experiment Station, Charleston, SC.

Treatments are replicated eight times on 0.16-ha plots. Treatments examined here are an un-bum control and biennial winter burning. The study was initiated in [illegible] and plots had been burned five *times* when data reported here were gathered. The last bum was applied about four months before sampling.

Florida. This study is on the Coastal Plain flatwoods in north central Florida. Soil on the study area is classed as sandy siliceous thermic (Aeric Haplaquods) with an organic pan between 46 and 61 cm deep. The overstory vegetation contains mixed, naturally seeded longleaf and slash (P. elliottii Engelm. var. elliottii) pines 60 to 70 years old. index (age 50) for the study area is 20 m, and average basal area is approximately 15.3 m^2 ha.

Treatments are replicated six times in a randomized block design on 0.81-ha plots. Treatments consist of an un-bum control, winter bum every four years, and annual winter burning. The annual winter bum was not imposed until six years after initiation of the study; at the time of sampling there had been 14 annual burns.

Georgia. The study is on a nearly level Coastal Plain site in south central Georgia. The site is poorly to somewhat poorly drained. Soils are loamy siliceous thermic (Arenic Paleaquults) covering about 2/3 of the site, loamy siliceous thermic (Arenic Plinthoquic Paleudults), fine loamy siliceous thermic (Plenthic Fraquidults), and loamy siliceous thermic (Arenic Paleaquults). Overstory trees are longleaf and slash pines from 25 to 30 years old.

Plots consist of pastures of about 19.7 ha on which grazing is also observed. Treatments consist of no burning, triennial winter burning, biennial winter burning, and annual winter burning. Treatments have been in force for 40 years except for a IO-year period 25 years previously when the stand was regenerated.

South Carolina. This study is in eastern South Carolina on a Pleistocene terrace of the lower Coastal Plain. The terrain is nearly level and is poorly to somewhat poorly drained. Soils are clayey mixed thermic (Umbric Paleaquults), clayey mixed thermic (Typic Albaquults), clayey kaolinitic thermic (Typic Paleaquults), clayey kaolinitic thermic (Aeric Paleaquult), fine loamy siliceous thermic (Aquic Paleudults), tine loamy siliceous thermic (Aeric Paleaquults). The overstory is 70-year-old loblolly pine (P. tacda L.) and the site index (age 50) is 27 to 30 m. Burning treatments were begun 30 years prior to the current sampling.

Plots are 0.10 ha in area. Treatments consist of an un-bum control, periodic winter burning, periodic summer burning, annual winter burning, and annual summer burning. Periodic burning was done every seven years, or when hardwood stems were approximately 2.5 cm d.b.h.

Sampling Methods

On each plot in the four studies, the forest floor and mineral soil were sampled at 40 points. Samples collected at 10 points were combined to make four composite samples per plot each for the forest floor layer and the mineral soil. Forest floor samples consisted of all material, including 01, 02, and 03 (L, F, and H layers), collected from within a 15-cm square frame. The forest floor was mor humus with little mineral soil mixed in it. No attempt was made to separate the forest floor by layers. Two 2.5-cm soil cores were collected from within the square of each sample point. Depth of the cores was 0 to 5 cm and 5 to 10 cm on the South Carolina site and 0 to 8 cm and 8 to 16 cm on the other sites. Only the surface samples were used for soil reaction properties. Analysis of both depths were used in computing total nutrients and organic matter levels. The South Carolina and Georgia sites were sampled in mid winter while the Florida and Alabama sites were sampled in early summer.

Laboratory Methods

Forest floor samples were dried at 70” C for 24 h, weighed, and ground to pass a 40-mesh screen. Nitrogen content was determined by a modified micro-Kjeldahl procedure, and ammonia was determined by the salicylate-cyanurate procedure (Nelson and Sommcrs 1973). Other analyses were made on material dry ashed for 2 h at 450° C and taken up in 0.03 M HNO,. Phosphorus was determined by the molybdovanadate procedure (Jackson 1958); calcium and magnesium were determined by atomic absorption. A separate sample was dry ashed at 500° C for 2 h to determine mineral content, which was subtracted from the dry weight. Thus, weights of forest floor material represent only the component lost on ignition.

Soil samples were air dried and crushed to pass a 2-mm sieve. Organic matter was assayed by wet oxidation (Jackson 1958). Exchangeable bases were determined by atomic absorption on extracts made with 1M NH, OAC (Jackson 1958). Available phosphorus was determined by extracting 2.5 g of soil with 20 ml of Bray P2 solution (Bray and Kurtz 1945). Inorganic phosphorus was fractionated by the method of Chang and Jackson (1957), and organic phosphorus was determined by the procedure outlined by Olsen and Dean (1965). Total soil nitrogen was extracted by micro-Kjeldahl digestion, and ammonia was determined by the salicylate-cyanurate method (Nelson and Sommcrs 1973). Soil pH was measured with a glass electrode on a 1:2 soil:water mixture.

Total levels of nutrients were computed using the concentrations observed in laboratory analysis, the volume of soil obseved, and bulk densities considered typical for the series in the case of the South Carolina site measurements were made of individual plots.

RESULTS AND DISCUSSION

Mineral Soil Properties

Burning effects tended to be consistent over the range of Coastal Plain soils examined, with the degree of effect reflecting soil properties of specific sites (Table 1).

pH. Soil pH increased slightly but significantly with intensity of burning on the Florida and South Carolina sites. In the South Carolina on the plots burned annually in summer soil pH was significantly higher than on control plots on periodically burned winter plots. The difference was about 0.4 pH unit. Periodic summer and annual winter burning produced intermediate pH values, which did not differ significantly from those of other treatments. On the Alabama site, prescribed burning did not significantly alter pH values; however, on burned areas, readings averaged 0.2 pH units higher. Soil pH ranged from 3.5 to 4.4 among burning treatments on the Georgia site. The effects were not significant, but pH tended to increase with frequency of burning.

For a wide range of soils and burning techniques, soil pH has been shown to increase to some degree shortly after burning (Wells and others 1979). As time passes, acidity increases and soil pH returns to its prebuming value. Degree of pH increase and time needed to return to the prcbuming level depend on burning intensity, amount of forest floor consumed, soil organic matter and clay contents, rainfall, and internal soil drainage. Results of these studies indicate that periodic burning raises pH values slightly. On heavy soils, this effect is apparent for at least 7 years after burning. For the sandy soil on the Florida site, the pH value for the periodic burning treatment did not differ from that of the unburned control. This result suggests that the pH increase had a shorter duration on this site, which was last burned two years before sampling.

TABLE 1. Soil reaction, exchangeable bases and cation ratios for four sites uith different burning treatments.

Sample site and burn treatment	Soil pH	Exchangeable bases Ca	Mg	Ratio Mg/Ca
		mmol kg		
Alabama (0-8 cm)				
No Burn	5.2	1.278	0.20A	0.16
Biennial uinter	5.4	1.89A	0.148	0.07
Florida (0-8 cm)				
No Burn	4.1AB	0.256	0.22B	0.88
Periodic winter	4.08.	0.45A	0.35A	0.77
Annual uinter	4.2A	0.57A	0.38A	0.66
Georgia (O-S cm)				
No Burn	4.1	0.11	0.05	0.42
Triennial winter	3.5	0.18	0.05	0.31
Biennial winter	4.4	0.29	0.07	0.36
Annual winter	4.1	0.16	0.05	0.32
South Carolina (O-5 cm)				
No Burn	4.18	0.63	0.286	0.44
Periodic minter	4.18	0.79	0.33AB	0.42
Periodic summer	4.2AB	0.87	0.33AB	0.38
Annual uinter	4.2AB	1.23	0.51A	0.41
Annual summer	4.5A	1.08	0.38AB	0.35

Within col- and sites. values followed by the same letter or no Letter do not significantly differ at the 0.05 Level.

Samples collected after 10 years of burning on the South Carolina site averaged within 0.1 to 0.2 pH unit of the values after 10 years of burning (Metz and others 1961). An exception is the annual winter plots with a pH value of 4.2, compared with 4.6 at 10 years.

Exchangeable bases. On the Alabama site, burning increased exchangeable calcium in the surface 8 cm of soil by 0.62 mmol kg^{-1} (Table 1). Similarly, on the Florida site the burned plots had 0.30 to 0.32 mmol more exchangeable calcium than did the control plots. On the Georgia site, exchangeable calcium increased slightly but not significantly with increased burning intensity. The difference was only .05 to .018 mmol kg'.

Burning treatments did not significantly alter exchangeable calcium concentration on the South Carolina site, but calcium tended to increase with increased burning in the O-5 cm soil layer. Ten and 20 years of burning significantly increased calcium on this site (Metz and others 1961; Wells 1971).

Values for exchangeable calcium 10 and 20 years after initiating treatments were within the range of the 30-year values. These data do not indicate any long-term change in quantities of calcium in the mineral soil.

Generally, magnesium responses to burning were similar to calcium. Exchangeable magnesium increased with burning by 0.06 mmol kg^{-1} in the O-8 cm soil layer on the Alabama site. On the Florida site, magnesium content was 0.13 to 0.16 mmol higher on burned plots than on control plots. Burning treatments had no detectable effect on the exchangeable magnesium levels on the Georgia site. The annual winter bum had 82 percent more exchangeable magnesium than did the control plot on the South Carolina site. Magnesium values for other burning treatments did not differ from those for the control or annual winter burning.

An indication of the degree of soil development or weathering is the ratio of exchangeable magnesium to calcium (Buol et al. 1973). As soils become more weathered, relative magnesium levels increase and calcium levels decline. Within the period of these studies, this effect is found only in the surface Al horizon. Burning did not change the ratio of exchangeable magnesium to calcium at lower depths. Over an extended period, the effect of the accumulated forest floor or presence of organic acids and leaching of cations from the upper horizon--as observed by Herbauts (1980)--should appear at lower depths, including the B horizon. In any case, prescribed burning apparently slows the process of soil formation and may help maintain soil productivity at a higher level. A final proof of this hypothesis would require a timespan approaching several hundred years.

A more immediate problem, as proposed by Lyle and Adams (1971), is a nutrient imbalance caused by higher concentrations of magnesium than of calcium. These authors observed that because of "mass action effects," magnesium in excess of calcium results in reduced loblolly pine root growth. According to this concept, the surface soil layer on unburned control plots on the Florida site is nearing this condition while that on burned plots is not. Such relationships also may bc important to microbial processes found on pine sites.

Heyward (1937) observed that the elimination of burning on Coastal Plain pine sites resulted.in abrupt changes in the visual characteristics of a soil profile. His interpretation was that exclusion of burning accelerates soil weathering or development. With moisture conditions and parent materials he was observing, the end results would probably be a spodosol without fire and no spodic horizon with fire. Specific reports of such effects of fire on soil formation have not be published. It appears that the natural evolutionary pattern of soil development caused by water-soluble carbon, as observed by Herbauts (1980), can be moderated by burning. This conclusion is based on lysimeter studies on soils under forest cover where the degree of soil weathering was found to relate to the amount of soluble carbon moving through the profile. Nutrients moving from ash material after burning are alkaline (Raison and McGarity 1978), at least until the ash has dissolved and moved into the mineral soil. To some degree, burning destroys the substrate and either consumes or volatilizes organic acids produced in the forest floor. Such a change is assumed to be roughly proportional to the reduction of organic matter in the tire. The water-soluble carbon may be in a humic and fluvic acid (De Kimpe and Mattel 1976), in carbonic acid (McColl 1971), or in other soluble organic acids. Observations of Binkley (1986) on a site similar to that reported for on the South Carolina site in this report found that burning may convey resistance to soil acidification from atmospheric deposition or other sources by reducing pools of acid in the forest soils. Where sulfur dioxide from burning fossil fuels significantly acidities precipitation, the resulting sulfuric acid is a much larger factor than carbonic acid (Cronan and others 1978). The acid radicals react with the soil to form salts with alkali, alkali earth, and amorphic metals that move through the soil horizons in the process of soil development.

Yaalon and Yaron (1966) indicate that any man-caused activity such as adding fertilizer or changing the pH will change the metapedogenetic processes that retard podsolization; the rate of change depends upon the intensity of treatments. Bidwell and Hole (1965) also discuss human practices as dominant factors in altering soil formation by controlling organic matter buildup. Thus, burning pine sites on the Coastal Plain tends to maintain soils in a less developed state and probably in a better tilth. Historically, such has been the case for much of the Coastal Plain, where tire maintains the pine ecosystem.

Phosphorus fractions in the surface mineral soil. Phosphorus was fractioned into various chemical forms in the surface 5 to 8 cm to determine the effect of prescribed burning on the disposition of phosphorus and its availability for plant uptake.

The amount of available phosphorus in the soil was slightly higher on burned than on control plots on all four study sites, but the differences were significant only on the South Carolina site (Table 2). On the Alabama site, phosphorus levels were 0.1 to 0.2 mg kg^{-1} higher on burned plots.

TABLE 2. Distribution of soil phosphorus in available, mineral and organic forms for the surface sample Layer of soil on four sites.

Sampled sites burn treatment	Phosphorus Fractions Available	Mineral	Organic	Total
	kg ha'			
Alabama (o-8 cm,!				
No Burn	2.3	11.6	20.18	31.70
Biennial. winter	2.4	12.0	23.3A	35.3A
Florida (O-8 cm)				
No Burn	7.1	15.4	18.0	33.48
Periodic uinter	9.5	19.0	21.6	40.6A
Annual winter	10.5	19.3	21.2	40.5A
Georgia (0-8 cm)				
No Burn	2.4			
Periodic winter	3.2			
Periodic summer	3.3			
Annual winter	2.7			
South Carolina (O-5 cm)				
No Burn	3.68	25.9	52.1	78.0
Periodic winter	4.5AB	27.5	45.8	73.3
Pecіodic summer	5.0AB	24.9	53.0	77.9
Annual tinter	5.4A	29.9	56.4	86.3
Annual summer	4.1AB	27.6	51.6	79.2

Within columns and sites, values for chemical fractions followed by the same letter do not differ significantly at the 0.05 Level. Available phosphorus represents both organic mineral fractions and is not used in computing the total phosphorus.

Annual and Periodic burns increased available phosphorus by 2.5 to 3.4 mg kg^{-1} in the O-8 cm depth on the Florida site. Available phosphorus ranged from 2.4 to 3.3 mg g^{-1} and increased with burning on the Georgia site.

Burning effect on individual mineral phosphorus fractions were relatively small and in most cases did not alter individual fractions, hence, the water soluble, aluminum and iron fractions are reported as mineral phosphorus. In general, the mineral phosphorus levels tended to increase with intensity of burning except on the South Carolina site where no trend was apparent. Changes in the available form of phosphorus or the magnitude of these changes do not appear to relate well to the phosphorus present in the mineral or organic forms.

Organic phosphorus accounted for 50 to 69 percent of total phosphorus in the surface 5 to 8 cm of soil on the three sites where measurements were taken. On the Alabama site, burning increased organic phosphorus by 16 percent or 3.2 mg kg'. On other sites, an apparent increase in organic phosphorus of 3 to 5 mg kg' was noted, but the increase was not significant. The amount of organic phosphorus was positively related to total phosphorus extracted from soils on these sites, accounting for 86 to 94 percent of the variation in total phosphorus.

Burning significantly increased total phosphorus (sum of the mineral and organic fractions extracted from sandy sites by 4 to 7 mg kg-‘. There is no apparent difference between the annual and periodic burning on the Florida site. Burning also tended to increase total phosphorus on the heavier soils of the South Carolina site, but the response was not significant. The large proportion of the total phosphorus in the organic form in soil indicates the need to investigate this form of the nutrient and to increase its availability to higher plants. Daughtrey and others (1973) found the release of organic phosphorus from a Coastal Plain soil was completely dependent on the activity of soil micro-organisms in decomposing organic matter. Nutrient release with burning would accelerate the breakdown of organic matter and release of organic phosphorus to the soil solution. Accumulation of organic matter and organic phosphorus is partly the result of small organic particles being washed from the forest floor into the soil.

Forest Floor Properties

Organic content. Prescribed burning predictably lowered the total weight and nutrient content of the forest floor on all four sites (Table 3). Across the range of sites, the unburned control plots contained from 13 to 59 T ha“ of organic matter. Annual and biennial burning reduced the weight of organic matter in the forest floor by 39 to 44 percent on the

Table 3.--Average weights of forest floor components after burning treatments on four study sites.

Site and burn treatment	Organic contest	N	P	Ca	Mg	C:N Ratio
	kg^{-1} X 1000	. . . . kg ha^{-1}				
Site #1						
No burn	13.86A	2264	8.7A	67.2~	9.3A	30:1
Biennial bum	5.440	276	3.18	29.28	3.58	100:1
Site #2						
No Burn	29.16A	131A	24.7A	115.0A	21.0A	111:1
Periodic winter	9.52A	378	6.78	40.08	11.0B	128:1
Annual winter	4.54C	7B	3.06	19.08	6.06	324:1
Site #3						
No burn	59.5	494	16.5~	83A	23.0A	60:1
Triennial burning	12.4	81	3.28	218	3.68	77:1
Biennial burning	7.48	56	2.28	15B	2.68	66:1
Annual burning	17.18	100	4.20	278	5.18	85:1
Site #4						
No burn	26.27A	408A	17.4	12.0A	19.0A	32:1
Periodic winter	18.468	3008	12.1B	91.08	19.0A	31:1
Periodic summer	17.566	2778	10.68	77.08	16.0AB	32:1
Annual tinter	10.48C	156C	7.28	52.0C	11.0BC	33:1
Annual summer	10.05C	129C	7.18	48.0C	6.0C	39:1

Within columns and sites, values followed bv the same letter do sot differ significantly at the 0.05 Level. Where no" letters am. shown, no significant differences are present.

Alabama site. Periodic burning on the Florida and South Carolina sites reduced the weight of the forest floor by 33 and 70 percent respectively. The forest floor reduction was 71 to 87 percent with burning on the Georgia site. Season of burning did not significantly affect the reduction total organic content.

Organic content of the forest floor on control plots is approximately the same for the South Carolina site as reported 10 years earlier (Wells 1971). On these plots the forest floor contained 18.57, 26.88, and 26.27 T ha" after 10, 20, and 30 years of measurements (Metz and others 1961; Wells 1971). Thus, in terms of weight, the forest floor reached an equilibrium between 10 and 20 years after initiating the study, when the pine trees were about 45 years old. At 30 years, the forest floor contained 18 to 39 percent mineral material (determined by dry ashing the combined L, F, and H layer samples).

Wells and Jorgensen (1975) found that forest floor biomass reaches its peak in loblolly plantations at about age 30 in Piedmont stands. The sites in this study had considerably older trees, which produced less needles, but greater production of litter by hardwoods and herbs probably compensated for lower needle production.

Nitrogen. Nitrogen content in the forest floor decreased by as much as 95 percent with annual tires and 72 percent with biennial fires. Part of this nitrogen loss was from leaching water-soluble components and tine particulates from the forest floor into the soil. The forest floor of periodically burned plots had nitrogen losses ranging from 26 to 32 percent on the South Carolina site which had not been burned for live years at sampling, to a 72 percent loss on the Florida site which had been burned the previous year. Wells (1971) observed that the periodic burning on the South Carolina site 10 years earlier resulted in a nitrogen loss of about 112 kg ha" by volatilization. The 408 kg ha^{-1} of nitrogen in the forest floor on the control plots appear to represent an "equilibrium" value for this nutrient under the conditions imposed by the stand and the climate (Wells and Jorgensen 1975). Values on control plots on the other sites probably also represent near-equilibrium levels. Of interest are the nearly equal amounts of organic matter on the control plots of the Florida and South Carolina sites but about a four-fold greater amount of nitrogen on the South Carolina site than on the Florida site. The amounts of nitrogen in the forest floor probably reflect species and site conditions specific to each location.

The C:N ratio is a major determinant of availability of nitrogen and potential decomposition of the forest floor. The ratio of carbon to nitrogen widened by 1- to 3-fold on the Alabama and Florida sites following annual or biennial fires. On the South Carolina site much smaller increases (5 to 20 percent) occurred after annual bums, and no increases occurred after periodic bums. An exact C:N ratio is difficult to obtain because much of the organic matter is charred after burning. The magnitude of observed change, however, reflects an apparent nitrogen mobilization that cannot be explained by degree of carbon reduction. A number of rains fell on all the burned plots between burning and sampling. Comparison of forest floor values on the South Carolina site after 20 years shows a similar trend.

Heyward and Bamette (1934) observed that the L layer had a C:N ratio 2 to 3 times as wide as that of the F layer. Wells and Jorgensen (1975) observed a similar relationship for loblolly pine plantations in the Piedmont, where the C:N ratio of litter narrowed over time. Because it is primarily the L layer that is consumed by tire, it is surprising that burning results in a wider C:N ratio. Apparently, low-intensity fires have a "mobilizing effect" on nitrogen in the F layer, which may in part account for the increased nitrogen concentration in the upper 5 to 8 cm of mineral soil. Nitrogen relationships are supported by findings of Klemmedson and others (1962), who showed that burning accelerated nitrogen movement into the mineral soil. Light burning in ponderosa pine (P. ponderosa Dougl. ex Laws.) stands caused movement of 12.4 kg ha^{-1} nitrogen per year into the surface 2.5 cm of mineral soil. Wells and others (1979) summarized a number of investigations which indicate that appreciable mobilization of nitrogen as well as volatilization of the forest floor occurs after burning.

Phosphorus. Biennial or annual burning reduced the amount of phosphorus in the forest floor by 42 to 88 percent on all four sites. Periodic burning resulted in a 39 to 73 percent decrease in phosphorus in the forest floor. The season of periodic or annual burning did not affect phosphorus loss, and there was no significant difference between annual and periodic tires.

Cakium. Annual or biennial burning reduced calcium in the forest floor by 50 to 92 percent. Periodic burning resulted in a 28 to 39 percent reduction on the South Carolina site. Season of burning had no effect on changes in calcium content of this site. Thus, prescribed burning accelerated the rate of calcium return to mineral soil. This movement probably results from cations moving in the soil solution, but ash conduction may also be a factor. Wells and Jorgensen (1975) indicate that without burning, calcium loss from the forest floor is slow compared to potassium or magnesium loss and that after eight years appreciable quantities of the nutrient remain in the forest floor from a given year's deposition. Quantitatively, 50 percent of the magnesium from a given year's accumulated litter is lost from the forest floor in less than one year, while three years are required to obtain this degree of calcium mineralization (Jorgensen and others 1980).

Magnesium. Amounts of magnesium in the forest floor were approximately 1/4 to 1/10 those of calcium. The mobilization of magnesium with burning appears to be similar to that of calcium; and 43 to 71 percent magnesium was lost from the forest floor with biennial or annual burning. Periodic burning on the Florida site reduced magnesium by 52 percent. The period between burns and the season of burning did not significantly affect magnesium losses from the forest floor on the South Carolina site. Based on values reported by Wells and Jorgensen (1975) for loblolly pine in the Piedmont, the forest floor on these sites contains about 1/2 to 1/3 as much magnesium as in the tree biomass, and the nutrient would be expected to move out of the floor faster than calcium.

Forest Floor Mineral Relationships

To understand the quantitative relationships of the forest floor and increased nutrient concentration, the total contents are presented together for the surface 10 to 16 cm of mineral soil and forest floor.

Organic Matter. Burning reduced the organic matter content of the forest floor but not of the mineral soil. In fact, burning may have actually increased organic matter content of the mineral soil for the Alabama and Florida site but the increase was not statistically significant (Fig. 1). The result was a rather small loss of total carbon from the system due to burning part of the forest floor. The study sites in Florida and South Carolina, which have poor drainage, appear to have higher organic content in the mineral soil than those of Alabama and Georgia.

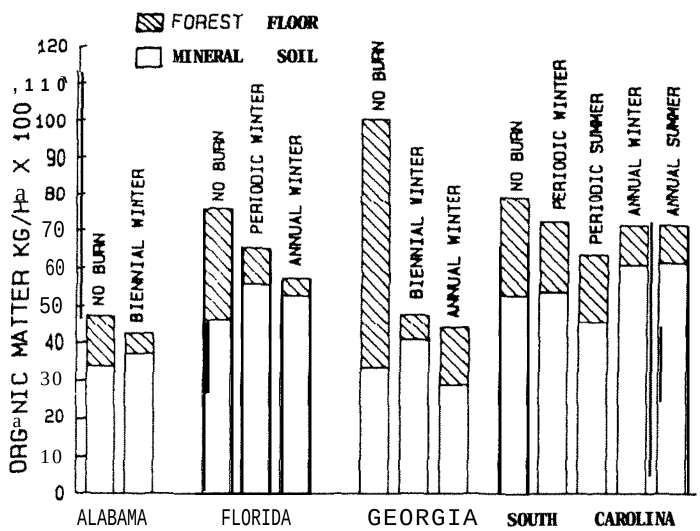

Figure 1. Organic matter content in the forest floor and soil after prescribed burning of coastal plain pine stands.

Nitrogen. On the sandy Alabama, Florida, and Georgia sites, burning caused a slight increase in nitrogen in the mineral soil despite a marked loss of forest floor weight after 8 to 40 years (Fig. 2).

Soil at the South Carolina site had been sampled after 10 years (Metz and others 1961), 20 years (Wells 1971), and 30 years (McKee 1982). Over 20 years between sample collection, total nitrogen changed little on the unburned control. After those treatments, there was a 20-year increase of 34 to 42 kg/ha--a four percent change for the periodic winter bum. The periodic summer bum (burned every seven years) resulted in a 128-kg nitrogen loss. The annual winter bum increased total nitrogen by 137 kg/ha. The striking effect was a 363-kg loss due to annual summer bum. Since both summer bums resulted in total nitrogen losses, summer burning apparently has a detrimental effect on the amount of nitrogen remaining in the surface mineral soil, while winter burning increases nitrogen. The exact cause is difficult to explain but may be related to a lack of nitrogen-fixing legumes that invade these treatment sites after summer burns.

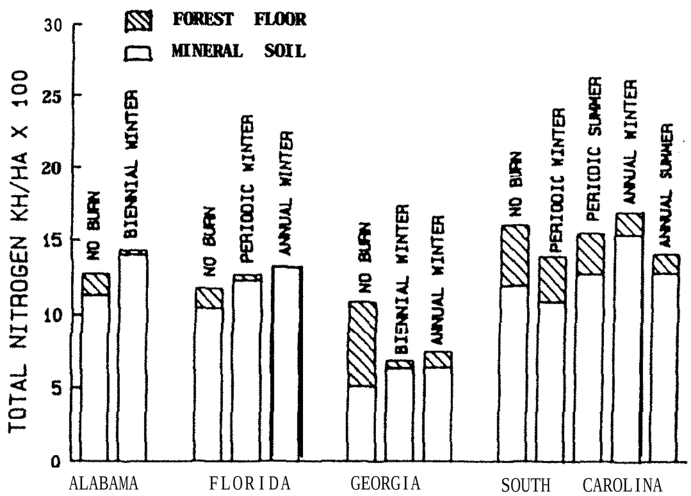

Figure 2. Nitrogen content in the forest floor and mineral soil after prescribed burning of coastal plain pine stands.

Phosphorus. Without burning, appreciable quantities of phosphorus were tied up in the forest floor on all four study sites (4 to 24 kg/ha) (Fig. 3). The amount of phosphorus in the mineral soil is difficult to relate to that of the forest floor. Available phosphorus was apparently increased by burning, but the quantities found did not relate well to frequency of burning. A standard chemical test suitable for all sites is difficult to select because numerous chemical forms of phosphorus are present. Available phosphorus levels appear to be slightly more responsive to treatments and are represented on all four sites.

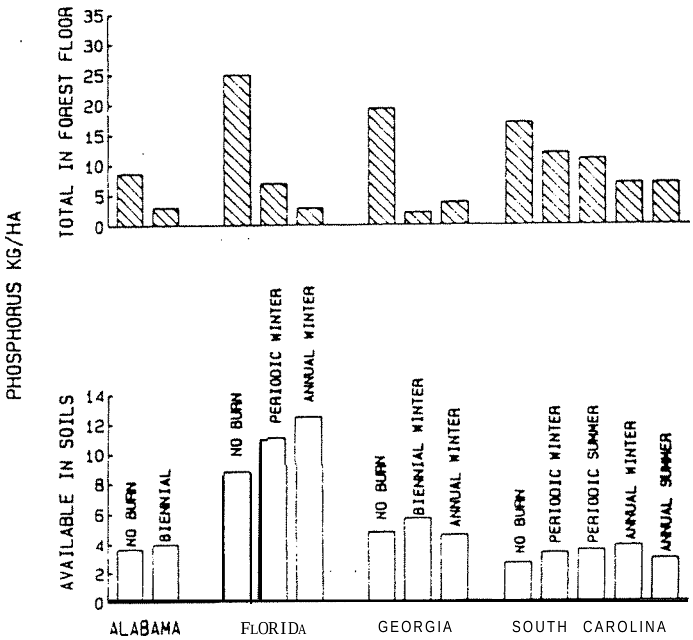

Figure 3. Phosphorus content of the forest floor and available phosphorus content in the mineral soil after prescribed burning of coastal plain pine stands.

Calcium. All the effects of burning on calcium appear to take place in the forest floor and the top 10 or 16 cm of mineral soil (Fig. 4). Without burning, 16 to 61 percent of the calcium present was in the forest floor. With burning, only 4 to 16 percent of the calcium was in there. The remainder was in the surface soil layers. These changes in calcium distribution logically account for the pH increase in the mineral soil associated with burning, and indicate a long-term effect on soil acidity. The amount of calcium in the forest floor decreased proportionally to the frequency of the burning on the Florida and South Carolina site. Earlier calcium observation on the South Carolina site, (Wells 1971) showed similar results, indicating little change in the calcium status of this site in the last 10 years.

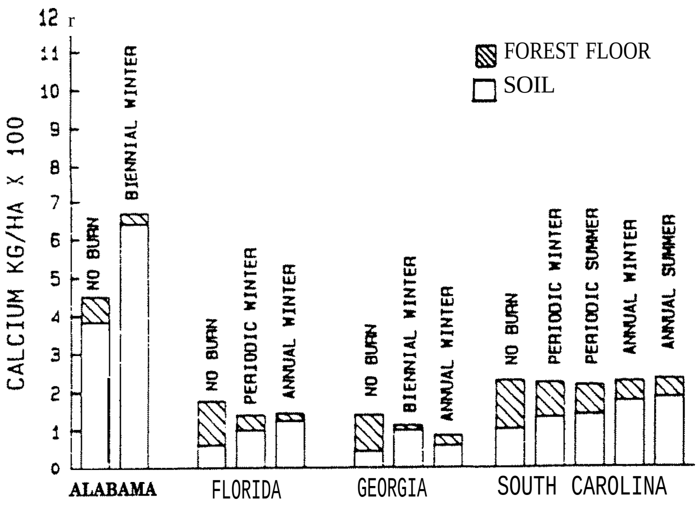

Figure 4. Calcium content in the forest floor and exchangeable calcium content in the soil after prescribed burning of coastal plain pine stands.

CONCLUSIONS

The most striking result of this analysis is the similarity of burning effects on soil properties despite obvious soil differences and probable differences in burning techniques, which were reported to be either low-tempcraturc flank fires, or backfires.

Organic matter consistently builds up faster in mineral soil on burned areas, and burning only reduces total nitrogen in the forest floor. On unburned plots, 6 to 11 percent of the nitrogen was in the forest floor. Over the range of study sites, annual burning reduced total nitrogen in the forest floor to 12 to 32 percent of the unburned levels, but burning did not appear to reduce total nitrogen in the mineral soil after up to 30 years of treatment. However, a balance sheet for the studies requires nitrogen data for the vegetation which may be causing an increase in soil nitrogen.

The consistent increase in available phosphorus in mineral soil caused by prescribed burning, may be one of the most beneficial effects of the treatment. No consistent pattern was found for burning effects on phosphorus fractions. The nature of compounds formed apparently represents specific pH conditions and mineral components in the soil. However, in all cases burning obviously accelerated mineralization.

The cation response was quite similar for all sites. The soil depth used appeared to represent complete cycling of calcium. Trends indicate that the unburned forest immobilizes a large proportion of the calcium altering the nutrient balance of the soil in some cases. Magnesium and calcium responded similarly to burning treatments, but their ratios indicate that magnesium recycles faster or at least accumulates in mineral soil in the absence of burning.

It is apparent that burning alters soil formation and long-term productivity over time. Evidence suggests that burning may improve soil by retarding soil development and, probably, formation of spodic layers in the profile. Proof of this observation would probably require five to six pine rotations to compare soil development with and without fire.

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FIRES, FORESTS, AND TRIBES IN THE NORTHERN PHILIPPINES: CULTURAL AND ECOLOGICAL PERSPECTIVES

Sharon Codamon-Quitzon[1]

Abstract-The study was exploratory. The researcher utilized participant observation, case study, and **interview-discussion methods** to gather data. Purposive stratified multi-stage sampling guided initial selection of 103 respondents in 3 groups: kaingineros, school teachers, and government officials. The study is an attempt to explain forest burning from the perspective of the tire-setter. It is the first of a series of investigations that interpret forest burning as a lifeway of a people who inhibit a rugged environment and who possess a unique s&o-cultural temperament. Specifically, research focused upon the forest fire-setting behavior of the Ifugao, an ethnic tribe in the Cordilleras, a mountain range in Northern Philippines. This paper reports impacts of socio-culturally sanctioned indigenous forest burning practices the local economy, ecology, and society. Central to the issue of forest burning is the highly institutionalized Ifugao practice of muyung, or inherited private ownership of forests. Muyung greatly complicates governmental efforts to promote forest fire control, sound forest management, and sustainable forest development in Ifugao.

INTRODUCTION

Fire accounts for one-third of the damage done to the Philippines' critical watershed and forest lands. The problem continues to be addressed largely as a technical one, and forest management continues to he forestry-oriented following inception of the Social Forestry Program in the DENR. (The Philippine SFP, which was launched in 1982, is a radical departure from traditional programs, which put the forest before its occupants. Creation of the SFP is a mute admission that the conventional methods used to conserve and protect the forest have not succecdcd.) Ifugao, now legally recognized as the Cordillera Autonomous Region, was chosen for study because it had the highest rate of forest fires in the Northern Philippines and because its supposedly civic-minded and law-abiding people continue to bum forests despite the region's long history of Spanish and American religious endeavor and continuing government administration.

The study was designed to:

- document relevant demographic, economic, and social attributes of selected kaingincro respondents involved in forest burning practices in the area of study;
- determine level and type of knowledge (awareness), assessment (perception), and **predisposition (attitudes)** toward forests, forest fires, and forestry policies (including the prcscncc and role of the local forestry agency in forest fire prevention and managcmcnt),
- determine the existence and nature of beliefs relevant to forests and forest burning activities among the natives in the area.;
- dctcrminc the role of revenge as a factor in forest burning;
- identify socio-cultural learning experiences that influence, reinforce, and institutionalize the practice of forest burning among the same; and
- review approaches adopted by the local forestry agency to prevention of forest fires.

LITERATURE REVIEW

Cruz (1985a, b) asserts that the fight against forest fire in the country is hampered by certain institutional and external problems compounded by public apathy toward forest protection due to the misconception that tire is the sole responsibility of the BFD. Misra (1983) described forest fire types, causes, uses, and prevention but did not focus on the personality of the fire-setter. Atabay (1978) and Binua (1978) argued for forest fire research to support forest protection, rcforcstation, and grassland management. Rabanal (1973) believes that the problem reflects a lack of knowledge on the part of those who regularly burn forests, who use fire to prepare land for planting and who do not fully understand the consequences of burning. Researcher like Duldulao, and others (n.d.) and Strasser (1970) stress the socio-economic angle, arguing that forest conservation consciousness cannot bc instilled among those involved in the destructive activity unless they are given an alternative way of earning their living. Social and cultural characteristics of people living near or within fire-prone forest areas, and attitudes of those people regarding forest burning, local forestry agencies, and their representatives, were identified by Bertrand and others (196.5) as factors relevant to the potential success of fire prevention programs. Forest fire has been attributed to plain ignorance of fire prevention practices, irresponsibility, carelessness, and grudges against forestry personnel.

METHODS

Place of Study

The study was conducted in the barangays of Bokiawan and Hucab in the municipality of Kiangan (1975 population

[1]Senior Science Research Specialist, Ecosystems Research and Development Bureau, College, Laguna, Philippines.

15,985; area 443.3 km^2), and in the barangays of Panopdopan and Nayon in the municipality of Lamut (1975 population 9,516; area 104.5 km*). These sites were selected based on greatest fire incidence, kaigin activity, concentration of forested area, food or eating habits, sustainability and availability of land, weather conditions and facilities affecting agriculture as principal mean of livelihood.

Research Design

Upland farmers or kaingincro (shilling cultivators), who are termed munhabals in the Ifugao vernacular, served as the primary source of data; teachers and government officials served as secondary sources. The kaingincros were covered by complete enumeration, which yielded 60 respondents. The teachers and government officials group were criteria-selected using purposive stratified and multi-stage sampling. The Bureau of Public Schools (BPS) Form as of October 1978 and the Sangguniang Panlalawigan, Sangguniang Bayan, Barangay Council, and local BFD personnel were the sampling frames. Twenty respondents (10 from each municipality) from each group made up the sample. There were a total of 103 respondents (60 kaingineros, 20 teachers, 20 government officials, 2 municipal mayors and 1 BFD district officer--the last 3 treated as special case studies).

Collection of Data

Interview Method. Semi-structured interviews, mostly without the schedule on hand, were generally conducted inside offices, school premises, business establishment, and residential buildings in Bokiawan, Bolog, Ambabag, Baynihan, Baguinge, Cawayan, and Poblacion for Kiangan and in Panopdopan, Lawig, Nayon, Payawan, Mabatobato, Pieza, Bunog, Magullon, and Poblacion for Lamut. The term “forest fire” was somttimes-used in place of “forest burning behavior” to make it easier for the kringineros to grasp the concept.

Interviews were sometimes recorded on tape, particularly “huddled types” when one interviewee suddenly became several as wives, children, and other members of the household also sought attention. The recorder was introduced as a radio set to prevent selfconsciousness. Inquiry was directed primarily to the head of family, who was informed beforehand of the object of research. For the secondary sources, the average interview time took 1 hour and 40 minutes. Most of these were approached during their “break” periods and were not briefed as to the purpose of the interview.

Participant Observation or Case Study Method. “Live-in” observations were made during waking hours and upon return of the kaingineros from their kaingins in the evenings. Interviews were conducted in the morning before the subjects set out, when they invariably spend some time huddled together outside their huts as if awaiting the sunrise. Some return at noon in order to have an early start on the next day’s work or because the kaingins are located some distance from the dwellings. The interviewers also observed the baki performed by the different households, and these occasions also presented opportunities for casual and natural talks with the natives. The babiis is an Ifugao native ceremony or rite performed to invoke the favorable intervention of spirits of dead ancestors and gods or deities on the occasion of sickness *in* the family or in token of thanksgiving for favors received. The last day was spent in the kaingins for a first-hand view of the situation.

FINDINGS AND DISCUSSION

The case of the kaingineros is highlighted in this report.

Socio-Economic Attributes

Rokiawan. The study centered upon the activities of an all native, almost SO-percent unconverted and non-formally educated majority in the sitios of Bunog and Kayapa. Farming is the main occupation, with almost 50 percent professing ownership of payo (ricefield), habal (kaingin), muyung, and animals? Per-family income is not computed. Most families are engaged in wood-carving business. Elementary school children earn an average of P21 .OO per week by carving pieces of spoon and fork figurines, while older children earn an average of P87.50 per week. In Bunog, all heads of families depend on sales of coffee for their monthly income. The average quantity brought by each family to the town proper is to 5 gantas of coffee valued at P40.00 at P1 .OO per chupa. Another source of money or cash income is the littuco (rattan fruit) which is harvested during September, October, and November and yields an average income of P250.00 at P25 per container. If they were to sell their palay, their income would be barely sufficient for daily needs. The *owners* of ricefields plant the traditional variety of palay and harvest only once a year. The yield is usually reserved for family consumption or for emergency barter in the adjacent or nearby barangays of Mungayang and Bayninan. Camote (sweet potato) harvested from the kaingins is the staple food. For those who own ricefields, rice is eaten alternately with camote.

Hucab. The study was centered in Hoba, where the kaingin system is the chief occupation. Camote is the main staple. The respondents also own pigs, chickens, and ducks. Cash income is derived from the sale of bananas and coffee grown in backyard gardens or in small orchards leased from other individuals (who arc not necessarily Ayangans). Unlike the other native respondents, the residents of Hucab do not own forests.

Nayon. The five primary subjects were predominately male, married, educated, but unconverted kaingineros of Binoblayan. All admit having a habal or patch of unirrigated agricultural land, but not all possess a payo and a muyung. The sale of bananas provides each family with an average weekly income of P24.00. Three to 400 pieces of unripe bananas are sold at an average of P6.00 per hundred. Camote and corn arc sold for about P20.00 per kerosene can.

Rice is harvested only once a year. The cash value of the palay harvested by a kainginero family averages P200.00 per year.

Panopdopan. The respondents have their own hospital, an elementary school building, and business establishments. Their characteristics are not basically different from those of residents of the other barangays studied. Those who were first to settle in the area are better off economically than those who came later. Panopdopan's forests were originally a public or communal forest site of the mother municipality of Kiangan. The residents of Panopdopan established ownership of these forests through the simple expediency of declaring them for taxation purposes and by claim of continuous and peaceful occupation. The privilege of developing these forests into ricefields or banana or coffee plantations has been exploited to the hilt. Residents leave their private forests well enough alone.

Cognitive Attributes

The findings about the kaingineros are generally applicable to all the groups studied. All kaingineros profess non-awareness of any government-promulgated law regulating kaingin. They believe that common law dictates that kaingins, are made in "open areas" regarded as "public land," and not on forests owned by private individuals. They do not understand why they should be prohibited from burning or utilizing fire as a tool in their kaingin practice. Forests are viewed primarily as private properties. The owner of a muyung is thought to be in the best position to care for it properly and manage it as a source of lumber, fuel, and the water that irrigates his ricefield. All claim that no one from the FNB had ever visited their areas. Non-observance of laws against burning accordingly stems in part from non-enforcement by the government. The local people arc scarcely aware of the presence of a local forestry service, and find it very difficult to conceive that the muyung could ever be placed under state control. All agree that public lands should bc distributed to the landless, who can develop these as sources of stable and adequate income and livelihood. All endorse stricter regulation and control of the activities of loggers and wood carvers in Ifugao, who arc held responsible for the wanton destruction of the public forests.

Beliefs Relevant to Forests and Forest Burning Activities

Two pervasive beliefs are relevant. The first has to do with forest ownership and seems to provide the key to the burning behavior. The natives know that the government has legal right over the forest, but they believe that the right belongs to the people who own the forests. Some natives explained that the government owned the public forests. The second belief relates to fires in the muyung. The natives do not regard these as forest fires but merely as a routine activity or tool for preparing the kaingin portion of the forest land for planting. The munhabal sets fire to what a non-native would consider as forest when there is no known claimant to the area and when customary law defines the area as public land primarily for kaingin. Burning preparatory to planting is indispensably customary.

Socio-Cultural Learning Experiences That Influence, Reinforce and Institutionalize the Practice

The native who lives in a more remote area learns to eat camote morning, noon, and evening, or, if he is luckier then the other kids in the neighborhood, camote alternated with rice. Camote is planted mainly in the family kaingin. Cleaning of rice fields starts in January, and rice planting is completed by March. The ricefields are then temporarily abandoned while the natives prepare their kaingins, which are usually located some distance away from the ricefields. Cutting down of vegetation starts by April. The grasses and trees are left to dry for at least a month, then the natives go back to bum them. Burning commences by May. Mongo is planted as soon as burning is completed, and camote is planted August after the mongo is harvested. The camote crop is harvested 5 months later. The habal is then left idle until April, when the grasses are cut, dried, and burned preparatory to planting activities. The process is repeated year in and year out unless, the place is totally abandoned in favor of another occupant. There is no room for idleness. Those who do not own any habal or payo earn their livelihood by helping clean and prepare rice fields for planting in consideration of wages in money, or by cultivating and planting someone else's ricefield in return for half of the harvest. The culture is highly animistic. The native believes in a supreme being whom he calls Maknongan, in a hierarchy of lesser deities, and in ancestral spirits (anito). When a baki is performed for a particular purpose, sacrificial animals are butchered and offered to the spirits. The number and kind of animals sacrificed depend upon the financial capacity of the family requesting the baki. The raising of animals is thus required by religious customs, and kaingins must be cultivated to provide food for the livestock.

Observing forest fires on mountainsides, especially during the night, is pani-o (taboo). Those who observe such fires accidentally are cautioned to keep the matter strictly to themselves. This taboo enables a public forest fire-setter in Ifugao to go about his way unchallenged.

Revenge as a Factor in Forest Burning

Envy, anger, or hatred were seen as motives for burning in only a few cases. Respondents suggested that laborers employed by the local BFD office in its nursery and plantation set reforestation projects on fire to get even for being laid off, for delayed payment of wages, or simply to ensure their period of employment. There were insinuations that the local forestry office was in cahoots with its laborers in perpetuating tires, especially in the reforestation plantations, to justify its continuing budgetary allocation for forest fire protection.

Approaches Adopted by the Local Forestry Agency to Prevention of Forest Fires

- Constant forest guard patrol in fire-prone areas before and during the dry season.
- Intensification of forestry information drives
- Constant dialogue with local leaders on forest conservation projects and programs.

Interestingly, the respondents interviewed in connection with this study declared non-awareness of these activities allegedly undertaken by the local BFD agency.

RECOMMENDATIONS

We recommend allocation of adequate funds for an intensive and extensive census to determine the number of people involved in kaingin-making throughout the country. The census should determine (a) the circumstances and factors that support kaingin-making, (b) the nature and extent of forest destruction resulting from fire and other causes, (c) local beliefs, customs, and practices pertaining to forests, their ownership, purpose, use, etc. in relation to govemment-promulgated forestry laws, rules, and regulations. The findings of the should be used to guide the repeal or amendment of existing forestry laws, which should be made compatible with local beliefs, customs, and practices.

We recommend allocation under title in favor of landless families solely dependent upon kaingin-making for survival of all available forest lands claimed under current ownership by reason of inheritance or succession or by actual, continuous, and peaceful possession for a period of more than 15 years provided that the recipients, their heirs, or their successors-in-interest shall not alienate their allocations or interests therein within 30 years from the date of allocation of title and, provided further, that no title of ownership shall be granted except after the lapse of 5 years from the date of allocation and upon proof of occupation, development, and improvement of his allocation particularly in tree planting of whatsoever kind suitable in the area. In the allocation of such forest lands, first priority should be given to the natives and second priority to local residents.

We recommend reorganization of the BFD, particularly on the district level. Personnel should be dedicated, competent, and active. Employment preference should be given to qualified applicants who are natives or residents of the districts served.

We recommend that adequate funds be allocated so that FEB offices throughout the country can regularly conduct information drives, and so that special educational efforts can be made in areas notorious for forest destruction.

The theoretical framework prcscntcd in this report should also receive further consideration. Some hypotheses worth testing are as follows:

- There is no relationship between level of education and level of information or knowledge about the destructive nature of forest fires.
- There is no relationship between level of information about the destructive nature of fires and forest burning behavior.
- There is no relationship between perception of the local forestry agency's role and forest burning behavior.
- There is no relationship between beliefs held about forest ownership and forest burning behavior.
- The indigenous institutions of the Ifugaos that may be related to forest burning should receive further consideration and study.
- Camineros, or road maintainers employed by the govemment, members of the local police force, out-of-school youths, and others should be officially consulted as respondents in studies of this nature; they can be sources of pertinent and valuable information.

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SMOKE MANAGEMENT: ARE RIGHTS INCLUDED WITH THE RESPONSIBILITY TO USE FIRE IN MANAGING PUBLIC LANDS?

Dean A. Shinn'

In the southeastern United States, the native biota of many natural ecosystems are adapted to periodic burning. It is generally believed that in Florida at the time of European intervention, these ecosystems were sustained as fire climax communities by relatively frequent fires, resulting both from natural and from cultural causes.

The preservation and where necessary the restoration of the aboriginal structure and function of biotic communities occurring on State Parklands is central to the mission of the Florida Park Service. In pursuit of this mission, park managers throughout the State have been charged with the responsibility of using fire and prescribed burning techniques to manage Florida's State Parks.

One might suppose that a public responsibility to use fire in this way would be accompanied by certain rights to produce and dispense smoke from the areas being burned. The premise of this paper is that such rights should naturally cmcrgc from that public charge. However, Florida Statutes and the contingencies that they govern arc not yet viewed in such a way that the practical circumstances associated with public land management can be administered form this point of view. In fact, potential liabilities, rather than rights, are among the most prominent aspects of the public responsibility to usc fire as a tool in modern management of commonwealth resources.

In Florida, many state parks are small and are defined by boundaries that are uneven and often broken by parcels of adjacent private land. Many parks contain private inholdings wholly within their boundaries. Many arc also situated in highly urbanized areas and are bordered, even surrounded, by high-value commercial and residential development. Very few of Florida's slate parklands arc located away from major roadways. In the Florida panhandle, large areas arc occupied by military installations, and many other areas arc traversed by military and commercial flight paths. In addition, a relatively high proportion both of the seasonal and of the year-round population is composed of elderly people, many of whom have respiratory problems.

As a result, the heat, smoke, and ashes emitted from prescribed fires are likely to affect people and property beyond state park boundaries. Because developed areas potentially affected by prescribed fires are so close to parklands, and in many places are a major component of a park's external environment, the weather conditions under which tire can be safely used in parks are seriously constrained. In many places, bum prescriptions can be written to accommodate only winds of a very specific speed and direction. Along the Panhandle Gulf Coast, many State parklands can be burned under prescription only after a winter cold front has passed. Under such circumstances, the wind blows rather predictably from the north for a relatively reliable period of time. This situation restricts the range of options open to park managers in their use of fire to restore and preserve Florida's original natural ecosystems.

It must be emphasized here that land managers employed by the Florida Park Service are well aware of the legitimate and compelling hazards associated with the smoke emitted from prescribed fires. They have been and will continue to be diligent in planning fire management activities to avoid traffic hazards along major transportation corridors and to protect public health.

Certain other problems, such as ash falling into nearby swimming pools, soot soiling laundry hung on clothes lines, or simply the unusual smell of burning vegetation, are also associated with the smoke and ash produced by prescribed fires. These problems can be characterized as nuisances rather than as genuine dangers or health hazards, however.

These problems should be addressed first by establishing open, good-faith communications between park personnel and local citizens. A conscientious public relations effort should be an integral feature of each park's fire management program. The park's neighbors need to be informed about the benefits of responsible fire management procedures and advised of the fire planning process prior to prescribed burning activities being undertaken. Adoption of seriously constrained prescribed fire management procedures as a means of avoiding inconvcnicnce, rather than genuine hazard, would be ill-advised and would likely not achieve anticipated long-range ecological objectives. Thorough, good-faith public relations efforts should be undertaken early in every prescribed fire and smoke management program.

Of course, even the best efforts to inform the public and to solicit the cooperation of all who might be affected may not be entirely successful. Some among a park's neighbors simply may not be reached or may not be persuaded to coopcrale. Litigation may result.

'District Ecologist, Division of Recreation and Parks, Florida Department of Natural Resources.

This being thc case, thc author sought to dctcrminc if a line of legal reasoning could bc sct forth to advance the notion that a set of legal rights to produce and dispense smokc should be acknowledged as being implicit to the public rcsponsibility to usc fire as a resource managemcnt tool on public lands. Howcvcr, the existing case law in Florida docs not spccifically address this issue. Certain judicial decisions and findings that can be grouped under legal classifications such as "nuisances ," "negligcnce," "environmental rights and remedies ," and "explosion and fire" pertain to this subject only in a very general sense. It is unlikely that a cogent legal argument in support of "smoke rights" could be derived from thc existing case law. Indced, the time invested in attempting to do so might be ill-spent in the absence of a tcst case well suited to the development of such an argument. However, it is not likely that the Florida Park Service would wish to promote circumstances under which suitable legal reasoning could be developed through litigation. Therefore, other means of establishing "smoke rights" wcrc investigated -- means that would also serve to support the assertion of such rights, should a judicial defcnse of this concept become necessary.

Thrce options were examined: casements, land usc plans, and original legislation.

Easements: Establishment of buffer zones around State parklands through the institution of conservation easements or other special land use agrccmcnts with owners of adjacent private lands can be used to codify mutual acceptance of specific fire and smoke management practices. This approach is most practical and most likely to bc successful if undertaken while private lands surrounding parklands remain open and undevclopcd. After residential or commercial development occurs, ownership -- and therefore decision-making authority -- is likely to bc dissipated among many separate private interests. To achieve agreement concerning prescribed burning and smoke managcmcnt contingencies with one, or with only a few, adjacent ranchers and timbermen can be a rather straightforward matter. On the other hand, reaching agreement among all potentially affected parties in an expanding area of mixed residential, commercial, and industrial land uses would be a much more ambitious undertaking. Therefore, conservation easements that acknowledge specific fire and smoke management rights and responsibilities should be established as early as possible in a region's development cycle. They should stipulate the conditions under which such rights and responsibilities can be exercised without risk of legal constraint and should attach in perpetuity to the land, with provision for conveyance with the deed to each succeeding owner.

Land Use Plans: In Florida. comprchcnsive growth managcmcnt planning at the local level has been mandated by stats law (Chapter 163, Part II, Florida Statutcs), and a local land usc planning process has bccn established by administrative rule (Chapter 9J-5, Florida Administrative Code). In this way, each county and municipal government in Florida has been charged with the responsibility to develop and to implement a comprchcnsive land use and growth management plan. This planning process can be used to cstablish an explicit public acknowlcdgcmcnt of the need to use prescribed fire as a land managcmcnt tool and of the implicit consequence of dispersing smoke from the areas burned. Local planning documcnts arc fitting legal instruments in which to codify this public acknowlcdgcmcnt of "smoke rights" in association with established fire managcmcnt responsibilities.

However, the local planning process is a long and open-cndcd procedure. Its results can vary widely from one county to another and also among the municipalities within a single county. Within certain general state-wide parameters cstahlishcd by rule and within certain basic standards set by cach county, the specific provisions incorporated into any particular plan can bc either favorable or vcry unfavorable with rcspect to fire management on public lands. The quality and strength of provisions addressing fire and smoke management on parklands as finally adopted in a plan depend largely on the commitment and tenacity of local park staff and of sympathctic citizens. Thc propriety of fire as an appropriate tool in modem land use management should be introducccd early and should be re-enforced at ever stage of the planning process. Because land use planning is a cyclic and reverberative process, specific achievements can be rather transitory. Involvement at the local level must be thorough and continuing.

Legislation: The Florida legislature is now debating enactment of the "Florida Prescribed Burning Act." (Aftcr this paper was presented, the Legislaturc cnacted this initiative as Chapter 590.026, Florida Statures.) This document states that prescribed burning contributes to public safety 1) by reducing fuels and the risk of wildfires; 3) by helping to maintain biotic diversity and the ecological integrity of native communities; and 3) by facilitating the rcvegctation, restoration, reforestation, and enhancement of public and private lands. The bill also authorizes public education and technical training programs, where appropriate, in order to assure general acceptance and proper usc of fire as a land management tool. It then declares that prescribed burning, when properly authorized, is in the public interest and does not constitute a public or private nuisance. Most important with respect to smoke management, the bill finds that prescribed burning is a property right of the landowner and that the owner or his agent, when conducting an authorized bum, is not to be held liable for damage or injury resulting from tire or smoke, unless negligence is proven.

This bill introduces into legal dcbate the prospect of establishing certain smoke rights in association with an acknowlcdgcmcnt of related prescribed burning and fire managcmcnt rcsponsibilitics. Unfortunately, languagc in the bill that is pcrtincnt to the concept of "smoke rights" is rather nebulous. It does not provide clear and precise guidance concerning assertions of negligence, especially where drifting or wind-driven smoke and ash arc concerned. Howcvcr, this draft legislation establishes a useful context for continuing public examination of the rights of land managers relative to fire and smoke management.

SUMMARY

Are smoke rights included with the responsibility to use fire in managing public lands? The premise of this paper is that ccrtain rights to produce and disperse of smoke from lands subject to prescribed burning should be implicitly associated with the public responsibility to use tire as a land management tool.

The existing case law will not explicitly support such an assertion through legal argumentation, while public agencies are not inclined to promote litigation for the purpose of establishing favorable case law.

However, three alternatives exist for establishing such rights, or at least for developing legitimate public acknowledgement of the concept of such rights. To be practical and reasonably effective, casements specifying smoke rights should be instituted early in a region's development history. Local land use planning processes can be used to develop explicit public acknowledgement of contingencies associated with the usc of tire as a land management tool, but involvement at the local level must be both consistent and persistcnt. In Florida, legislation specifically addressing fire and smoke management as a property right has been drafted (and was enacted as of October 1, 1990.) This latter alternative is a particularly straightforward approach. In each case, however, clear and direct communication with the public concerning the role of prescribed burning and smoke managcmcnt in public land management is ncccssary.

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Chapter 590.026, Florida Statutes: Florida Prescribed Burning Act.

SPATIAL DYNAMIC FIRE BEHAVIOR SIMULATION AS AN AID TO FOREST PLANNING AND MANAGEMENT

Maria J. Vasconcelos and José M. C. Pereira'

Abstract-Mediterranean shrub communities dominate fire-prone landscapes in many parts of Portugal. It is feared that streamside anti-erosion buffers of natural shrub vegetation represent a fire hazard lo plantations of eucalyptus and other trees. The FIREMAP system, which can simulate fire behavior in spatially nonuniform environments, was used to assess the extent to which fire buffers can become main vectors of fire spread in Portuguese landscapes. FIREMAP predicted that tire will spread across landscapes consisting of Eucalyptus sp. plantations and streamside borders of natural Mediterranean vegetation much more rapidly than across landscapes consisting of Eucalyptus plantations and streamborders of planted Quercus sp.

INTRODUCTION

About 70 percent of Portugal's land area is unsuitable for agriculture. It has been suggested that these areas should be the subject of reafforestation programs (Grupo Coordcnador do Projecto Florestal 1986). Forests cover only about 36 percent of the country, so there is much room for this kind of initiatives, such as the ones recently attempted with support from organizations such as the World Bank and the European Economic Community.

Due to climatic and socio-economic factors, wildfires are a major threat to Portuguese forests. An average area of 42 000 ha burned yearly from 1973 through 1985 and in 1989 about 54 COO ha of forests werc destroyed by wildfircs.

A recent trend in Portuguese forcstry is the rapid expansion of plantations of exotic species for short rotation biomass production, for use by the paper and pulp induahies. The environmental impacts of those plantations have been a topic of heated debate, and legislation was issued regulating soil preparation and plantation and silvicultural practices, with special emphasis on minimizing soil erosion, hydrological disturbances, and loss of biological diversity.

The legislation that regulates these plantations requires that natural vegetation be lcft along stream channcls for erosion protection. The widths required depend on particular situations but are generally betwccn 20 and 60 m. Consequently, the majority of the projects generate a striped landscape where buffers of constant width indiscriminately marginate stream channels.

In this paper WC investigate thc possibility that where natural vegetation consists of Mcditcrranean-type shrubs, this landscape structure may contribute to improved fire propagation by creating paths of faster spreading fire that make otherwise unavailable fuels more likely to bum. in fact, these shrub communities bum intensely and contribute to more effective preheating of the less easily ignited fuels in the neighboring plantation forest, thus setting the stage for larger, more intense fires.

The objective of this work was to usc a PC-based spatial analysis system that simulates the spread of fire in a spatially nonuniform landscape in discrete time steps (the FIREMAP system) to assess the extent to which anti-erosion buffers along streams can become the main vector of tire propagation, or on the other hand, work as barriers to the spreading fire.

We simulated structurally simple landscapes, not only to facilitate interpretation of the results, but primarily because this corresponds to the actual spatial structure of Eucalyptus plantations.

FIREMAP

This fire spread simulation system, designed at the University of Arizona (Vasconcelos 1988), estimates tire characteristics in spatially nonuniform environments, and displays areas burned on maps. FIREMAP consists of the integration of the DIRECT module from the BEHAVE system (Andrcws 1986) with a raster-based geographic information system, the Map Analysis Package -MAP- (Tomlin 1986), and allows distributed predictions of fire characteristics and simulation of fire spread.

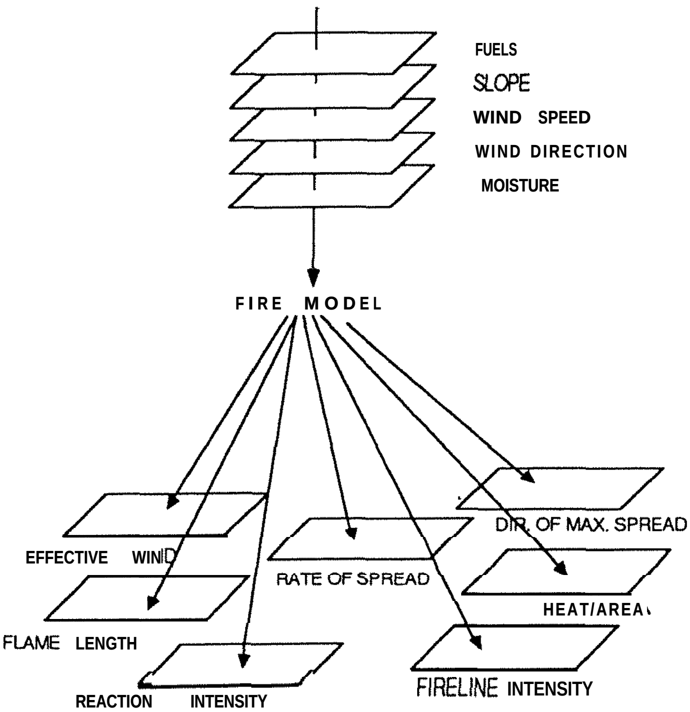
In this framework, nonuniform fuels, wcathcr, and topography data arc encoded, stored, and manipulated on thematic maps, where the field is represented as cells of a grid corresponding to uniform parcels of land. Because the homogeneity assumptions are met, Rothermel's model can be used within each unit.

The dynamic process of a spreading tire is simulated through the use of the distance functions of MAP. Distance functions deal with the measurement of weighted distances, allowing

'Forester, Centro Nacional de Informação Geográfica, Rua Braancamp, 82 1 ºD, 1200 LISBOA, Portugal; Assistant Professor, Departamento de Engenharia Florestal, ISA, Universidade Técnica de Lisboa, Tapada da Ajuda 1399 LISBOA CODEX, Portugal.

simulation of movement on a previously computed surface of "frictions". These are defined as the rate at which the fire spreads from one cell to its neighbors given the direction of the prevalent wind. The rates of spread overlay utilized depends upon weather conditions, and a new rates of spread overlay has to be utilized whenever there is a change in the weather. This is done by stopping the simulation at the end of a time step and proceeding with the spread process on a new rates of spread overlay that was calculated according to the new weather conditions.

Figure 1 illustrates how fire characteristics are computed for each cell of the data base and set of constant meteorological conditions, based on input overlays generated within MAP. These input overlays are created from the topography, vegetation, and weather data using the standard arithmetic and reclassification capabilities of MAP and the tables presented in Rothermel (1983).



APPLICATION

We ran four simulations to test fire sensitivity of four possible forest landscapes corresponding to four management alternatives for Eucalyptus sp. stands in a Mediterranean-type region. The simulations are for a 1.5 hour bum, in three 30-minute time steps, with a likely early summer weather scenario, which is summarized in table 1.

Table 1. --Weather conditions

	Temperature		Relative humidity	Wind	
	Dry	Wet		Speed[a]	Direction
	- Degrees F -		- Percent -	- Mph -	
First step	82	52	15	12	S
Second & third steps	84	51	12	12	S

[a] wind speed at midflame height

Some comments may be appropriate regarding the temporal and spatial scales we used. Under a normal weather scenario, it seems reasonable to assume constancy of temperature and relative humidity during 30 minute intervals. Windspeed and wind direction probably vary significantly at a finer time scale, and Fischer and Hardy (1972) indicate that the standard time for averaging windspeed is 10 minutes. However, Rothermel's model was designed to predict fire behavior under relatively uniform weather conditions (Rothermel, 1983), and although considerable weather changes in a 24-hour period should be expected, projection times of 2 to 4 hours, under constant meteorology are reasonable (Andrcws 1986). A more sophisticated treatment of the interactions between wind, terrain, and fire behavior will probably require expansion of the FIREMAP system to include a surface windflow model such as KRISSY (Fosberg and Sestak 1986).

Spatial resolution of the database is considered appropriate since it satisfies what we believe to be the two most important considerations. On the one hand, cell size is small enough to capture all essential landscape features and overall structure. On the other hand, the cells are large enough in comparison to average flame front depths to ensure that steady state spread conditions are almost always present (Catchpole et al. 1989).

The Digital Data Base

The digital cartographic data base corresponds to a 2280 ha area of undulating terrain. Altitudes range from 200 m to 600 m with aspect predominantly to the east, northeast, and southwest on steeper slopes. The scale is 1: 12,000 and there are 7.5 rows by 76 columns with a cell size of approximately 0.4 ha (1 acre). The data base consists of the following information layers: TOPOGRAPHY, STREAM CHANNELS, an LANDSCAPE1 , 2, 3, and 4.

The landscape maps correspond to different management alternatives for vegetation buffers along ephemeral streams in Eucalyptus plantations. LANDSCAPE1 represents a landscape of continuous Eucalyptus stands without any kind of stream buffering. LANDSCAPE2 and LANDSCAPE3 represent soil conservation alternatives favored by Portuguese environmental legislation regarding fast-growing plantation forests. In landscapes 2 and 3, natural vegetation is retained as stream side buffer strips of predetermined minimum width. Different stages of shrub development are considered in landscapes 2 and 3. Landscape 2 represents the case of having medium height evergreen sclerophyllous shrubs along the streams and landscape 3 the case of tall and dense stands of the same shrub types. In the fourth vegetation alternative (LANDSCAPE4) a more balanced and diverse landscape is considered with wider strips of deciduous Quercus sp. planted along stream banks. Figure 2 shows the stream channel pattern.

Simulation

Four sets of input maps for the fire model were generated as explained above. The FUELS overlays were created by reclassifying the vegetation types to one of the 13 standard fuel models (Anderson 1982) based on a correspondence presented in Barreto (1985). Barreto classifies most of the vegetation cover types found in Portuguese landscapes as the models included in the mentioned set of 13 models. The correspondence we used for this particular case is as follows:

Eucalyptus sp. stands- fuel model 5
Medium evergreen sclerophyllous shrub stands- fuel model 6
Tall, dense evergreen sclerophyllous shrub stands- fuel model 4
Deciduous oak stands- fuel model 9

FIREMAP generates maps with the expected fire characteristics for the 4 landscape alternatives in the 3 time steps and then simulates the spread of tire, with a given source point, for the alternatives considered. Maps of the expected flame lengths at each database cell are also provided.

RESULTS

The maps displaying the predicted areas burned and respective expected flame lengths are shown in figures 3 and 4. Table 2 shows the number of burned cells for each time step and landscape and Table 3 the number of cells in each flame length class for each of the 4 simulation scenarios.

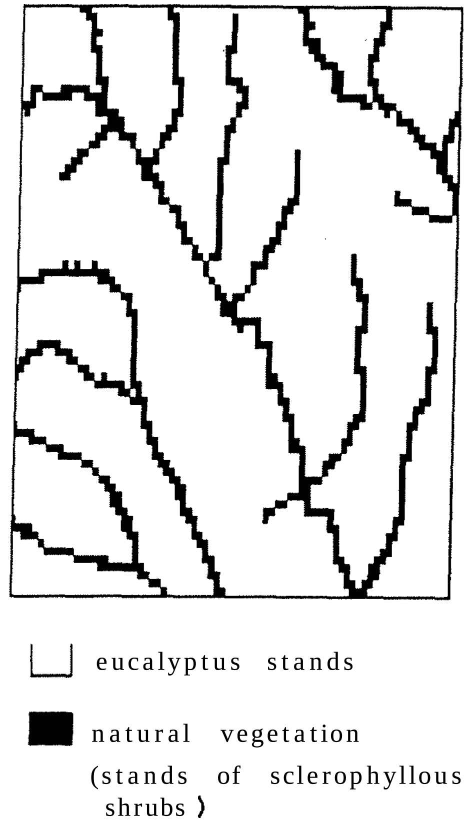


Figure 2.--The stream channels.

Table 2.--Cells burned

	1st step	2nd step	3rd step
	. . . . . . & r		________
Simulation 1	66 (26.4)[a]	81 (32.4)	48 (19.2)
Simulation 2	91 (36.4)	102 (40.8)	a2 (32.8)
Simulation 3	154 (61.6)	117 (46.8)	124 (49.6)
Simulation 4	38 (15.2)	20 (8.0)	31 (12.4)

[a] area burned, in hectares

Table 3.--Expected flame lengths

	0 - 4 feet	4-a 8 feet	- 11 feet	>11 feet
	. . . . Number of ceils			
Simulation 1	4	153	38	
Simulation 2	4	216	55	
Simulation 3	6	218	87	84
Simulation 4	16	64	9	

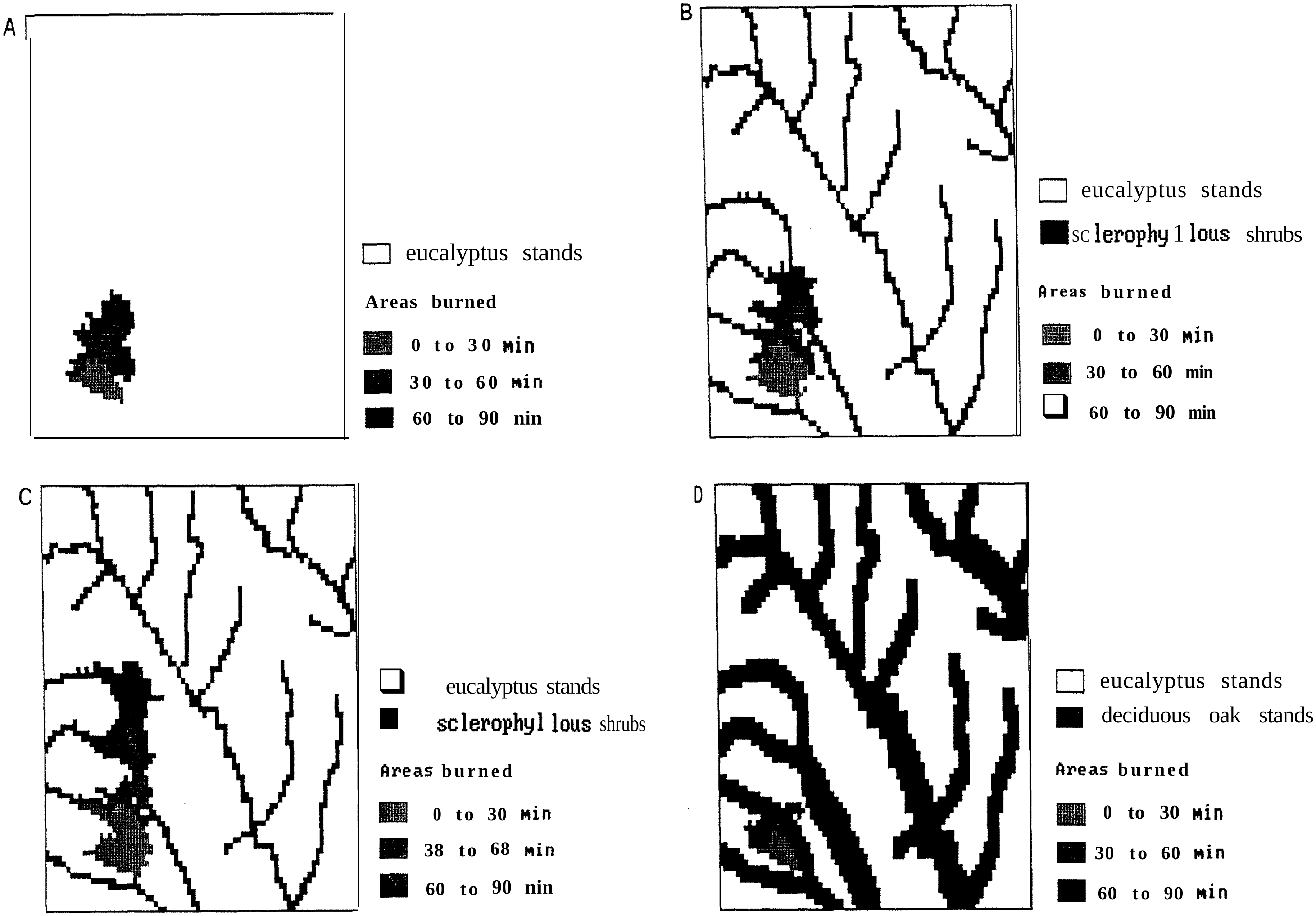


Figure 3.-Areas predicted to bum: (a) simulation 1, (b) simulation 2, (c) simulation 3, and (d) simulation 4.

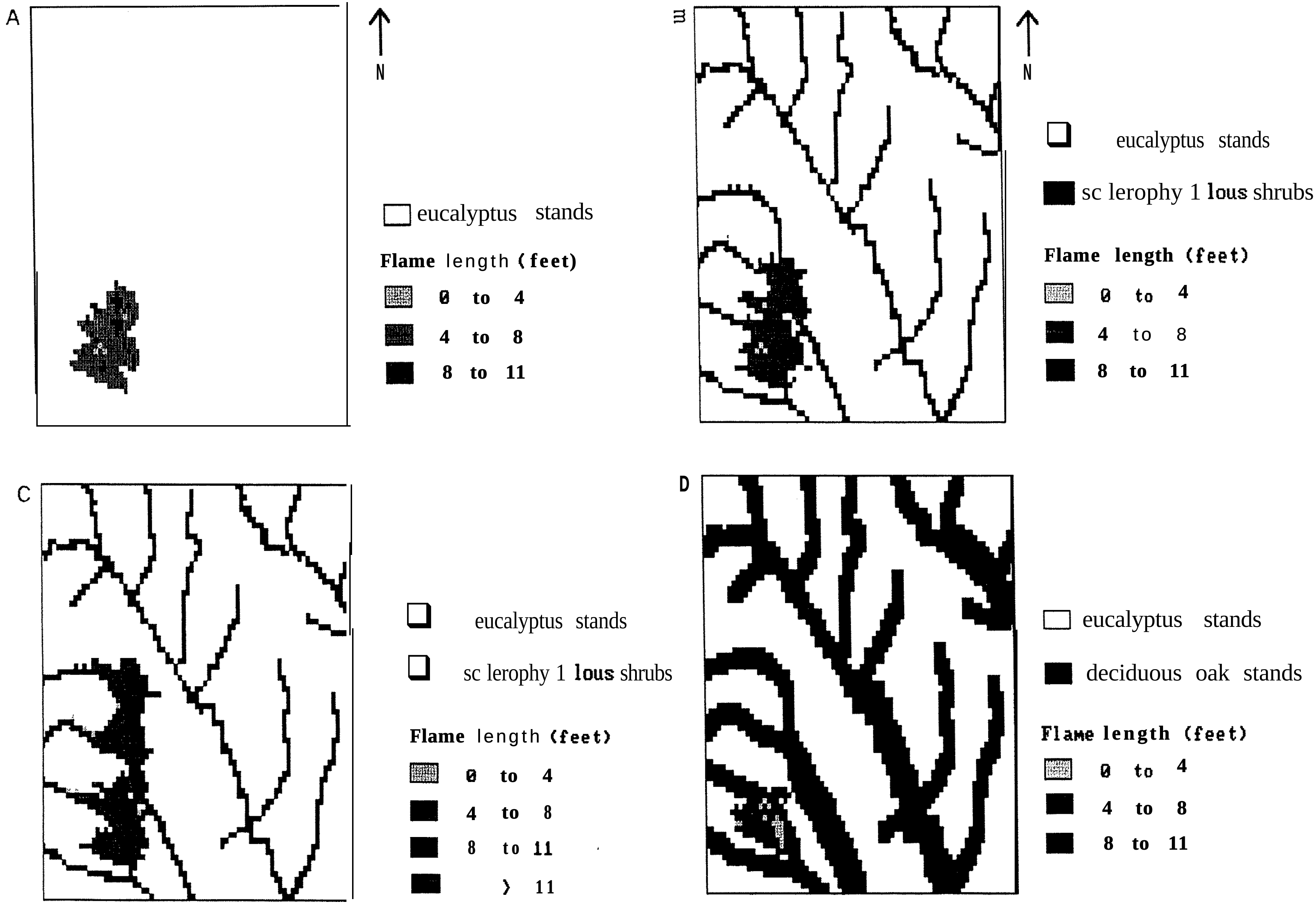


Figure 4.–Expected flame lengths: (a) simulation 1, (b) simulation 2, (c) simulation 3, and (d) simulation 4

DISCUSSION AND CONCLUSIONS

The results above indicate that under the simulation conditions, natural vegetation left along stream banks may actually contribute to increased fire problems. In fact, there was an increase of 41 and 102 percent of predicted burned area on the second and third alternatives (shrub stands along stream banks) relative to the first alternative (Eucalvntus sp. only)

The simulation outputs suggest that the striped patterns generate preferential paths for fire, creating spreading conditions that lead to higher perimeter-to-area ratios of the burning area, thus improving propagation chances by increasing the length of contact with unburned fuels. On the other hand, the deciduous oak stands have lower rates of spread and create zones of "higher friction" that retard propagation of fire to the Eucalyptus stands. There was a decrease of 46 percent of predicted burned area for this alternative when compared with the first alternative. Given the importance of convective heat transfer in deep fuelbeds such as those represented by shrub formations, a worst case scenario involving higher windspeeds would probably emphasize even more the rapid spread of fire along the stream buffers.

Landscape planning in areas of intensively managed plantation forests is a problem involving multiple, potentially conflicting objectives. Conflicts arise not only between economic production and environmental protection, but also between different ecological concerns. In the present case study, FIREMAP was used to emphasize one such conflict, between erosion protection and tire hazard, in a way that provides information about fire characteristics in a surrogate laboratory mode. These quantitative data can be integrated with other economic and environmental information to support cost-benefit or multiobjective decision analyses of forest management alternatives.

ACKNOWLEDGMENTS

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