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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

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(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

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,

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[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
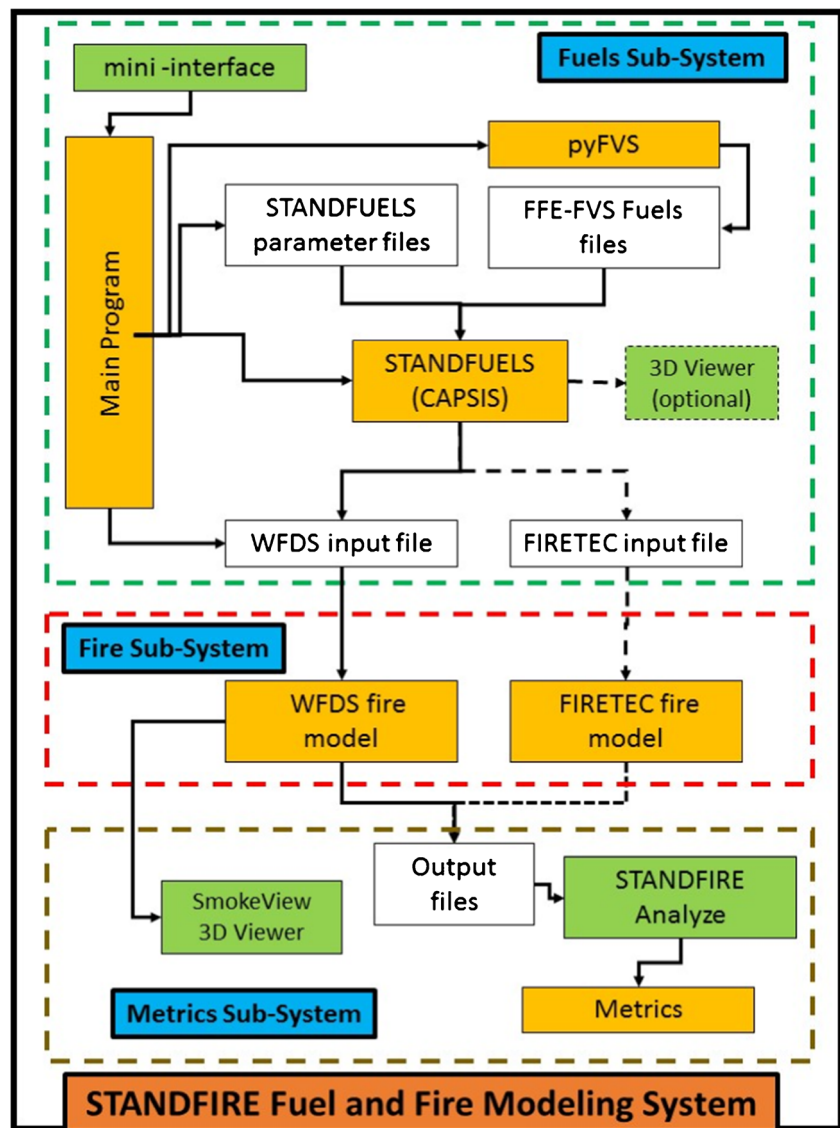
and the voxelization of fuel distributions that can be exported in a format adapted to physics-based models. Additional description of *Fire*Lib is provided in Supplementary Materials (SM Fig. S1). As a CAPSIS module, STANDFUELS is simpler than FuelManager, since most 3D fuel properties as well as tree 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
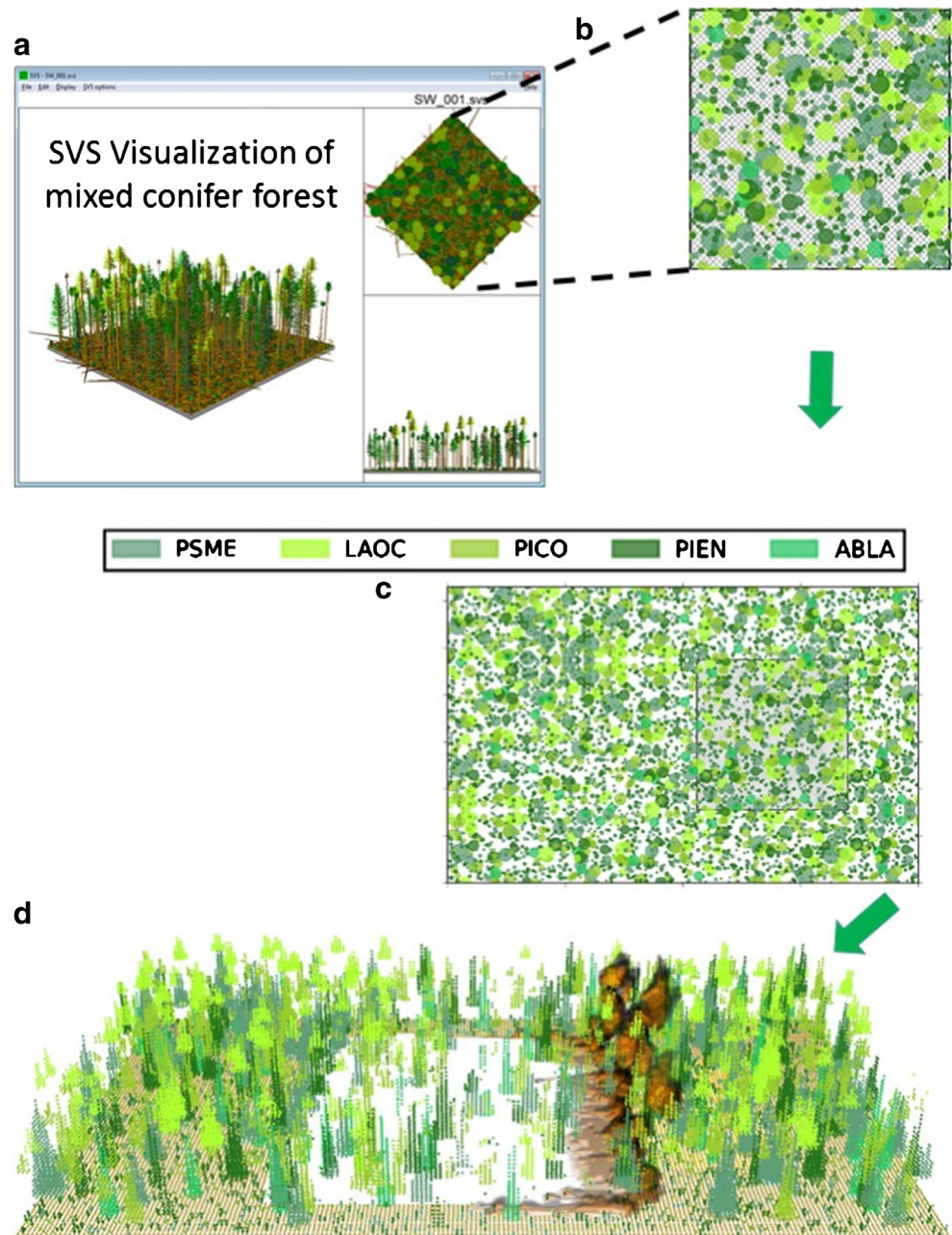
et al. 2009). These models produce a wide range of complex outputs that require further processing to aid in interpretation; this post-processing is carried out by the metrics sub-system.

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
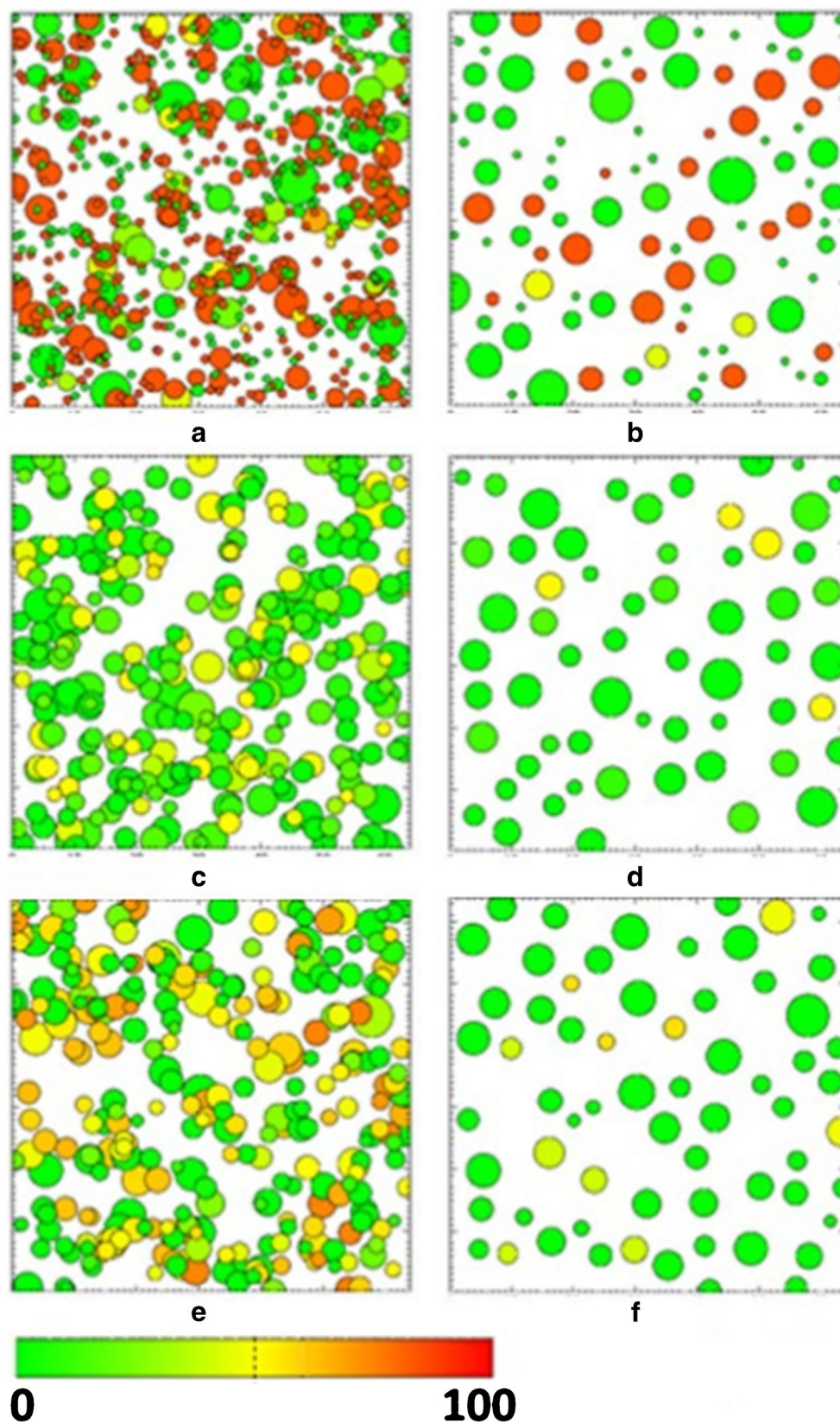
resistant to torching, requiring wind speeds in excess of 76 km h^{-1} for torching for all three sites; thinned cases had

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

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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.

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CORRECTION

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Correction to: "Modeling thinning effects on fire behavior with STANDFIRE"

Russell A. Parsons[1] · Francois Pimont[2] · Lucas Wells[3] · Greg Cohn[4] · W. Matt Jolly[1] · Francois de Coligny[5] · Eric Rigolot[2] · Jean-Luc Dupuy[2] · William Mell[6] · Rodman R. Linn[7]

Correction to: Annals of Forest Science
https://doi.org/10.1007/s13595-017-0686-2

In Table 2 in the original article, torching index (TI) and crowning index (CI) values were incorrectly expressed in km/s. The correct units are km/h. The original article has been corrected.

The online version of the original article can be found at https://doi.org/10.1007/s13595-017-0686-2

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