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Modeling thinning effects on fire behavior with STANDFIRE

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Abstract

• ***Key message*** **We describe a modeling system that enables detailed, 3D fire simulations in forest fuels. Using data from three sites, we analyze thinning fuel treatments on fire behavior and fire effects and compare outputs with a more commonly used model**.

• ***Context*** Thinning is considered useful in altering fire behavior, reducing fire severity, and restoring resilient ecosystems. Yet, few tools currently exist that enable detailed analysis of such efforts.

• ***Aims*** The study aims to describe and demonstrate a new modeling system. A second goal is to put its capabilities in context of previous work through comparisons with established models.

• ***Methods*** The modeling system, built in Python and Java, uses data from a widely used forest model to develop spatially explicit fuel inputs to two 3D physics-based fire models. Using forest data from three sites in Montana, USA, we explore effects of thinning on fire behavior and fire effects and compare model outputs.

• ***Results*** The study demonstrates new capabilities in assessing fire behavior and fire effects changes from thinning. While both models showed some increases in fire behavior relating to higher winds within the stand following thinning, results were quite different in terms of tree mortality. These different outcomes illustrate the need for continuing refinement of decision support tools for forest management.

• ***Conclusion*** This system enables researchers and managers to use measured forest fuel data in dynamic, 3D fire simulations, improving capabilities for quantitative assessment of fuel treatments, and facilitating further refinement in physics-based fire modeling.

Keywords Fuel treatments · Fire behavior · Modeling · Physics-based · WFDS · FIRETEC · FuelManager

1 Introduction

Fuel treatments, such as thinning, are intended to limit catastrophic fires (Covington and Moore 1994), increase ecosystem resilience to future disturbances (Crotteau et al. 2016; Hood et al. 2016), and to aid fire management efforts (Moghaddas and Craggs 2007). Attaining these goals, as well as potential impacts of fuel treatments to forest structure and composition (Clyatt et al. 2017), hydrologic regimes (Jones et al. 2017) and other ecosystem processes such as carbon storage (North and Hurteau 2011) motivate an interest in assessing their performance. While empirical evidence suggests that fuel treatments are often successful in achieving ecological objectives, the degree of success is dependent on many factors, and understanding remains limited in many areas (Omi and Martinson 2010; Kalies and Kent 2016). Both pre-treatment stand conditions and the nature of the treatments can affect outcomes, and uncertainty in the conditions under which a fire may burn through a treatment makes direct measurements challenging (Omi and Martinson 2010; Kalies and Kent 2016). An additional complicating factor is time: effectiveness tends to decrease as fuels change over time (Stephens et al. 2012). As managers need to

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prescribe treatments to meet multiple objectives and account for these uncertainties and potential tradeoffs over the long term, modeling-based analyses play an important role in evaluating fuel treatments (Jiménez et al. 2016; Cary et al. 2017; Cruz and Alexander 2017).

In the USA, forest managers commonly use the Fire and Fuels Extension (FFE) to the Forest Vegetation Simulator (FVS), (Reinhardt and Crookston 2003) to evaluate different stand management scenarios and their subsequent fire behavior (e.g., rate of spread, Torching Index) and fire effects (tree mortality). FVS is an empirical forest growth model (Crookston and Dixon 2005) that simulates forest dynamics and tree growth over time. FFE calculates individual tree biomass and other fuel inputs used in current models for surface and crown fire spread (Rothermel 1972; Rothermel 1991), crown fire initiation (VanWagner 1977), and fire effects (Reinhardt et al. 1997). However, much of the detailed fuel data in FFE-FVS cannot be used in these simple models as their underlying assumptions of fuel homogeneity and continuity preclude such consideration. Instead, surface fuels are represented with predefined fire behavior fuel models (FBFMs) or sets of parameters (Anderson 1982; Scott and Burgan 2005), and individual tree-level data is reduced to a few single values representing stand attributes. These simplifications often result in low sensitivity to fuel changes (Johnson et al. 2011; Noonan-Wright et al. 2014), inconsistent results (Fernandes 2009), and under-prediction of both crown fire occurrence and spread rates (Cruz and Alexander 2010). These issues limit the utility and reliability of fuel treatment analysis and suggest the need for development of alternative approaches which might improve fire behavior calculations for fuel treatment analysis.

Over the last several years, new physics-based fire behavior models such as HIGRAD/FIRETEC (Linn et al. 2005) and the Wildland-Urban Interface Fire Dynamics Simulator (WFDS) (Mell et al. 2009) have emerged that represent fuels and fire behavior with much greater detail. For brevity, more information on the nature, applications, and current state of these models is provided in the Supplementary Materials (SM). These models dynamically simulate fire spread within a forest stand; in this context, individual tree attributes and spatial relationships play a key role in how fire interacts with the fuels. This capacity enables detailed examination of the impacts of fuel heterogeneity on fire behavior (Pimont et al. 2009; Parsons et al. 2011; Pimont et al. 2011; Linn et al. 2013; Parsons et al. 2017; Ziegler et al. 2017) and provides an opportunity to assess fuel treatment effects outside the constraints of stand level summaries as inputs.

While the complexity of the physics-based fire models has been a barrier to their use, Pimont et al. (2016)'s recent development of a modeling system, called FuelManager, opens new possibilities. Implemented in the CAPSIS platform (Dufour-Kowalski et al. 2012), FuelManager provides a robust conceptual and computer science basis for three-dimensional (3D) fuel modeling, enabling generation of input data for physics-based models from field data; applications to date have focused on ecosystems in Europe. Here, we extend this system to ecosystems in the USA by incorporating fuel data from FFE-FVS and components of FuelManager together in a fuel and fire modeling system, called STANDFIRE, with two objectives. We first describe this system and illustrate some of its capabilities with example simulations developed with forest data from three sites in western Montana, exploring effects of thinning on fire behavior and fire effects. Second, to put its capabilities in context of previous work, we compare simulation output from STANDFIRE with that of FFE-FVS.

2 Material and methods

2.1 Model overview

STANDFIRE is a modeling system with four components (Fig. 1): (1) FFE-FVS, which simulates forest growth and fuel properties in a wide range of US ecosystems; (2) STANDFUELS, a CAPSIS module (Dufour-Kowalski et al. 2012), which develops 3D fuels using the conceptual and computer science basis shared with FuelManager; (3) WFDS or FIRETEC, which simulate fire behavior; and (4) post-processors for visualization and calculation of fire behavior and effects metrics. A modular design, in which the different components are connected through text files, facilitates active testing and new science development. Graphical user interfaces are independent and optional, facilitating batch processing or integration with larger systems. Using pyFVS, a Python wrapper built upon the OpenFVS open source FVS model, STANDFIRE accesses user data through standard FVS input files and simulates fire for one stand, for a single year at a time. Tree growth is handled by the FVS growth model.

2.1.1 Fuel sub-system

The fuel modeling sub-system combines pyFVS, with STANDFUELS, a stand-alone CAPSIS module that develops 3D fuel data suitable for physics-based fire models from FVS data. Since STANDFUELS is based on concepts and functionalities similar to FuelManager, we refactored most of the code shared by the two modules in an object-oriented JAVA library, called *Fire*Lib.[1] *Fire*Lib implements fuel items either as individual *plants* (typically a single tree or a large shrub) or as groups of plants called *LayerSets* (see Pimont et al. 2016 for details). *Fire*Lib provides numerous capabilities, including interactive 3D visualization system, some spatially explicit fuel treatments,

[1] http://capsis.cirad.fr/capsis/help_en/firelib

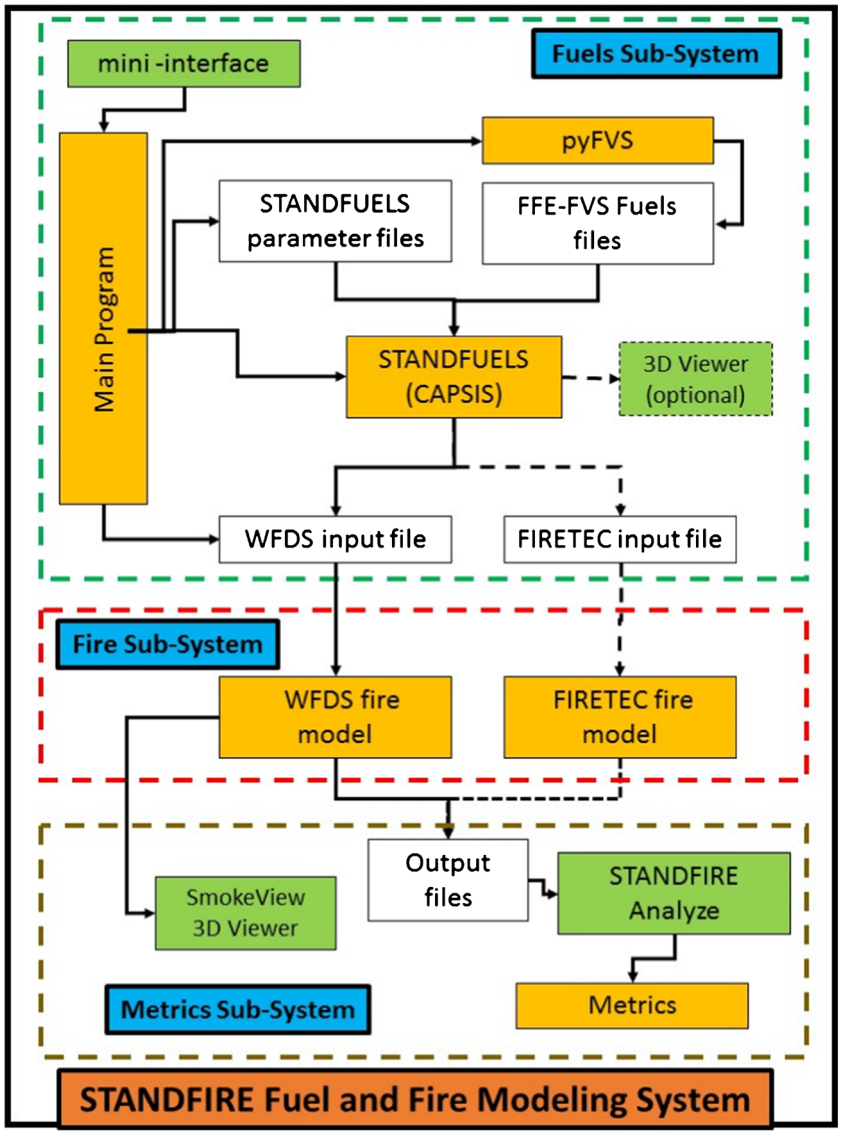

Fig. 1 Flow chart illustrating components in STANDFIRE, a prototype system for 3D fuel and fire modeling at stand scales, which links several models (orange boxes), through text files (white boxes); interfaces (green boxes) facilitate user inputs, visualization, and analysis. STANDFIRE consists of three sub-systems: fuels, which develops fuel inputs to physics-based fire models; fire, consisting of two independent fire models; and metrics, which visualize and quantify simulation outputs

and the voxelization of fuel distributions that can be exported in a format adapted to physics-based models. Additional description of *Fire*Lib is provided in Supplementary Materials (SM Fig. S1). As a CAPSIS module, STANDFUELS is simpler than FuelManager, since most 3D fuel properties as well as tree growth are computed by FVS. STANDFUELS can be used in a stand-alone mode, offering additional functionalities, but was mostly developed as a component of STANDFIRE.

STANDFIRE uses pyFVS to run the Stand Visualization System (McGaughey 2004), which computes spatially explicit trees with coordinates within a representative one-acre (0.4047 ha) area and extracts detailed biomass data for each tree in a special text file. Additional parameter files (Fig. 1) complete this information with species characteristics, understory details (cover fraction and clump size), and fuel treatment parameters, if any. Both files are then used by the CAPSIS STANDFUELS module to statistically extend that data to a larger, user-specified area. The one-acre (0.4047 ha) area is used by STANDFIRE as a focus for analysis, while the larger area provides more space and time for the wind field and fire to develop before entering the focus analysis area (Fig. 2). The CAPSIS STANDFUELS module then optionally provides a 3D visualization of the stand and converts the fuels into the voxelized formats required by the physics-based fire models.

2.1.2 Fire behavior sub-system

The fire modeling sub-system in STANDFIRE consists of two independent, physics-based fire models: HIGRAD/FIRETEC, developed at the Los Alamos National Lab (Linn 1997), and WFDS, developed in partnership between the National Institute of Standards and Technology (NIST) and the US Forest Service Pacific Northwest Research Station (Mell

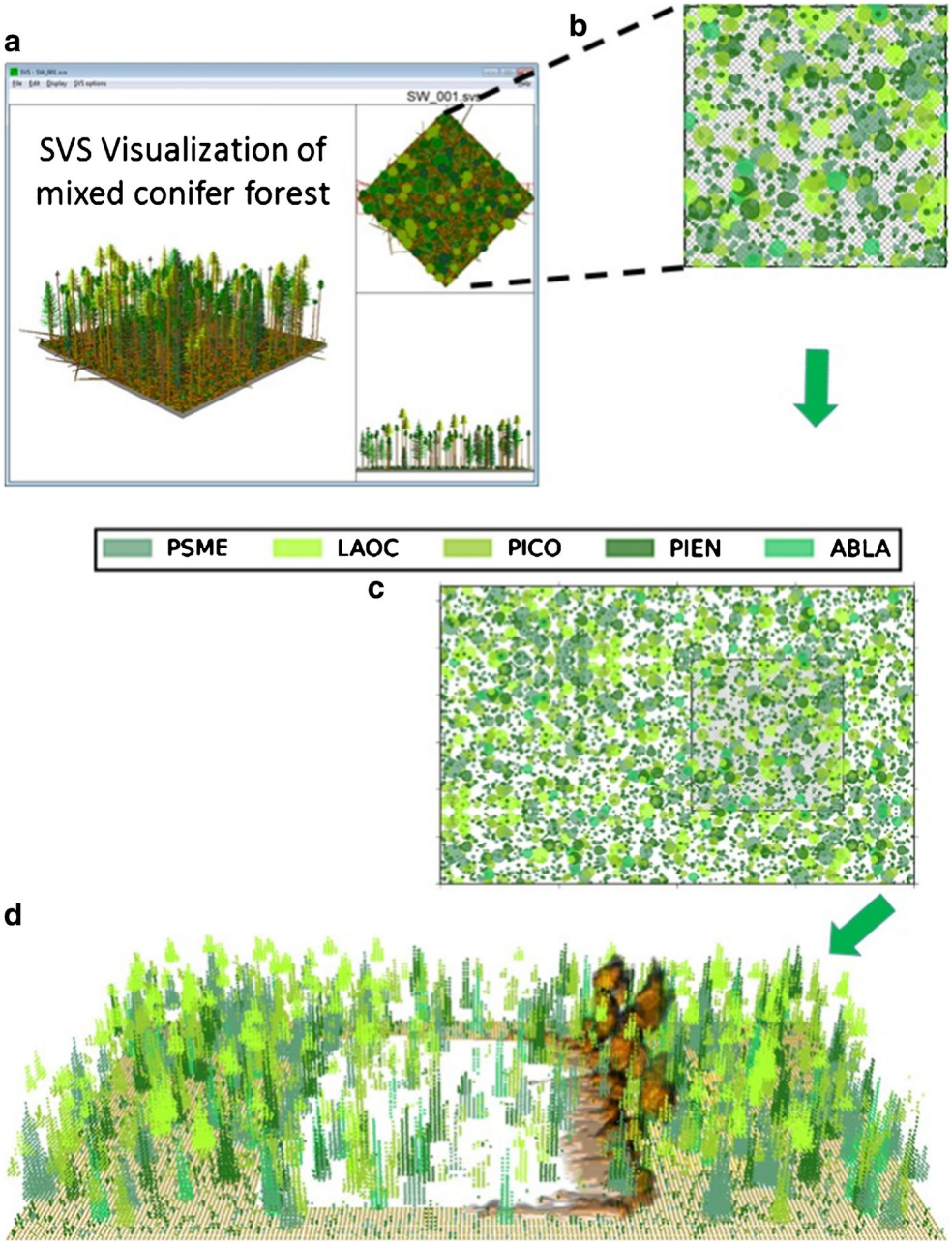

Fig. 2 STANDFIRE requires spatially explicit forest inventory data with biomass quantified for each tree. As such data are not typically available, STANDFIRE's default approach appends biomass data from the FFE-FVS model for each tree represented in the one-acre visualization produced by the Stand Visualization System (SVS) (**a**), statistically extending that forest to a larger area specified by the user (**b**, **c**). These data are translated from 2D to 3D, populating voxels (3D cells) with quantitative fuel properties for 3D fire simulations (**d**). The larger area serves to allow the fire to burn into the one-acre area, which is used as a focus for analysis

et al. 2009). These models produce a wide range of complex outputs that require further processing to aid in interpretation; this post-processing is carried out by the metrics sub-system.

2.1.3 Post-processing sub-system

At present, post-processing in STANDFIRE is only provided for WFDS output, through a program called STANDFIRE Analyze. Additionally, STANDFIRE includes Smokeview (Forney and McGrattan 2004), an interactive 3D viewing program developed at NIST that works with output from the WFDS model. In STANDFIRE Analyze, fire behavior and fire effects are calculated for the one-acre analysis area. At present, four fire behavior-related metrics are calculated: rate of spread (ROS), canopy fuel consumption (CONS), and spatial and temporally averaged heat transfer from canopy fuels (QCAN) and surface fuels (QSRF). Unlike the point functional fire calculations in FFE-FVS, which calculate single values such as flame length or Torching Index, these values summarize fire behavior outcomes over thousands of individual cells, each changing over time. Details regarding the calculation of these metrics are provided in the Supplementary Materials. Tree mortality, a key fire effect, is calculated using crown scorch-driven standard equations by species (Hood et al. 2008) and bark thickness (Ryan and Reinhardt 1988). At present, individual tree crown fuel consumption is used as a proxy

for crown volume scorched; trees with a probability of mortality greater than 0.5 are assumed to be killed, providing a stand level metric. More details regarding this topic are provided in Supplementary Materials.

2.2 Example thinning cases

We carried out example simulations for three sites in western Montana, representative of common forest types (Table 1): Seeley-Swan (SW), in dry-mesic montane mixed conifer forest; Lubrecht (LB), in ponderosa pine/Douglas-fir forest; and Tenderfoot (TF), in lodgepole pine forest. In each site, canopy and surface fuels were measured or estimated in the field, and fuel moistures typical of wildfire conditions were assigned based on weather data from nearby weather stations. For brevity, additional details regarding these study sites and sampling methods are included in Supplementary Materials (SM). Field data were formatted for use in FFE-FVS and run through STANDFIRE to provide fuel inputs for the WFDS fire model, with two fuel cases for each site: untreated, with no modification to fuels, and thinned, using a spatially explicit crown space thinning procedure (Pimont et al. 2016), with 1.5 m between crown edges. To isolate the effects of thinning, surface fuels were kept constant for untreated and thinned cases.

2.3 Fire behavior simulations

Fire simulations were carried out with the WFDS physics-based fire model (Mell et al. 2009) within a simulation domain 200 m × 126 m × 100 m in length, width, and height. Fuels were simulated in this volume using STANDFUELS. Wind entered the domain from the left side as a smooth (laminar) flow with velocity increasing with height. Fire ignition was done as a line ignition and allowed to burn into the analysis area. For brevity, more details regarding simulations are provided in the Supplemental Materials.

2.4 Comparison between fire models

The nature of fire behavior calculations in STANDFIRE is very different from FFE-FVS, so direct comparison is only possible for some outputs; we provide output from both models. FFE-FVS calculates a series of standard fire behavior outputs such as flame length (FL), Torching Index (TI), and Crowning Index (CI) which indicate wind speeds necessary for torching or crowning (Scott and Reinhardt 2001); higher values indicate increased resistance to occurrence. For thinned cases, the explicit thinning done in STANDFUELS was reproduced in FFE to calculate the corresponding standard fire behavior outputs. Details describing the development of these cases are presented in Supplemental Materials. All in all, data assembled for examining effects of thinning on fire behavior and effects with the two models included a few forest stand measures, quadratic mean diameter (QMD) and basal area (BA), the standard FFE fire outputs, and the STANDFIRE post-processing metrics.

3 Results

A summary of STANDFIRE results is presented in Table 1; additional figures and tables are provided in Supplementary Materials (SM). Initial untreated stand conditions for the three sites were similar in basal area, ranging from 29 to 36 m^2 ha^{-1} but varied widely in size class distributions; thinning changed these distributions, increasing QMD and removing about half of BA. STANDFIRE consistently predicted faster surface fires (ROS) and somewhat increased surface fuel heat transfer (QSRF) in thinned stands, due to reduced canopy drag effects, but greatly reduced canopy fuel consumption (CONS), canopy fuel heat transfer (QCAN), and tree mortality following thinning; mortality varied between sites (Table 1, Fig. 3).

Thinning effects on potential fire behavior and effects with FFE results (Table 2) appear counterintuitive but are ultimately consistent with FFE model logic. Untreated cases were very

Table 1 Quantitative metrics from STANDFIRE describing simulated changes in forest structure, fire behavior, and fire effects from thinning for three sites in western Montana, USA: Seeley-Swan (SW), Lubrecht (LB), and Tenderfoot (TF). QMD, BA, Q_{canopy}, $Q_{surface}$, and ROS stand for quadratic mean diameter, basal area, total heat transfer from canopy, total heat transfer from surface fuels, and surface fire rate of spread, respectively. Abbreviations describing forest types: *MC* mixed conifer, *PP/DF* ponderosa pine/Douglas-fir, and *LP* lodgepole pine

Site (forest)	Case	QMD cm	BA m^2 ha^{-1}	CONS. %	MORT. %	QCAN kW m^2	QSRF kW m^2	ROS m s
SW(MC)	Untreated	15.1	29.4	62.8	34.7	4161	205	0.87
SW (MC)	Thinned	19.1	17.0	18.8	7.8	541	203	1.33
LB (PP/DF)	Untreated	23.3	30.0	59.2	5.4	4823	288	1.22
LB (PP/DF)	Thinned	26.5	15.3	0.0	1.8	0.0	290	1.44
TF (LP)	Untreated	25.8	36.5	53.8	39.1	5702	300	0.77
TF (LP)	Thinned	27.8	17.0	19.1	10.3	852	312	1.01

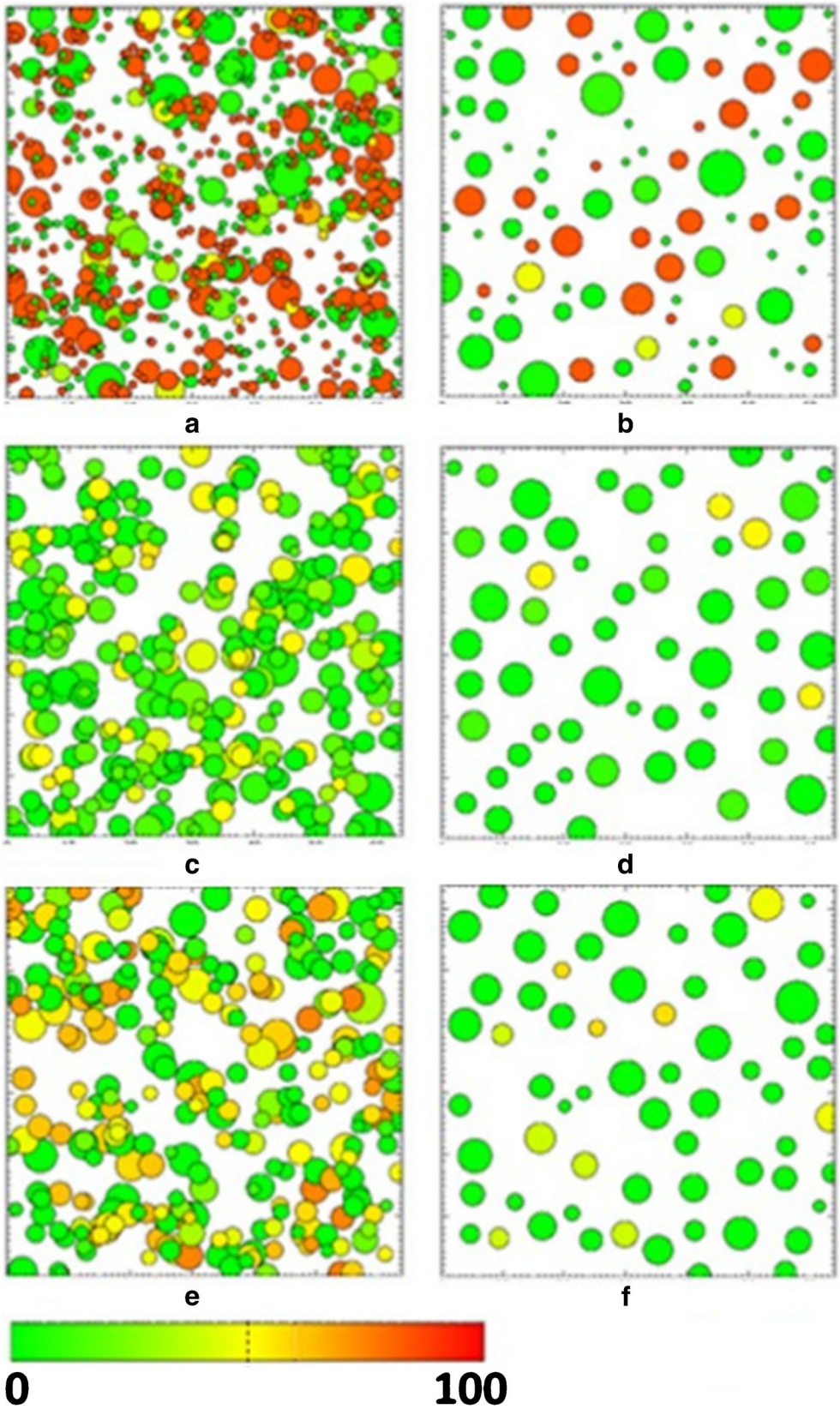

Fig. 3 Overhead perspective maps of predicted tree mortality based on physics-based fire model behavior outputs for untreated cases (left columns, panels **a**–**c**) and thinned cases (right columns, panels **d**–**f**), respectively, for three sites in Montana, USA: Seeley-Swan (SW, panels **a**, **d**), Lubrecht (LB, panels **b**, **e**), and Tenderfoot (TF, panels **c**, **f**). Tree colors show probability of mortality, ranging from low (green) to high (red), calculated with standard mortality equations

resistant to torching, requiring wind speeds in excess of 76 km h^{-1} for torching for all three sites; thinned cases had lower Torching Index values, indicating increased potential for torching. Conversely, Crowning Index values were low

Table 2 Quantitative metrics from FFE-FVS describing simulated changes in forest structure, fire behavior, and fire effects from thinning the same sites in Table 1. FFE metrics include crown base height (CBH), flame length (FL), fire type (FT), where S = surface, P = passive crown fire, and C = conditional crown fire, torching and crowning indices (TI and CI), pTorch (pT) and % mortality (MORT.), respectively. Abbreviations describing forest types: *MC* mixed conifer, *PP/DF* ponderosa pine/Douglas-fir, and *LP* lodgepole pine

Site (forest)	Case	CBH m	FL m	FT Cat.	TI km/h^{-1}	CI km/h^{-1}	pT prob.	MORT. %BA
SW (MC)	Untreated	3.4	0.9	S	124.2	48.0	0.11	43
SW (MC)	Thin	1.5	1.4	P	30.7	77.9	0.13	44
LB (PP/DF)	Untreated	2.7	1.0	S	76.4	41.8	0.39	32
LB (PP/DF)	Thin	4.0	1.5	S	56.2	91.8	0.54	39
TF (LP)	Untreated	4.0	0.9	C	160.9	31.9	0.18	100
TF (LP)	Thin	8.8	1.6	S	146.8	106.2	0.12	58

for untreated cases and increased with thinning, indicating decreased potential for crown fire spread. The pTorch metric varied between sites, increasing in the ponderosa pine site (LB) but decreasing or only marginally changing in the mixed conifer (SW) and lodgepole pine (TF) sites. These changes correspond to decreases in stand level crown base height as a result of thinning. Despite holding surface fuel constant, flame length (FL) increased following thinning in all three sites, likely from decreases in stand level canopy cover and corresponding increases in effective wind speed, ROS, and fireline intensity. Percent mortality increased marginally in two of the three sites (SW and LB sites) and decreased in the lodgepole site (TF) following thinning. Increases in mortality can be attributed to decreases in stand level base height as well as increases in flame length.

4 Discussion

Comparison between STANDFIRE and FFE-FVS results is challenging as the two models have very different outputs; FFE uses ROS and fire intensity in internal calculations of flame length but does not report those values. However, assuming that flame length increased with effective wind speed, the models qualitatively agree on this point, as ROS and QSRF both increased (QSRF only slightly) in STANDFIRE. Mortality, one of the few metrics they have in common, however, showed very different outcomes between the two models, with predicted mortality decreasing following thinning for all sites with STANDFIRE, while increasing in two of the three sites with FFE. This difference is important, as reduced fire-induced mortality relates to resilience, and increasing resilience is an important goal of fuel treatment efforts (Larson and Churchill 2012). Most likely, the driving factor between these differences is the dependency in FFE on stand level values, such as CBH, in mortality calculations. These single stand values are often highly volatile, changing substantially from small changes in stand structure or composition; the pTorch metric was itself added to FFE-FVS to attempt to reduce this volatility in outputs, by statistically simulating a more realistic quasi-geometry and testing across a set of cases in an ensemble-like effect (Rebain 2015). This is similar both to other recent work which seeks to provide added value to fire calculations through ensemble outputs of simple models (Cruz and Alexander 2017) as well as to the dynamic outputs from physics-based fire models. Unlike the single values of flame length from Rothermel's surface fire spread model in FFE, the QCAN and QSRF measures in STANDFIRE derive from thousands of individual cells and their quantitative changes over time and could thus be represented as distributions, characterizing both variability and probability of outcomes. Future work should emphasize characterization of fire behavior in such more descriptive ways.

By modeling trees as individual entities in space and having fire calculations that account for fuel geometry and spatial relationships, STANDFIRE provides a basis which leads away from single stand values and which embraces the complexity of wildland fuels and their intrinsic heterogeneity (Keane et al. 2012). The cases we explored here were intended as a simple first step, rather than a comprehensive evaluation; many aspects of fuel heterogeneity that can be represented in STANDFIRE and FuelManager were not used to their full effect in these examples. This capacity for finer detail should also enable use of more detailed fuel mapping approaches (Loudermilk et al. 2012; Pimont et al. 2015; Almeida et al. 2017).

STANDFIRE was designed to leverage the detailed fuel data in FFE-FVS to add greater detail in fire behavior and fire effects outputs. Thus, the intention of STANDFIRE is not to replace FFE-FVS, but rather to extend its capabilities in new directions, providing a greater depth of information. STANDFIRE is a prototype platform and should not be considered as "finished," but

rather, as a work in progress. Many aspects of the modeling in STANDFIRE can be improved. For brevity, some limitations are presented in the Supplementary Materials. Future work will strengthen connections between FFE-FVS and should provide a stronger basis for comparison.

5 Conclusions

With the long-term viability of many forest ecosystems in jeopardy (Adams et al. 2009), modeling plays a critical role in enabling us to isolate and assess the magnitude and effects of different drivers. Many contemporary issues threatening forest ecosystems lie at the intersection of different disturbances, such as growing impacts of exotic species (Ziska et al. 2005) or beetle outbreaks (Hoffman et al. 2015), which affect fuels and interactions with fire in complex ways. FuelManager and STANDFIRE provide an opportunity to explore such interactions with greater detail than has been possible before. With further refinement, we hope that improved understanding at fine scales will translate to clearer guidance for management decisions at landscape scales. Continued development of cross-scale modeling capabilities will be of paramount importance as we face future challenges to forest ecosystems.

Authors Contributions Authors PIMONT, WELLS, COHN, De COLIGNY, JOLLY, and PARSONS developed the modeling system. Authors PARSONS and PIMONT wrote most of the paper with contributions from all other authors. Authors MELL, LINN, de COLIGNY, DUPUY, and RIGOLOT provided key information used in the development of the project. Authors WELLS and COHN carried out simulations; WELLS, COHN, and PARSONS analyzed data. PARSONS, WELLS, COHN, and PIMONT produced figures.

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Supplementary Materials

Physics-based fire models

In recent years, physics-based fire behavior models such as HIGRAD/FIRETEC (Linn et al. 2005) and the Wildland Urban-Interface Fire Dynamics Simulator (WFDS) (Mell et al. 2009) have helped improve our understanding of how different wildland fuel characteristics affect fire behavior. These models employ computational fluid dynamics (CFD) approaches, which solve partial differential equations (PDEs) for conservation of mass, energy, and momentum to simulate the dynamic spread of fire and its interactions with the atmosphere, vegetation, and topography at spatial scales on the order of meters and temporal scales less than seconds, which enables them to represent the effects of heterogeneous and discontinuous fuels. Recent work with these models has explored various aspects of wildland fire, including fine scale fuel heterogeneity (Parsons et al. 2011), stand scale fuel heterogeneity (Pimont et al. 2011; Linn et al. 2013; Parsons et al. 2017; Ziegler et al. 2017), beetle killed trees and fire (Hoffman et al. 2012; Hoffman et al. 2015; Sieg et al. 2017), and effects of physiological changes in plants on flammability (Jolly et al. 2016). While many technical aspects of WFDS, such as flame geometry and smoke spread have been validated and tested against lab experiments (Hu et al. 2007; McGrattan et al. 2017; Wang et al. 2017), the validation of wildland fires in field settings is challenging, often limited by available data (Hoffman et al. 2016) or how available data, such as weather station measurements, are interpreted (Linn et al. 2012); validation efforts are ongoing. While incomplete validation may raise concerns regarding their applications (Alexander and Cruz 2013), several evaluations of WFDS and FIRETEC show favorable results in a diversity of topics, including tree scale experimental fires (Mell et al. 2009), field burns in grass fuels (Linn and Cunningham 2005; Mell et al. 2007), wind field dynamics (Pimont et al. 2009; Mueller et al. 2014), turbulent and convective heat fluxes above fire experiments (Dupuy et al. 2014), and crown fire rate of spread comparisons (Hoffman et al. 2016).

Demonstration Simulations

Fuels sampling, parameterization and modeling

We selected three sites in western Montana representative of common forest types: Seeley-Swan (SW), in dry-mesic montane mixed conifer forest, Lubrecht (LB), in Ponderosa pine / Douglas-fir forest, and Tenderfoot (TF), in Lodgepole pine forest (Figure S1). In each site, we sampled and measured canopy fuels using fixed radius plots of 11.3m (0.04 ha) to define the sampling area for trees of 12.7 cm diameter at breast height (DBH) or larger, and 2.07m (0.0013 ha) for trees smaller than 12.7 cm DBH, respectively. Tree measurements included DBH, height, crown base height, crown diameter, and species. Shrub, herb and litter surface fuel loads in kg m^{-2} were estimated with four 1 m^2 micro plots per site, using the PhotoLoad method (Keane and Dickinson 2007), a rapid estimation approach in which ocular estimates are calibrated against a series of downward facing photos corresponding to measured fuel loads. While quick, this approach has compared favorably with other more laborious procedures (Keane and Gray 2013). Fuel moisture content (FMC) for all canopy fuels, expressed on a dry weight basis, were set at 100%. Shrub and herb fuel moisture contents were set based on conditions typical for high potential fire spread (90th-97th percentile) based on the Spread Component Index (Deeming et al. 1977), calculated using FireFamilyPlus (Bradshaw and McCormick 2000), and weather data from the closest weather stations to each site. Fuel load and moisture parameters are presented in SM Table 1. Although specific to these sites, these conditions are quite comparable to the standard severe fire conditions used in FFE-FVS calculations.

Fuels data from each site were then formatted for use in FFE-FVS and run through the STANDFIRE system to provide fuels inputs for use in physics-based fire model simulations using the WFDS model. Critical to this capability is the *Fire*Lib Java code library, common to both FuelManager (Pimont et al. 2016) and STANDFIRE, shown in Figure S1. *Fire*Lib constructs a three dimensional fuels *Scene*, in which wildland fuels are represented either as discrete entities called *Plants*, or as collections of entities called *LayerSets*; these structures are highly versatile and can be used to represent a wide range of fuel types and situations. FireLib provides an array of tools for both

visualization and manipulation of fuels, including fine scale spatially explicit fuel changes, such as thinning or pruning for an area within a given stand. The crown spacing algorithm, for example, simulates line transects ("marking walks") along which trees are selected for thinning, keeping preferentially the largest trees (Pimont et al. 2016). These new tools provides an expanded toolbox for forest management activities in a modeling context. However, perhaps the most important capability of *Fire*Lib is to carry out the calculations by which different fuel components, such as individual trees or patches of shrubs, are quantitatively modeled and assigned to 3D cells, called voxels, in the numerical grid. This process requires detailed calculations as individual trees may span many cells and in many cases, a given cell may have only a portion of a tree crown or other fuel element. For this reason, fuel loads must be appropriately divided between different cells. FireLib also associates each fuel cell with appropriate parameters for the selected fire model. This process is explained in detail in a recent paper (Pimont et al. 2016).

FireLib provides the capability to export fuels data to either WFDS (Mell et al. 2009) or FIRETEC(Linn 1997). For these simulations, fire simulations were carried out with WFDS. WFDS contains two different methods for modeling wildland fuels: 1) the particle or element model, which describes fuels as Lagrangian particles which can populate individual voxels that are air permeable and can be discontinuous from neighboring fuels, or suspended above the ground; or 2) the boundary model, that creates a uniform, impenetrable surface with specified combustion characteristics. Both fuel modeling approaches require a series of parameters describing fuel properties. These include the model type (particle or boundary), the surface area to volume ratio (SVR), the char fraction, the material density, the drag coefficient, the maximum mass loss rate (Maximum MLR), and the height of the fuel above the surface. Char fraction refers to the proportion of initial dry mass which remains after the dry vegetation undergoes complete thermal degradation in an oxygen free environment. Parameters used for fuels in WFDS fire simulations are provided in SM Table 2.

Fire behavior simulations

Fire simulations were carried out with the WFDS model, a computational fluid dynamics physics-based fire model. Such models carry out complex calculations using partial differential equations tracking numerous physical quantities in space and time. The three dimensional space in which these calculations are done is referred to as the domain. For our simulations, the domain was 200m X 126 m X 100 m in length, width and height, with 1m resolution in x and y, and with stretched resolution in the vertical direction, with resolution of 0.3m at the bottom of the domain. The top boundary condition was open. Lateral boundaries were set as mirrors to emulate an infinite width fire line and mitigate certain boundary effects. Wind entered the domain on the inlet (left) boundary as laminar flow with an atmospheric profile and a velocity of 8.43m s^{-1} at the top of the canopy (27m). Fires were ignited with a line fire, 4m wide and 96m long, perpendicular to the wind flow direction, initiated at t=60s, ramping up to a maximum of 1000 kW m-2 and then ramping back down to 0 over 10s. Simulation duration was 350s, and took approximately 30 hours to run on nine processors for each simulation.

STANDFIRE fire behavior metrics

Models such as WFDS are capable of producing many diverse kinds of outputs quantifying different aspects of a fire simulation. Data can be output for points, planar slices aligned in x, y or z dimensions, or volumes, typically over time. In most cases, these outputs require further analysis or summarization before they can be useful in forest management applications. Of particular significance to quantifying fuel treatment effects on fire behavior and effects are text files which track fuel consumption and heat transfer for individual tree crowns over time. STANDFIRE Analyze is a prototype post-processor code used to calculate a series of metrics characterizing fire behavior outputs for WFDS simulations. At present, four fire behavior metrics are calculated. The first metric, surface fire rate of spread (ROS), is measured as distance across the analysis area (a one-acre-square area located towards the right side of the simulation domain) divided by the time the fire took to cross that area, measured from surface fuel consumption. The second metric, canopy fuel consumption (CONS)

is computed as the total loss of canopy fuels within the analysis area over the course of the simulation and converted to a percent. The third and fourth metrics, total heat transfer from canopy (QCAN) and surface fuels (QSRF), are calculated as the integral of the heat transfer rate for the analysis area, divided by the analysis area, and duration of combustion, providing a spatially and temporally-averaged heat transfer rate, for surface fuels and canopy fuels, respectively.

Modeling of tree mortality

An additional metric calculated for these simulations was fire induced tree mortality, a key fire effect, and useful for assessing potential effects of thinning vs effects of fire (SM Table 3). Prediction of tree mortality was based on standard tree mortality equations (Hood et al. 2008), which use percent crown volume scorched, a measure typically estimated in the field post-fire, and bark thickness (Ryan and Reinhardt 1988), calculated from tree diameter, as independent variables. A probability of mortality exceeding 0.5 was classified as dead (Keyser et al. 2006), permitting an overall stand level measure. Physics based fire models can calculate quantities from which crown scorch could be calculated, but this post-processing capability has not yet been fully developed. Thus, instead of crown scorch, we used proportion of crown mass loss for each tree as a proxy for crown scorch in mortality predictions. While STANDFUELS can generate tree crowns with variable density, we did not assess these trees in this paper, instead modeling tree crowns as homogeneous volumes, with constant density within an individual crown, making mass consumed directly linked to volume consumed. While crown volume consumption is not a perfect proxy for crown volume scorch, estimating mortality this way has the advantage of incorporating simulated fire behavior specific to the area around each tree, which could presumably be affected by the number, size and arrangement of trees within that area.

This approach of linking physics-based fire models to empirical mortality equations may provide a range of useful outcomes, however, it should be recognized as a method that is still in development. The empirical equations used here use one direct measure of fire effects (crown volume scorched) and

one indirect measure (bark thickness) which is an estimator of possible bole damage. Together these capture much of the variation in post-fire tree mortality. Our use of canopy fuel consumption rather than crown scorch thus is a more conservative measure than was used in the empirical relationship because crown scorch can occur at approximately 60°C by protein denaturation (Rosenberg et al. 1971) where no canopy fuel is consumed. Higher mortality would be predicted if we had calculated crown scorch. This could explain, to some degree, why FFE consistently predicted higher mortality than STANDFIRE for our sites (Main paper, Tables 1 and 2). In addition, while important, damage to the canopy is not the only mechanism for tree mortality; factors like cambium destruction and root damage are also important to fire mortality, but were not addressed here. Smoldering phase combustion can contribute significantly to such tissue damage due to longer term exposure to high temperatures, and should be included in future work. Subsequent work should refine these approaches and validation efforts should be carried out comparing actual tree mortality with predictions generated from physics-based fire models. The modular formulation of STANDFIRE makes it possible to integrate new approaches for calculating mortality as they become available.

FFE – STANDFIRE comparisons

The spatially explicit fuel modeling in STANDFIRE enables detailed comparison of fire behavior and effects, taking into account the removal of specific trees, as well as identical fire conditions (i.e. wind, ignition, surface fuels, and fuel moistures), as were carried out here to isolate thinning effects. Although the three sites are different in species composition and would presumably have different management prescriptions, we applied the same thinning approach to all three cases to facilitate more straightforward between-site comparisons. This thinning approach was spatially explicit but did not preferentially cut trees on the basis of diameter or species. Although the stand visualization system (SVS) provides an interactive, spatially explicit tree marking and treatment mode, this capability does not feed back to FVS, so such spatially explicit stand manipulations cannot be carried out in FFE-FVS. In future work, this capability in SVS should enable subsequent

manipulation via STANDFIRE, but this connection is not yet established. For this reason, the thinned cases used here were developed external to FVS, and thus did not have FFE fire outputs. To provide cases for comparison, we used the THINSDI keyword in FVS to thin the untreated stands, using stand density index (SDI) (Reineke 1933) values calculated from our treated cases as the target value. Similar to the thinning carried out in STANDFIRE, this thinning approach was agnostic with respect to diameter or species. We used the FUELMODL keyword to enforce unchanging fire behavior fuel model parameters for the surface fuels, and used the FUELMOVE keyword to remove all surface fuels added for each fuel category through the thinning operation for consistency with the STANDFIRE simulations, where surface fuels were kept the same between cases. As recent studies have shown little sensitivity to, or advantage from, the use of custom fuel models (Johnson et al. 2011; Noonan-Wright et al. 2014), we used relatively simple weighted sets of standard fire behavior fuel models, based on our field sampled data, to represent surface fuels in the FFE simulations. FBFM weightings were as follows for each site: SW: 8(75%),5(5%),2(20%); LB: 9(75%), 5(15%),2(10%); TF: 8(75%), 5(15%),2(10%). It is unlikely that these weighted sets of FBFM's exactly reproduce the fire behavior in STANDFIRE but they represent reasonable approximations of between-site differences from our field data. Most importantly, by holding the same set of surface fuel models constant between untreated and thinned cases, they provide a reasonable comparative basis against STANDFIRE results, in which surface fuels were similarly held constant for each site.

Limitations in our fire simulations

The simulations described here demonstrate model capabilities, but are limited in key ways. First, we did not model changes in surface fuels arising from the treatment, longer term fuel accumulation or forest succession following treatment. Such changes over time could be expected to affect fire behavior and effects, and should be explored in subsequent work; the link to FVS makes this possible, as STANDFIRE can be run for different points in time over the course of an FVS simulation. One key limitation at present is that, like other post-processors to FVS, such as the Stand Visualization System

(SVS), STANDFIRE can receive information from FVS, but is not yet set up to send information back to FVS. This capacity will be important for incorporating outcomes of fire simulations, such as trees killed by a fire, into the longer term stand dynamics of FVS. Future work will develop this connection.

An additional limitation in our simulations are the microclimate conditions within a stand, which may be altered by a fuel treatment (primarily solar radiation, fuel moisture and wind regimes). While the modification of wind regimes is accounted for in WFDS due to the drag and turbulence model (Mueller et al. 2014), these other microclimate aspects are not currently accounted for in our simulations, which may affect fire behavior as well. Efforts linking a wider range of forest microclimate processes would be valuable improvements in this arena in future work. Other models within the larger CAPSIS forestry modeling platform (Dufour-Kowalski et al. 2012), with which STANDFIRE is integrated, such as the SamsaraLight model (Ligot et al. 2014), may provide key capabilities in this regard.

Finally, our simulations employed relatively small domains (200 m), fairly short periods of time (350 s) and simple approaches regarding wind flows (laminar flow) and fire (infinite fire line), which could affect fire behavior predictions (Linn et al. 2012; Linn et al. 2012; Mueller et al. 2014), so our results should be considered with caution. At present, little guidance is available quantifying the degree to which such aspects might change fire behavior results. We hope that systems such as STANDFIRE will help establish best use practices as the use of physics-based models becomes more widespread.

Computer requirements and software availability

STANDFIRE has been developed for Windows, Mac and Linux operating systems. Due to the computationally demanding nature of the WFDS physics-based fire model, STANDFIRE requires a 64 bit operating system, at least 4 GB RAM per processor, and a large amount of storage, as outputs for a single simulation may require more than 1 GB of disk space. STANDFIRE can be run on a

typical laptop for small simulation domains with single processors but for most purposes should be run on higher end computers with multiple processors.

STANDFIRE continues to be in active development. The software is available on request.

Tables

SM Table 1. Site specific fuel parameters in fire simulations examining fuel treatment effects in three sites in western Montana, U.S.A. Fuel load and bulk densities were estimated from field sampling, while fuel moisture contents were based on conditions typical for high potential fire spread (90th-97th percentile) based on the Spread Component Index (Deeming et al. 1977), calculated using FireFamilyPlus (Bradshaw and McCormick 2000), and weather data from the closest weather stations to each site. Abbreviations describing forest types: MC = Mixed Conifer, PP/DF = ponderosa pine/ Douglas-fir, and LP = lodgepole pine.

			Site (Forest Type)	
Fuel type	Parameter	SW (MC)	LB (PP/DF)	TF (LP)
Litter	Load (kg m^{-2})	0.33	0.26	0.37
Litter	Moisture Content (%)	5	5	5
Shrub	Bulk Density (kg m^{-3})	0.052	0.17	0.16
Shrub	Moisture Content (%)	99	70	91
Herb	Bulk Density (kg m^{-3})	0.211	0.097	0.082
Herb	Moisture Content (%)	3.8	5.1	5.8

SM Table 2. Fuel parameters required for WFDS fire simulations, and applied across sites in fire simulations examining fuel treatment effects in three sites in western Montana, U.S.A.

			Fuel Type	
	Units	Litter	Shrub	Herb
model	NA	boundary	particle	particle
SVR	$m^2\ m^{-3}$	5710	9600	9500
Char Fraction	proportion	0.265	0.25	0.25
Material Density	$kg\ m^{-3}$	400	512	512
Drag Coefficient	dimensionless	0.05	0.125	0.125
Max MLR	$kg\ m^{-3}\ s^{-1}$	0.35	0.35	0.35
Height	m	0.05	Variable	Variable

Figure Captions

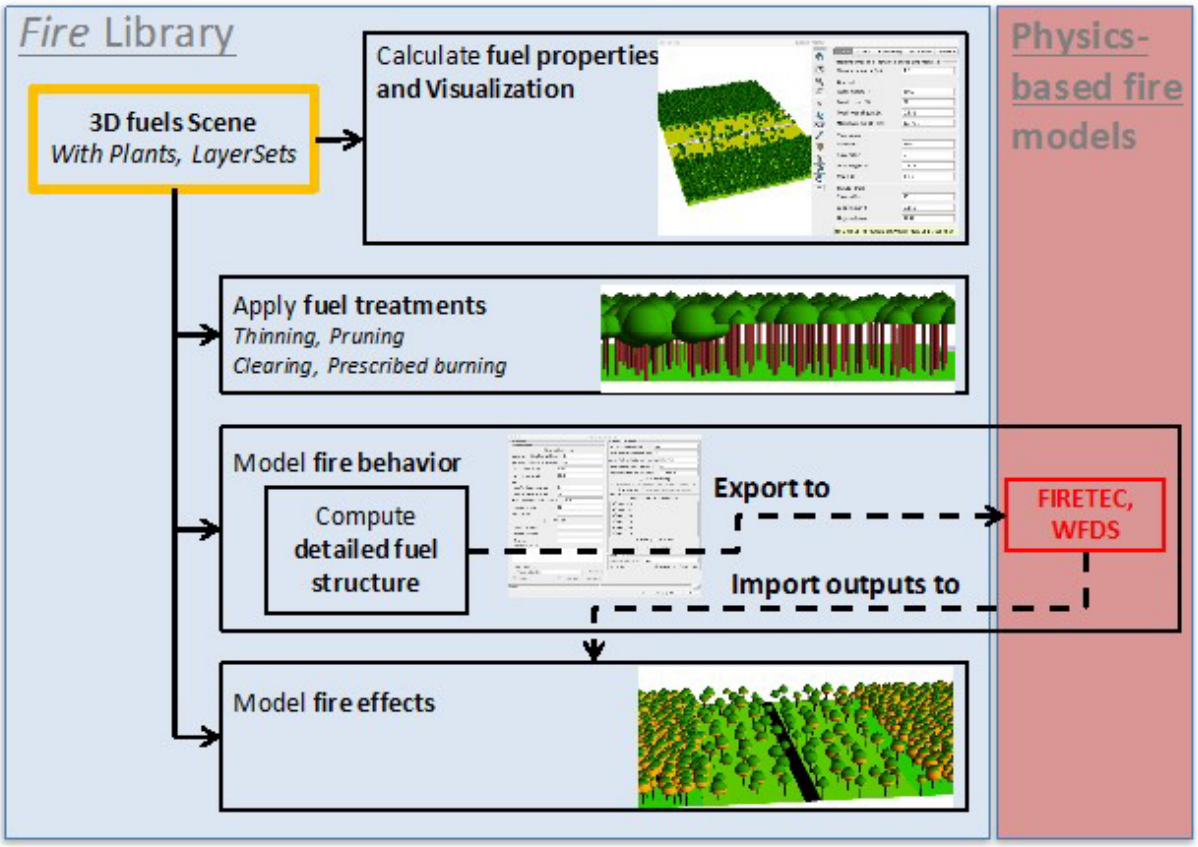
Figure S1. Features available in the Fire library, used by both FuelManager and STANDFIRE. The Fire library enables the user to construct a 3D fuels scene consisting of individual *Plants* or groups of plants called *LayerSets*. These components can then be visualized and manipulated, such as fuel treatments, before they are exported as fuels inputs for the physics-based fire models, WFDS and FIRETEC. The Fire library also provides tools for calculation of fire effects from simulation outputs.

Figure S2. Graphic showing location of three field sites in Montana used in examples described in this paper: Seeley-Swan (SW), Tenderfoot Experimental Forest (TF) and Lubrecht Experimental Forest (LB). Inset graphic shows location of Montana within the United States.

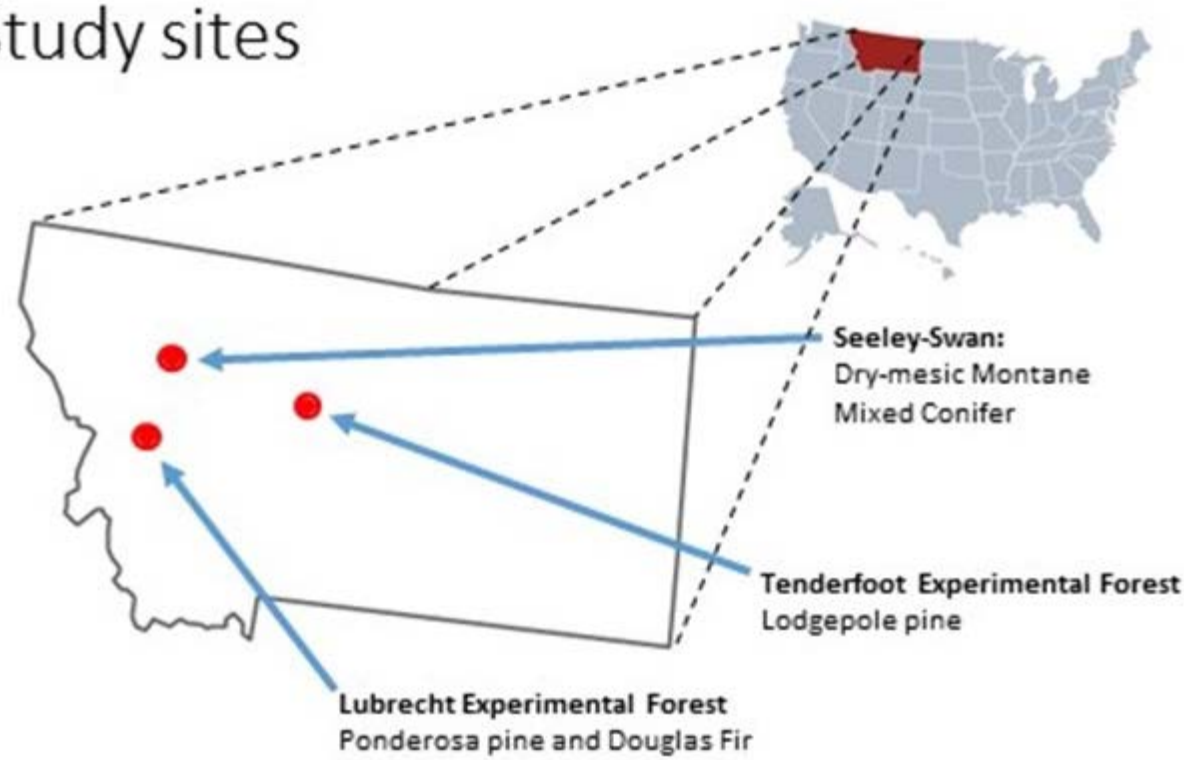
Figure S3. Changes in tree diameter distributions between untreated (solid colored lines) and thinned cases (dashed black lines) for three sites: a) SW (red), b) LB (green) and c) TF (blue). Note that SF site has a different y axis limit than the other two sites to permit display of large number of smaller diameter trees. Numbers of trees shown are counts over entire simulation area, of 2.52 ha.

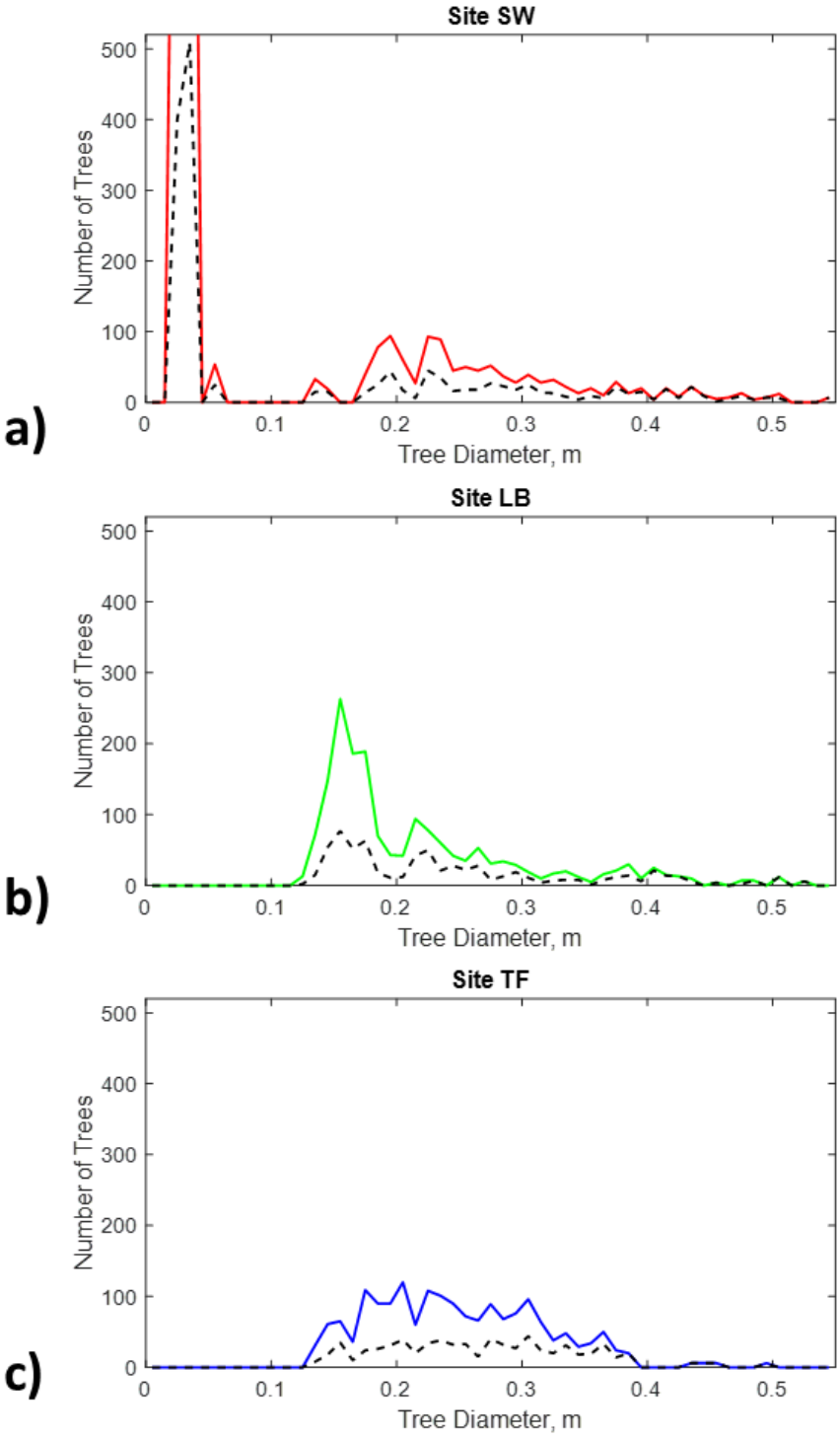
Figure S4. Overhead perspective maps of untreated cases (left columns, panels a,b and c), and thinned cases using a spatially explicit, 1.5m distance crown space thinning (right columns, panels d, e and f), respectively, for three sites in Montana, USA: Seeley-Swan (SF, panels a and d), Lubrecht (LB, panels b and e) and Tenderfoot (TF, panels c and f). Within each graph different colors show species while circle sizes show tree size differences.

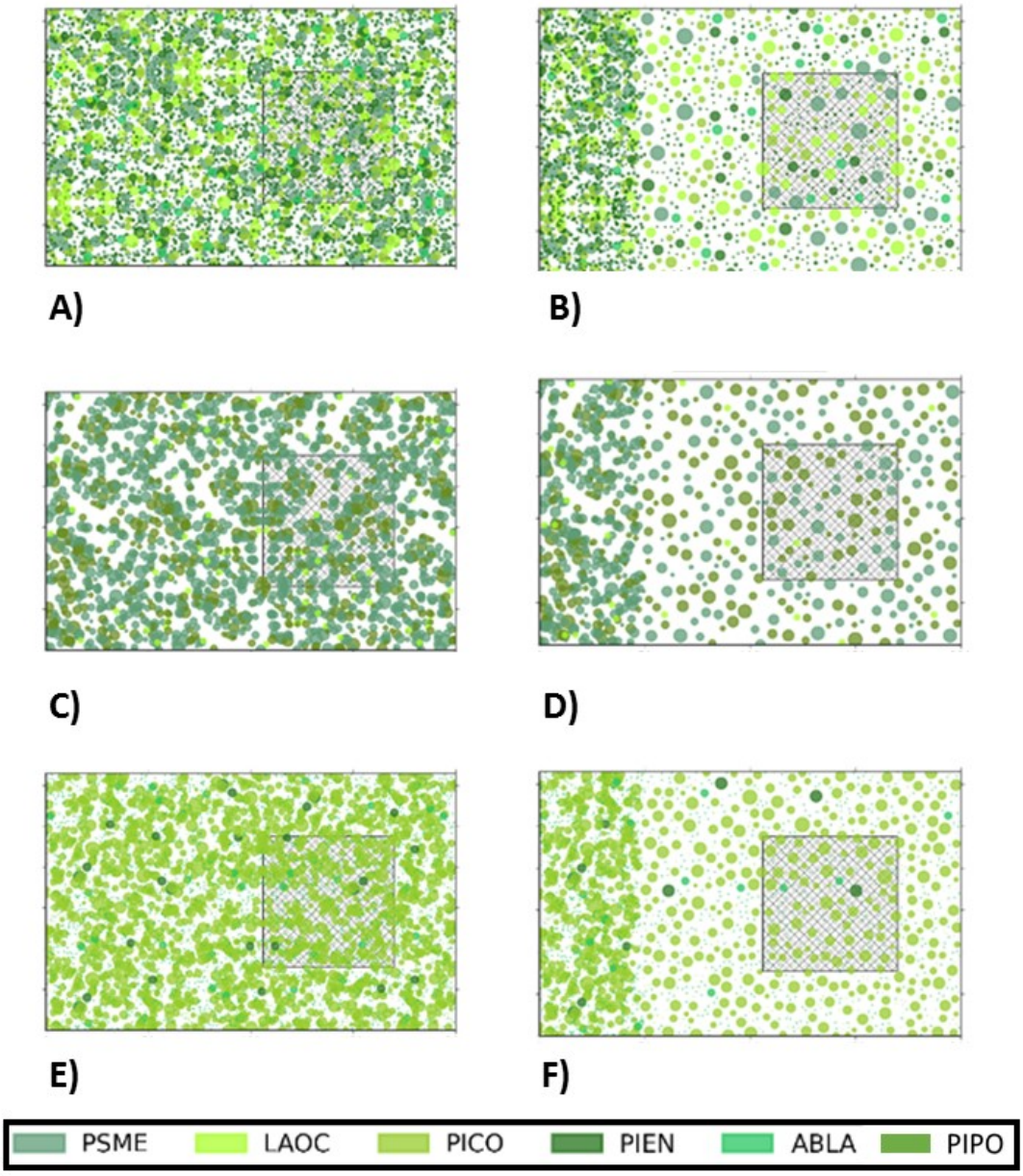
Figures


Fire Library
3D fuels Scene
With Plants, LayerSets
Calculate fuel properties and Visualization
Apply fuel treatments
Thinning, Pruning
Clearing, Prescribed burning
Model fire behavior
Compute detailed fuel structure
Export to
Import outputs to
FIRETEC, WFDS
Model fire effects
Physics-based fire models

Study sites


Seeley-Swan:
Dry-mesic Montane
Mixed Conifer
Tenderfoot Experimental Forest
Lodgepole pine
Lubrecht Experimental Forest
Ponderosa pine and Douglas Fir


Site SW
Number of Trees
Tree Diameter, m
a)
Site LB
Number of Trees
Tree Diameter, m
b)
Site TF
Number of Trees
Tree Diameter, m
c)


A)
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D)
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F)
PSME
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PIEN
ABLA
PIPO

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