STANDFIRE: An IFT-DSS Module for Spatially Explicit, 3D Fuel Treatment Analysis

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ABSTRACT

Managers are increasingly called upon to implement fuel treatments to alter potential fire behavior, in order to mitigate threats to firefighters and communities, or to maintain or restore healthy ecosystems. While some case studies have shown positive results, many questions remain about how effective certain kinds of fuel treatments are, how long they remain effective, and under what conditions they will work. Because real world fuel treatments are only actually tested when faced with a fire, modeling plays a key role in evaluating the potential effectiveness of fuel treatments. In the United States, most detailed, stand scale fuel treatment analysis is conducted with the Fire and Fuels Extension of the Forest Vegetation Simulator (FFE-FVS), which links tree growth models to biomass and simple fire calculations. However, assumptions of homogeneous and continuous fuels, and lack of spatial or mechanistic detail in the underlying fire modeling within FFE-FVS and other widely used fire models greatly limits their application to fuels treatments, as well as to fuel changes arising from disturbance processes such as beetle outbreaks or windthrow events. In recent years, 3D dynamic, physics-based fire behavior models have emerged which model fire with much greater detail and which can thus more robustly capture effects of fuel treatments on fire behavior. While these models have already played a key role in advancing our understanding of numerous aspects of fire behavior, they have been largely inaccessible for broader use due to the complexity involved in developing fuels inputs.

The STANDFIRE project was funded by the JFSP to develop a prototype modeling system that could link widely available fuels data from FFE-FVS to physics-based fire models, providing an alternative approach for calculating fire behavior at stand scales. The objectives of the project were: 1) to develop and analyze a new approach for stand-scale fire behavior analysis, 2) to investigate metrics for evaluating fuel treatment effectiveness and 3) to provide a new platform for fire science development. The original FON required that new systems developed would be ‘command line’ programs that could be integrated into a larger system, such as IFT-DSS.

Our project successfully developed STANDFIRE, a prototype fuel and fire modeling system. This open source software, developed in python and Java, links a forest growth model (FVS) through a state-of-the-art fuel modeling system (FuelManager) to two independent physics-based fire models, WFDS and FIRETEC. STANDFIRE brings a number of capabilities to the table, each with significant potential benefit. First, STANDFIRE provides a pathway for researchers and managers to use real world forest inventory and fuels data in dynamic, 3D fire simulations, opening up new ways to evaluate fuel treatment effectiveness. Second, STANDFIRE can be used to produce input files for both WFDS and FIRETEC using the same fuels, opening the door for collaborative interaction between these two modelling groups towards further refinement in physics-based fire modelling. Third, STANDFIRE offers a platform within which further development can be carried out, allowing testing and continuing refinement of fire modeling as time goes on. Finally, STANDFIRE makes physics-based fire modeling accessible to a much wider pool of potential users. With executables for Windows and Linux platforms and very simple beginner interfaces, less technical users will be able to carry out example simulations using the test data provided or with their own data. Meanwhile, more technical users, such as other researchers and developers, can use the open source code repository and online documentation to work collaboratively towards future science development. This open source code base is built with a strong modular programming architecture and command line operability that should make it feasible to incorporate

STANDFIRE into larger systems. In 2016, two journal articles were published in peer reviewed journals. The first peer reviewed paper, *Pimont et al 2016. Environmental Modelling & Software, 80, pp.225-244.,* details the FuelManager software, a key component in STANDFIRE. STANDFIRE builds on FuelManager, extending its application to a large number of US forest species through links with FVS, and by connecting it to the WFDS fire model. The second paper, *Jolly et al 2016. Forest Ecology and Management 373 (2016): 167-178.,* represents fundamental science work linking shifts in live fuel moisture and chemical composition to flammability and fire through bench scale experiments and physics-based simulation modeling at stand scales carried out with the FIRETEC model.

Background and Purpose

Forests across the country are challenged on multiple fronts, with overgrown conditions, increasing insect epidemics, climate-change induced drought and longer and more intense fire seasons. In this context, fuel treatments are increasingly viewed as essential management actions for mitigating the risk of catastrophic fires, restoring ecosystems and increasing their resilience to future situations. However, planning effective fuel treatments poses unique challenges. First, despite the widespread application of fuel treatments, there are few opportunities to directly assess fuel treatment effectiveness in terms of their impacts on mitigating a wildfire (Omi and Martinson 2009). Second, unlike responding to a wildfire, where the weather conditions are known and the scope of action is immediate, fuel treatments must be carried out in advance of a future fire which will burn under unknown conditions. Fuel treatments can also modify forest structure and composition for many years. The uncertainties and potential tradeoffs that arise from this longer term time frame are challenging to assess directly, making modeling-based evaluation efforts a key analysis approach.

The Fire and Fuels Extension to the Forest Vegetation Simulator (FFE-FVS, Reinhardt and Crookston 2003) is the most common framework currently used to evaluate fuel treatments or to examine how other forest changes affect fire. This modeling system links the Forest Vegetation Simulator (Dixon 2002, Crookston and Dixon 2005), an empirical forest growth model with geographic variants characterizing species and growth relationships for different regions in the US, to a series of simple fire models representing different aspects of wildland fire behavior (Rothermel 1972, Van Wagner 1977, Rothermel 1991, Scott and Reinhardt 2001) and effects (Reinhardt et al 1997). FFE-FVS models quite a lot of detail in forest fuels, such as the biomass in individual tree crowns, and accumulation of surface fuels over time. However, at present, much of this detail cannot be used to full advantage because the fire modeling within FFE-FVS cannot accommodate such information. For example, surface fuels data are not used directly but are instead used to select predefined fire behavior fuel models (Anderson 1982, Scott and Burgan 2005). Similarly, despite the detail in FFE-FVS characterizing the vertical structure, species composition, and individual tree biomass elements in the stand, current fire behavior calculations are based entirely on a handful of summarized values such as overall stand canopy bulk density, crown base height, and the surface fire predicted using the predefined fire behavior fuel models parameters. The outcome of these calculations, typically measured with the Torching and Crowning Indices (Scott and Reinhardt 2001), often provide highly questionable results, such as unrealistically high wind speeds required to sustain a crown fire (Cruz and Alexander 2010). In many cases, modeled outcomes show relatively low sensitivity, in terms of changes in predicted fire behavior, between treated and untreated cases, particularly with respect to changes in surface fuels (Johnson et al 2011).

The bulk of these issues arise not from the fuels data but from the fire modeling approach (Cruz and Alexander 2010), and underline the need for developing alternative approaches for fire behavior calculations in the context of fuel treatment analysis.

Over the last several years, physics-based fire behavior models such as HIGRAD/FIRETEC (Linn et al 2005) and WFDS (Mell et al 2009) have had an increasingly important role in improving our understanding of wildland fire, and particularly with respect to how different aspects of wildland fuels affect fire behavior. These models employ computational fluid dynamics (CFD) approaches, which solve partial differential equations for conservation of mass, energy, and momentum to simulate the dynamic spread of fire and its interactions with the atmosphere, vegetation, and topography at fine spatial and temporal scales. The much higher resolution with which these models operate enables them to consider the effects of heterogeneous and discontinuous fuels. Recent work with these models has explored various aspects of fine scale heterogeneity (Parsons et al 2011), stand scale heterogeneity (Pimont et al 2011), beetle killed trees and fire (Hoffman et al 2012, Hoffman et al 2015), fire in discontinuous pinyon-juniper fuels (Linn et al 2013), as well as providing new understanding of critical fire/atmosphere interactions (Cunningham et al 2005, Canfield et al 2014). Although these models are in active development and will doubtless undergo further refinement as time goes on, validation studies have shown very good agreement in a number of aspects, including tree scale experimental fires (Mell et al 2009), field burns in grass fuels (Linn et al 2005, Mell et al 2007), wind field dynamics (Pimont et al 2009), and validation against detailed flux tower fire measurements in experiments (Dupuy et al 2014). Of particular relevance is a recent study comparing physics-based fire model simulations against observed crown fires. This study demonstrated that these models performed very well, with 86% of simulated crown fire rates of spread falling within the 95% prediction interval of the empirical data (Hoffman et al 2016), considerably better than the simpler fire models in FFE-FVS and other systems (Cruz and Alexander 2010). The successes of these models in a range of fuels and with crown fire suggest that they can bring useful perspectives to fuel treatment analysis at stand scales.

The STANDFIRE project was established to meet this need, providing a link between current systems used in fuel treatment analysis (FFE-FVS) and advanced physics-based fire models. An additional objective was to carry out fundamental research examining fire behavior at stand scales.

Overview of the STANDFIRE modeling platform

The STANDFIRE software is documented in a General Technical Report, and is available for download through the JFSP project page, along with example simulation output data which the user can view interactively with the Smokeview software, provided with the STANDFIRE software. Open source computer code and online source documentation is provided as well. As these other venues provide more in depth description, we only briefly describe STANDFIRE here.

STANDFIRE is comprise of three main parts: fuel modeling, fire modeling, and post-processing, to analyze fire simulation outputs. The fire models in STANDFIRE were developed by other institutions; STANDFIRE simply gets data into the fire models, and then deals with the outputs. Within each part there are at least two component parts. **Figure 1** shows a flow chart of the parts and components in STANDFIRE; blue boxes show labels for the main parts.

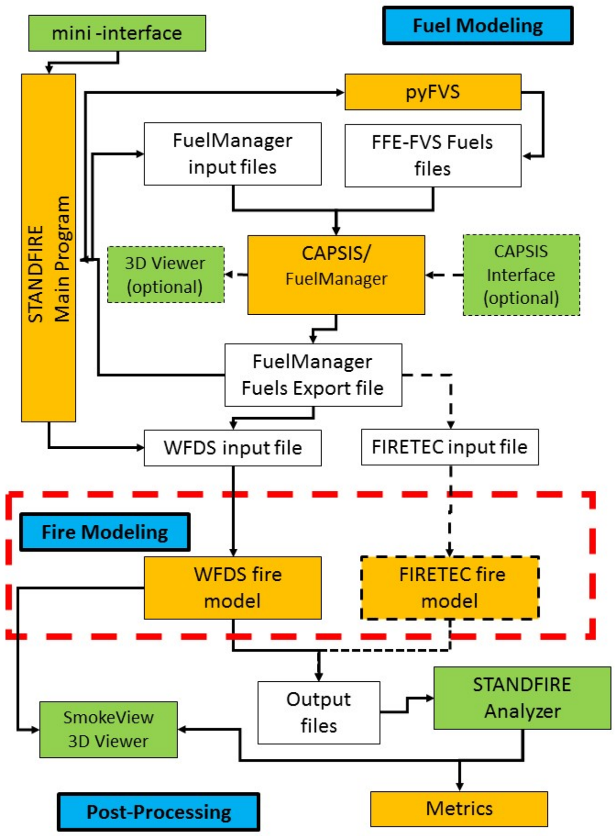

Figure 2. Flow chart of the STANDFIRE prototype 3D fuel and fire modeling platform. Blue boxes identify main parts, orange boxes identify models, and green boxes are interfaces. White boxes are files.

A thick dashed red line box surrounds the fire modeling part of STANDFIRE. Within the subsystems, light green boxes represent interfaces, light orange boxes represent models, and white boxes represent text files. The first part of STANDFIRE deals with fuel modeling, and is the heart of STANDFIRE, and is the most complex, sub-system, preparing 3D fuels data to be used as input for the physics based fire models, and includes several components. Fire modeling in STANDFIRE fire consists of two different, independent, physics-based fire models: HIGRAD/FIRETEC, developed at the Los Alamos National Lab, and the Wildland Urban Interface Fire Dynamics Simulator (WFDS), developed by the National Institute of Standards and Technology (NIST) and the US Forest Service Pacific Northwest Research Station. The third and final part of STANDFIRE post-processes simulation output. At present, post processing is only provided for output for the WFDS physics-based fire model. STANDFIRE includes Smokeview, an interactive 3D viewing program that works with output from the WFDS model, as well as a very simple interface called STANDFIRE_analyzer, which demonstrates some fire behavior outputs calculated from WFDS output.

STANDFIRE makes it possible to run physics-based fire simulations using fuels data from FFE-FVS. **Figure 2** shows an example 3D fire simulation, made with the physics-based fire model WFDS, using fuels data and inputs assembled using the STANDFIRE system, at two points in time. The red rectangle indicates the area where the fire started from, and the fire can be seen as it burns though the 3D vegetation.

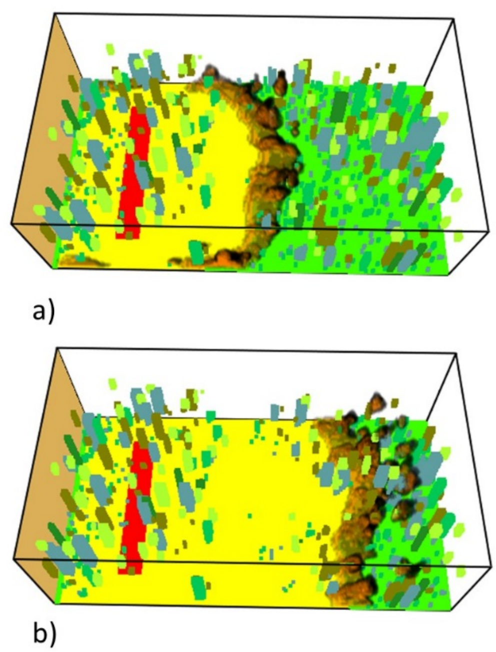

Figure 1. Example physics based fire simulation at two points in time.

Study Description and Location

The STANDFIRE project was primarily focused on the development of the STANDFIRE software platform so field data collection was not a major component of this project; there is no specific study site associated with this project. However, fuels data from a few different locations played a role in this project.

A key component within STANDFIRE is the FuelManager software. This software has been in development for a few years as part of a larger effort of the large scale European Union collaborative project, Fire Paradox (http://www.fireparadox.org/fuel_manager.php). In 2016, led by Francois Pimont, we published a paper (Pimont et al. 2016) describing this software and a number of applications carried out with FuelManager. These applications drew upon fuels data from several locations. The first site from which fuels data were used is FluxFire field experiment, a heavily instrumented grass fire experiment located in Galveston County in Texas. This site is characterized by tall grass prairie species, described in detail in Clements et al 2007. FuelManager was used to build fuels inputs for a validation study comparing FIRETEC simulation output with flux tower measurements (Dupuy et al 2014). The second site from which fuels data were used with FuelManager was a site in the Northwest Territories where the International Crown Fire Modeling Experiment (ICFME) project was carried out (Stocks et al 2004, Alexander et al 2004). This forested site was characterized by jack pine (Pinus banksiana Lamb.) with a minor black spruce (Picea mariana) component. FuelManager was used to develop fuels inputs to the FIRETEC physics-based fire model based on data collected in the ICFME experiment. The third site in which fuels data were used with FuelManager was 40m x 40m plantation dominated by Aleppo pine (*Pinus halepensis*) and Stone pine (*Pinus pinea* L.) near Avignon, France. These three sites, comprising very different fuel types and ecosystems, demonstrate the flexibility of FuelManager for modeling diverse fuels. STANDFIRE builds on the capabilities of FuelManager, extending its application to US species through links to FFE-FVS, and by linking it to the Wildland Urban Interface Fire Dynamics Simulator (WFDS), a physics-based fire model.

An additional objective of our project was to contribute to fundamental research. Towards this aim, our project carried out physics-based fire simulation modeling in support of a project, led by Dr. Matt Jolly, incorporating field fuels sampling and laboratory experiments to examine seasonal changes in flammability in red pine (*Pinus resinosa*) and jack pine (*Pinus banksiana*) foliage. Dr Jolly's project had been initiated independently of the STANDFIRE effort. The STANDFIRE project added value to this study, extending analysis to stand scale fire through simulation modeling. Two sampling sites in Dr. Jolly's study were located within a kilometer of each other in central Wisconsin, USA, approximately 10 miles from Wisconsin Rapids, at elevations of 265m (873 ft) and on generally flat terrain. Field sampling involved weekly collection of foliar samples, from 10-12 trees, in sealed containers. Samples were separated by species and foliar age class, and were divided into subsets for subsequent laboratory measurements examining chemical composition, physical properties and ignitability. This work was published in 2016 (Jolly et al 2016).

Key Findings

The development of the STANDFIRE prototype modeling platform represents a substantial step forward in terms of fuel modeling, representing wildland fuels in the United States with more detail than has been possible before. Rather than representing canopy fuels inputs to fire models as single, stand level values of canopy height, canopy cover, canopy base height and canopy bulk density, STANDFIRE represents forests as collections of individual trees with their own attributes, taking advantage of all the detail provided by forest inventory and associated modeled outputs from FVS. STANDFIRE also provides a new set of capabilities for addressing surface fuel heterogeneity, allowing the representation of fuels that are discontinuous and/or overlapping; important heterogeneities, such as mixes of live and dead components within the same fuel type (i.e. grass or shrub) can be represented as well. Surface fuel heterogeneity is ubiquitous (Keane et al 2012) and often highly significant to fire behavior and effects (Hiers et al 2009) but largely has not been possible to address in most fire modeling systems due to their underlying limitations (Johnson et al 2011, McHugh 2006). These enhanced capabilities for representing wildland fuels more realistically will enable researchers and managers to take better advantage of the data they collect in the field.

The STANDFIRE modeling platform advances fire modeling capabilities as well by making state of the art physic-based fire models accessible to a much larger potential user community. Fire modeling systems used operationally are based primarily on the Rothermel surface fire spread model (Rothermel 1972). STANDFIRE is the first system developed in the US that makes it possible to use an entirely different fire modeling basis, connecting fuels data from FFE-FVS to two distinct and independent physics-based fire models, WFDS and FIRETEC. There are a number of ways in which modeling forests as individual trees has important implications for the outcomes of fire simulations. First, similar to real fires, the location and geometry of trees can affect how a fire burns through them, so differences in stand structure can greatly affect fire behavior. Similarly, differences between species, or in tree health/vigor (i.e., live, unhealthy or dead) can result in significant differences in flammability (Jolly et al 2012 a, Jolly et al 2012 b) which can translate to fundamentally different fire behavior at stand scales (Jolly et al 2016). The capacity to model fuels with higher detail thus makes fire behavior simulations sensitive to species composition and disturbed fuel conditions such as the presence of beetle killed trees (Hoffman et al 2015).

Our project contributed to a fundamental research investigation examining seasonal variations in foliar chemical and moisture content. This study, led by Dr. Matt Jolly, provided a coherent explanation for a phenomenon that had been observed, but poorly understood for many years. For several decades, managers and researchers have been aware of the spring dip effect, in which foliar moisture content is observed to drop for a period of a few weeks in the springtime. This period often coincided with time periods in which more intense fire behavior was often possible, including crown fires. Conventional thinking over this time suggested that the increase in potential fire behavior during this period was simply due to a drop in live foliar moisture content. However, there was little understanding of the underlying mechanisms behind this shift. Dr. Jolly's field and lab work clarified that the apparent drop in moisture content was, in fact, driven by profound and rapid shifts, not only in moisture content, but also in chemical composition, and increases in foliar density, associated with the accumulation of carbon resources within the tree before those resources are translocated from older needles to newer needles.

Stand scale physics-based fire simulations with FIRETEC examining this fuel change illustrated very significant effects. For the lowest canopy density and wind speed scenario, simulated fires in dormant condition stands did not propagate as crown fires. However, for the same conditions, spring dip stands successfully spread as crown fires as a result of the higher potential energy content of the canopy. Simulated wildland fire spread rates increased by as much as 63%, nominal fireline width increased by as much as 89% and active fire area more than doubled relative to dormant season fuel conditions. The most significant changes were observed in areas with low canopy cover and low within-tree bulk density. This ground-breaking study demonstrated coherently the importance of plant physiology to wildland fire science, linking fine scale fuel properties to larger scale wildland fire behavior.

Management Implications

As a software platform, STANDFIRE is different from most JFSP funded studies, which tend to focus on a specific data set which can be summarized to provide specific management implications. STANDFIRE does not have immediate answers that translate directly to clearer directions for management. However, STANDFIRE provides many new capabilities that will likely have significant management implications as time goes on, and we use STANDFIRE to learn more about fuel and fire interactions.

In analyzing fuel treatments, fire modeling plays an important role in giving us quantitative measures that are often used as a diagnostic. For example, in many studies, changes in the Torching and Crowning Indices (Scott and Reinhardt 2001) between treated and untreated cases are used as a metric of improvement. While fire models will likely continue to be useful as diagnostic tools, at present, the lack of spatial detail or heterogeneity in current fire modeling approaches makes it difficult to assess the potential impacts of many aspects of fuel treatments, or fuel changes arising from other disturbances. For example, managers face significant challenges anticipating how fire behavior will change in the millions of acres that have been affected by beetle kill. The limitations of current fire modeling approaches in these situations are known (Jolly et al 2012 b), but there has not been an available alternative fire modeling approach. By addressing fuel heterogeneity more explicitly, and by providing a number of different quantitative measures characterizing fire behavior changes, STANDFIRE changes the dialogue about how we measure fuel treatment effectiveness. STANDFIRE is not intended to replace the FFE-FVS model, but rather, to extend it, offering a more detailed “second opinion” in terms of diagnosing how fuel changes will translate to fire changes.

One of the immediate benefits that STANDFIRE brings is the capability to represent surface fuels with realistic heterogeneity. Shrub, grass/herb and litter fuelbed characteristics can be entered in seconds with a simple interface. This interface permits characterization of these fuel components in basic, directly measurable quantities, such as height, fuel load, moisture content and percent cover. Dead or cured components of shrub and grass/herb fuels are modeled independently of live components, offering a simple but powerful representation of surface fuels that has not been available before. As understory fuels and their characteristics are a known weakness of FVS, this capability will help managers anticipate fire behavior in prescribed burn planning or in risk assessments.

The research study examining the spring dip effect, led by Matt Jolly, has significant implications for both prescribed and wildfire management. First, the stand scale fire simulations with the physics-based fire model, FIRETEC, illustrate the significant changes in fire behavior that can occur with spring dip conditions. Our simulations spanned a range of forest densities and wind speeds. We found the most significant effects under marginal conditions; at the lowest wind speed and lowest within-tree bulk densities, spring dip conditions turned surface fires to crown fires. Differences were less noticeable for higher wind speed and higher canopy mass scenarios. By linking plant physiology to crown fire phenomenology, this work represents an important step forward in improving our understanding of the complex drivers of crown fire behavior.

Relationship to other recent findings and ongoing work on this topic

Development of the STANDFIRE system relates to several other ongoing developments. STANDFIRE is directly relevant to fuel treatment planning, assessment and analysis. Over the last few years, a strong management need for better science for fuel treatment analysis has driven a rapid expansion of new tools intended to help managers design and analyze fuel treatments. These tools include ArcFuels (Ager et al 2006), the Inter-Agency Fuel Treatment Decision Support System (IFT-DSS), and an expanded set of capabilities using FLAMMAP (Ager et al 2010). STANDFIRE plays an important role in the context of these other systems in that it is the only tool that provides new capabilities for examining effects of fuel treatments at the stand scale. Without discounting the value of understanding fuel treatments at landscape scales, there is much to be said for building a more robust understanding of fuel treatments at the greater detail of the stand scales. This is particularly true when considering that fuel treatments often result in changes in stand structure and composition that can have tangible and lasting effects not only on fire behavior, but on habitat, carbon, hydrology and numerous other ecosystem functions. Many of these aspects are not represented well in current systems at landscape scales. There is, thus, a need to more closely connect our understanding of processes at stand scales to the larger landscape. STANDFIRE can play a role in improving that understanding.

STANDFIRE is also directly relevant to ongoing and future coordinated research fires, where multiple research teams examine fuels, fire, meteorology, smoke and fire physics. The FuelManager paper (Pimont et al 2016) describes the application of FuelManager, a key component in STANDFIRE, to such fire experiments in Texas, Canada and France, using the FIRETEC physics-based fire model. STANDFIRE builds upon the capabilities of FuelManager, greatly broadening the range of fuels that can be modelled through incorporation of biomass from FVS, and including an additional physics-based fire model, WFDS. This offers much potential for aiding future coordinated fire experiments, providing a useful platform in which field data from such efforts can be incorporated into simulations for testing fire models. Physics-based models can also provide critical guidance as to how such experiments can be optimized, such as how wind measurements should be made (Linn et al 2012, Pimont et al 2017).

A key design criteria of STANDFIRE was that it be built in such a way that it could potentially be incorporated into larger systems such as ArcFuels or IFT-DSS. This capability is carried out through a modular programming design, de-coupling of the main code from graphical interfaces and by using file I/O interactions to pass information between different models rather than forcing the different models into the same code. These aspects of STANDFIRE ensure that it could be built into a larger system if desired.

The fundamental science work carried out by Matt Jolly, examining the spring dip effect, is an important piece in the growing body of new science examining wildland fuels from a plant physiological perspective. This body of work has significant potential to help us navigate the complexities of a world increasingly affected by climate change, where climate changed drought will likely increase forest mortality (Allen et al 2015), as well as changing the timing, intensity and duration of the fire season (Westerling et al 2006). As plant phenology is affected by climate, these changes may also impact the timing of the spring dip.

Future work needed

STANDFIRE is fully functional; all the models and components within it work. With their own FVS data as inputs, users can run a physics-based fire simulation and view the output interactively with the Smokeview software. Instructions for getting started with the STANDFIRE fuel and fire modeling system are provided in the General Technical Report. While the physics-based fire models in STANDFIRE have been in existence for several years, this is the first time they are made available, with a system to build wildland fuels data inputs. The STANDFIRE platform brings, for the first time in many years, an entirely different kind of fire behavior modeling to the wildland fire community than what has been available.

That said, it is very important to understand that STANDFIRE is a **prototype platform.** In our view, it should not be considered as “finished”, but rather, as a work in progress. In the past, it has been a fairly common practice for models that have not been fully vetted to be rapidly developed into applications for management use, often creating problems further down the line (Alexander and Cruz 2013). The issues that have arisen in this regard have been significant, probably slowing down the progression of new wildland fire science. In making a software platform that incorporates advanced models that are themselves, still active works in progress, our intent is not to repeat this same problem, but rather, to provide a path by which advancement can be made systematically. We fully support the need for continuing testing and evaluation of physics-based fire models. We expect that as time goes on, the physics-based fire models will continue to be refined. Our vision for STANDFIRE is that it should constantly be growing and changing over time, as well, connecting new fuel and fire science components as time goes on.

Toward that end, we envision STANDFIRE as a collaborative platform in which different research groups can work together on different components. There are several areas where we hope to work together with expanding groups of partners:

AREAS FOR COLLABORATION IN 3D FUELS AND FIRE

1. ***Metrics*** – STANDFIRE currently includes a series of post-processing algorithms to summarize complex physics-based simulation outputs for canopy fuel consumption, surface fire rate of spread, wind profiles, and heat release from canopy fuels. These metrics at present should be considered as “first cut” versions and will likely become more refined over time. There is a need for a much larger set of metrics, describing the fuels and fire in different ways. We look forward to collaborating with other research teams to develop robust metrics for a number of purposes.
2. ***Sensitivity Analysis and Standards Development*** – There are numerous aspects of setting up physics-based fire model simulations where how things are set up can affect the outcomes. To arrive at robust and broadly applicable standards, there is a need for sensitivity analysis, examining model resolution, windfield representation, boundary conditions etc. These aspects

often make it difficult to directly compare different simulations, even if they were carried out with the same model. There is a need to establish some norms and conventions that people can then cite and use to provide a greater degree of coherence and standardization between different model groups, similar to standards used among the global climate modeling community.

3. ***Fire Modeling*** – STANDFIRE provides fuels inputs to both WFDS and FIRETEC, facilitating the potential for comparative analysis across models. The modular design of STANDFIRE should permit inclusion of additional fire behavior models within this same system.
4. ***Fuels Characteristics*** – Physics modeling opens up new possibilities for how we think about, and measure wildland fuels. We have only scratched the surface so far in terms of the potential of new fuels science work can improve our understanding of wildland fire. Much more work is needed. The fundamental science work carried out by Matt Jolly, and supported in part by the STANDFIRE project, is an excellent example of how improved understanding of fuels properties can translate to significant new understanding in wildfire behavior.
5. ***Fuel Parameterization*** – STANDFIRE facilitates modeling of a large number of species in the United States through incorporation of FVS. Numerous species in Europe are also parameterized within the FuelManager software (a key component within STANDFIRE). However, there are many other areas in the world where fuels data are not yet parameterized for use in fire modeling. The flexible and powerful fuel modeling in STANDFIRE/FuelManager presents an opportunity to collaborate with fuels researchers in other countries and include their fuels as well.
6. ***Fuels Sampling*** – The three dimensional fuels represented within STANDFIRE offer an opportunity to test new fuels sampling approaches in a simulation environment. Simulation studies have proved extremely valuable to sensitivity analyses of sample size and for comparing methodologies.
7. ***Disturbance Interactions*** – Many natural or human caused disturbances change fuels, with potential consequences for fire behavior. Beetle killed forest are simply one example. There is a need to build new disturbance models to act upon the 3D forests modeled in STANDFIRE.
8. ***Microclimate modeling*** – Fuel treatments and other disturbances alter numerous aspects of forest environments, including solar radiation, interception, to name a few. There is a need to incorporate modeling of these processes to evaluate interactions with fire.

In all of these topic areas, we encourage other researchers and developers to contact us regarding possible collaborations. We are, of course, also open to collaborations in other themes.

PLANNED MODIFICATIONS

In addition to the themes above, where we envision collaborative work, there are several modifications we plan to incorporate in STANDFIRE on the nearer term.

1. ***Incorporation of Spatially explicit input data*** -- At present, as a first step prototype, STANDFIRE is designed to operate on the simplest possible inputs: an FVS key file and forest inventory data. As the vast majority of FVS users do not have data which include spatial coordinates, STANDFIRE builds the coordinates for trees using the SVS visualization stand output from the FVS system; this area is augmented to a larger area using statistical modeling. This enables STANDFIRE to use 3D forests that are built from the FVS-SVS data without requiring the user to have stem mapped

data. However, in recent years there has been increasing interest in the spatial pattern of forests and of treatment alternatives. We hope to build new capabilities in STANDFIRE to accommodate spatially explicit inputs, such as stem mapped research plots.

2. ***Topography*** – For simplicity, STANDFIRE does not at present include topography. However, topography is, of course, a primary factor in wildland fire behavior, and likely affects fuel treatment effectiveness. We hope to add topography to STANDFIRE soon.

Deliverables Crosswalk Table

Deliverable	Description	Status
Computer model/ software/ algorithm	STANDFIRE prototype fuel and fire modeling platform	**Complete:** links to downloadable zip file with executable working model, downloadable zip file with example simulation input and output data, links to open source code repository, and online documentation provided on JFSP project deliverables page.
Refereed publication	Pimont, F., Parsons, R., Rigolot, E., de Coligny, F., Dupuy, J-L., Dreyfus, P., and Linn, R. R. 2016. Modeling fuels and fire effects in 3D: model description and applications. *Environmental Modelling & Software* 80: 225-244.	**Complete:** published in peer reviewed journal 2016
Refereed publication	Jolly, W.M., Hintz, J., Linn, R. R., Kropp, R. C., Conrad, E. T., Parsons, R. A., and Winterkamp, J. 2016. Seasonal variations in red pine (Pinus resinosa) and jack pine (Pinus banksiana) foliar physio-chemistry and their potential influence on stand-scale wildland fire behavior. *Forest Ecology and Management* 373: 167-178.	**Complete:** published in peer reviewed journal 2016
Non- refereed publication (General Technical Report)	USFS General Technical Report documenting the module, its development and applications for management.	**Complete**: Draft uploaded to JFSP project page.
Dataset	All data generated as model inputs as well as data used in project analysis will be made	**Complete:** Input data and output data for example simulation are archived and downloadable (see software deliverable above).

	available the Forest Service R&D data archive.	
Website	Project website	**Complete**: http://www.fs.fed.us/rmrs/projects/evaluating-fuel-treatment-effectiveness-stand-scales-using-standfire
Workshop	Workshop with managers. (see note 1 below)	**Complete**: Workshop put together at AFE/IAWF Large Wildland Fires Conference, Missoula, MT, May 2014

Notes:

1. In the original proposal, we proposed to carry out three workshops, to ensure that manager's needs were met and that they were involved in the development of STANDFIRE. Subsequent emails with the JFSP leadership reduced this deliverable to a single workshop, and requested that the purpose of the workshop be to solicit ideas from managers regarding their views on fuel treatment analysis. Toward this aim, we carried out an interactive exercise as a workshop during the AFE/IAWF Large Wildland Fires conference in Missoula, MT in May 2014, with the support of the Northern Rockies Fire Science Consortium.

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