FINAL REPORT

Title: Assessing factors that influence landscape fuels treatment effectiveness

JFSP PROJECT ID:14-1-01-18

June 2021

Hoffman, Chad M

Colorado State University

Mell, William E

USDA Forest Service PNWRS

Parsons, Russell A

USDA Forest Service RMRS

Ex, Seth A

Colorado State University

Ziegler, Justin

Colorado State University

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List of Abbreviations

BA - Basal area
CAC - Criterion for active crown fire spread
CBD - Canopy bulk density
CBH - Canopy base height
CFB - Crown fraction burned
CFIS - Crown Fire Initiation and Spread Model
CROSa - Active crown fire rate of spread
CROSp - Passive crown fire rate of spread
DBH - Diameter at breast height
DF - Drought factor
EFFM - Estimated fine fuel moisture
FDS - Fire Dynamics Simulator
FFE-FVS - The Fire and Fuels Extension for the Forest Vegetation Simulator
FLI - Fireline intensity
FIA - Forest Inventory and Analysis
FSG - Fuel stratum gap
FVS - Forest Vegetation Simulator
I_i - The surface fireline intensity threshold for crown fire ignition
I_s - The surface fireline intensity
JFSP - Joint Fire Science Program
KBDI - Keetch-Byram Drought Index
LB - Length to breadth ratio
P_c - probability of crown fire occurrence
QMD - Quadratic mean diameter
R'_{SA} - The surface fire rate of spread that corresponds when there is complete crown consumption
R_A - Rate of active crown fire spread
R_S - Rate of Surface fire spread
R_f - Final rate of spread
R_0 - No wind, no slope rate of spread
RAC - Critical minimum ROS to sustain active crowning
Ro - Critical rate of spread for a crown fire
ROS - Rate of fire spread
SFC - Surface fuel consumed
SI_{100} - Site index base age 100
TPH - Trees per hectare
U_{10} - 10-m open wind velocity
$U_{virtual}$ - Virtual wind velocity
WFDS - Wildland Urban Interface Fire Dynamics Simulator
WFDS-LS - Wildland Urban Interface Fire Dynamics Simulator Level Set
WFDS-PB - Wildland Urban Interface Fire Dynamics Simulator Physics Based

Keywords

WFDS; fuel treatment longevity; fuel treatment placement; fire behavior modeling

Abstract

Policy initiatives such as the Collaborative Forest Landscape Restoration Program (Rep. Holt, 2009) have emphasized landscape-scale (> 10,000 ac) fuel reduction treatments to mitigate adverse impacts of large, uncharacteristic wildfires in the western United States. Over the past two decades, a nuanced understanding of the design and implementation of stand-scale treatments that reduce the behavior of future fires and enhance fire suppression capabilities has been developed across the western US. These approaches are referred to as fuel reduction treatments and involve the purposeful use of silvicultural methods to alter the fuels complex and reduce the behavior and effects of future fires. Although fuel reduction treatments are commonly implemented at stand scales, previous research has suggested that the strategic placement of fuel treatments across a landscape can effectively reduce fire's negative impacts. However, the implementation of strategic landscape-scale treatments is complicated by the large areas that require treatment to achieve beneficial landscape-scale effects and legal and physical constraints associated with land use and access and our conceptual understanding of the complex interactions between fuels complex, topography, and atmosphere on landscape scale fire behavior. Failure to consider these interactions has limited the development of theoretical frameworks that describe the influence of fuel treatment patterns and amount on landscape-scale fire effects and reduces the applicability of any gained knowledge to real-world landscape-scale fuel treatment planning. Our overarching objective was to increase our understanding of the mechanisms that influence the effectiveness of landscape scale fuel treatments. More specifically we 1) developed and evaluated a new level set approach for landscape scale fire spread in WFDS and an open-source stand scale fire behavior in the R programming language, 2) Investigate how proportion of landscape treated and treatment placement influence landscape-level fire spread patterns and behavior across a suite of topographies, and 3) Investigated how treatment placement influences landscape scale fuel treatment longevity.

Objectives

This project was initiated in response to JFSP FON 14-1-01 Task Statement 1, Fuel treatment effectiveness across landscapes. Our overarching objective was to increase our understanding of the mechanisms that influence the effectiveness of landscape scale fuel treatments. The original proposal had two broad objectives; 1) Investigate how proportion of landscape treated and treatment placement influence landscape-level fire spread patterns and behavior across a suite of topographies, and 2) Investigate the factors that influence landscape scale fuel treatment longevity. Although not one of our original objectives, significant investment in time and resources was needed to develop and test a new level set approach for landscape scale fire spread in WFDS and an open-source stand scale fire behavior in the R programming language.

Background

Policy initiatives such as the Collaborative Forest Landscape Restoration Program (Rep. Holt, 2009) have emphasized landscape-scale (> 10,000 ac) fuel reduction treatments to mitigate adverse impacts of large, uncharacteristic wildfires in the western United States. Over the past two decades, a nuanced understanding of the design and implementation of stand-scale treatments that reduce the behavior of future fires and enhance fire suppression capabilities has been developed across the western US. These approaches are generally referred to as fuel reduction treatments and involve the purposeful use of silvicultural methods to alter the fuels complex and ultimately reduce the behavior and effects of future fires (Hoffman et al., 2020). Although a spectrum of treatments can reduce fire behavior and effects, they have traditionally emphasized removing small diameter, fire-sensitive species combined with reductions in the surface fuel load and thus limiting the potential for crown fire ignition and spread (Stephens et al., 2021). Land managers typically prioritize fuel hazard treatments within or around the wildland-urban interface (WUI) or in strategic locations to aid in fire suppression activities.

Previous research has suggested that the strategic placement of fuel treatments across a landscape can effectively reduce fire's negative impacts (Finney, 2001). However, the implementation of strategic landscape-scale treatments is complicated by the large areas that require treatment to achieve beneficial landscape-scale effects and legal and physical constraints associated with land use and access. Furthermore, our conceptual understanding of landscape-scale fuel treatment placement is primarily based on simulations in idealized hypothetical landscapes (e.g., Finney 2001). While useful, such hypothetical landscapes typically do not account for the complex interactions between fuels complex, topography, and atmosphere on fire spread and intensity. Failure to consider these interactions has limited the development of theoretical frameworks that describe the influence of fuel treatment patterns and amount on landscape-scale fire effects and reduces the applicability of any gained knowledge to real-world landscape-scale fuel treatment planning. There is, therefore, a critical need to investigate the feedbacks created by interactions between fire, fuels, topography, and the atmosphere influence fuel treatments' effectiveness across landscapes and time. In the absence of such knowledge, it will be difficult for managers to assess the potential benefits and tradeoffs of alternative landscape-scale treatment designs. There will consequently remain a risk of implementing fuel treatments that do not meet management goals.

Methods

Fire Model Development

Wildland fire behavior and subsequent fire effects are driven by complex interactions among the fire, fuels, atmosphere, and topography (Hoffman et al., 2020; Linn et al., 2013; O'Brien et al., 2018). One of the primary challenges in the development of wildland fire behavior models is balancing the representation of these complex interactions with the ability to produce predictions in a timeframe that is useful for fire management (Hilton et al., 2018; Linn et al., 2020). Over the past sixty years, fire behavior model development in the U.S. has favored empirical modeling that can rapidly make predictions with minimal inputs over process-based models, which more completely capture complex interactions driving fire dynamics but are computationally slower. For example, many of the fire behavior models commonly used in the U.S. rely on linkages between the empirical Rothermel (1972, 1991) and Van Wagner (1977) empirical models to produce either point functional fire behavior predictions (e.g., Behave; Andrews 1986) or to simulate fire front propagation across a landscape (e.g., FARSITE; Finney 1998). More recently, several models have attempted to include the influence of dynamic interactions between the fire and atmosphere on fire spread by coupling simpler empirical fire spread models such as Rothermel (1972) with an atmospheric fluid dynamics model (e.g., WRF-Fire, Coen et al. 2013; QUIC-Fire, Linn et al. 2020). Here we present an overview of our development of 1) an open-source empirical point functional fire behavior modeling package called firebehavioR (Ziegler et al., 2019b), and 2) the development of an empirically based fire front propagation model within Wildland-Urban Interface Fire Dynamics Simulator (Bova et al., 2016) called WFDS-LS.

firebehavioR

firebehavioR is open-source software written in the R programming language (add download documentation) that includes fire behavior predictions based on the Rothermel (1972, 1991) and Van Wagner (1977) linkages or the CFIS modeling system (Alexander and Cruz, 2006). The software also includes additional functions for fire danger estimation. The R software (R Core Team, 2019) is open-source software with over 14,000 packages that support considerable flexibility in data management, analysis, and visualization. firebehavioR consists of three major functions: 1) the rothermel() function, 2) the CFIS() function and 3) fire danger indices through the fireindex() and fireIndexKBDI() functions.

The rothermel() function allows the user to estimate several nonspatial fire behavior metrics, including the fire ROS (m/min), FLI (kW/m), and type of fire (surface, passive, or active crown) (Table 1). Estimated fire behavior in the rothermel() is based on linking the equations of Rothermel (1972), which determine surface fire ROS, Van Wagner's (1977) model of crown fire initiation, and Rothermel's (1991) model for crown fire spread rate. The user can estimate CFB following one of three methods (Table 1). This allows the user to mimic the approach used in several popular point-functional fire behavior models including, Behave (), Nexus (), and FFE-FVS (). The inputs include standard or customized surface fuel models, the moisture content of surface and canopy fuels, physical attributes of the canopy, and a description of the physical environment (Table 1). To help the user estimate these variables, we also included an implementation of the Canopy Fuels Stratum Calculator (Cruz et al., 2003) and the ability to estimate the wind reduction factor based on known fuelbed characteristics using the waf() function. Finally, we included a function called rosMult()which allows the user to calibrate the ROS predictions through a multiplier effect.

The cfis() function implements the crown fire modeling framework described by Alexander and Cruz (2006). This model is primarily used to estimate the likelihood of crown fire initiation (Cruz et al., 2004), the type of crown fire (active or passive), the crown fire ROS, and the separation distance (Table 1). The input for the cfis() function includes the fuel stratum gap (FSG; m), open wind speed 10 m above the canopy (m/min), estimated fine fuel moisture (%), surface fuel consumed (Mg/ha), canopy bulk density (kg/m3) and ignition delay time (min). Like the rothermel() function, users can estimate unknown canopy fuel parameters using the canFuel() function.

Table 1. Inputs and outputs for the rothermel() and *cfis( )* functions.

Input	Description
surfFuel[1]	Surface fuel attributes consisting of: the fuel model type, either (S)tatic or (D)ynamic fuel load transferring; fuel loads (Mg/ha) for litter, 1-hr, 10-hr, 100-hr, herbaceous, and woody fuels; surface area-to-volumes (m^2/m^3) for litter, 1-hr, 10-hr, 100-hr, herbaceous, and woody fuels; fuel bed depth (cm); moisture of extinction (%); and heat content (kJ/kg), in order.
moisture[1]	Surface fuel moistures on a dry-weight basis (%) for litter, 1-hr 10-hr, 100-hr, herbaceous, and woody fuel classes, in order. Entered as *n* x 6 data frame.
crownFuel[1]	Canopy fuel attributes consisting of: canopy bulk density (kg/m^3); foliar moisture content ("%"); canopy base height (m); and canopy fuel load (kg/m2), in order.
enviro[1]	Environmental variables including: topographic slope ("%"); open wind speed (m/min); wind direction, from uphill (deg.); and wind adjustment factor (0-1), in order.
rosMult[1]	Crown fire ROS multiplier, defaults to 1. Array of length one.
cfbForm[1]	String specifying estimation method for crown fraction burned. Options are "sr" (Scott and Reinhardt, 2001), "w" (Van Wagner, 1993), or "f" (Finney, 1998).
fsg[2]	Fuel stratum gap (m)
u10[2]	Open wind speed, 10 m above the average canopy height (m/min)
effm[2]	Effective fine fuel moisture (%)
sfc[2]	Surface fuel consumed (kg/m^2)
cbd[2]	Canopy bulk density (kg/m^3)
id[2]	Ignition delay time for a spotting firebrand (min)

Output	Description
fireBehavior[1]	Fire behavior summary: fire type, crown fraction burned (%), ROS (m/min), heat per unit area (kW/m^2), fireline intensity (kW/m), flame length (m), direction of spread (°), scorch height (m), torching index (m/min), crowning index (m/min), surfacing index (m/min), effective midflame wind speed (m/min), flame residence time (min)

detailSurface[1]	Surface fire behavior intermediates: potential ROS (m/min), no wind & no slope ROS (m/min), slope factor (-), Wind factor (-), characteristic fuel moisture (%), characteristic SAV (m^2/m^3), bulk density (kg/m^3), packing ratio (-), relative packing ratio (-), reaction intensity (kW/m^2), heat source (kW/m^2), heat sink (kJ/m^3)
detailCrown[1]	Crown fire behavior intermediates: potential ROS (m/min), no wind & no slope ROS (m/min), slope factor (-), wind factor (-), characteristic fuel moisture (%), characteristic SAV (m^2/m^3), bulk density (kg/m^3), packing ratio (-), relative packing ratio (-), reaction intensity (kW/m^2), heat source (kW/m^2), heat sink (kJ/m3)
critInit[1]	Critical values for crown fire initiation: fireline intensity (kW/m), flame length (m), surface ROS (m/min), canopy base height (m)
critActive[1]	Critical values for active crown fire: canopy bulk density (kg/m^3), crown fire ROS (R'active) (m/min)
critCess[1]	Critical values for cessation of crown fire: canopy base height (m), O'cessation index (m/min)
type[2]	Type of fire (surface, passive, or active crown fire)
pCrown[2]	Probability of crown fire (%)
cROS[2]	Crown fire rate of spread (m/min)
sepDist[2]	Minimum distance for a spot fire to not be overrun by an advancing fireline (m)

[1] Inputs and outputs for *rothermel( )*; [2] Inputs and outputs for *cfis( )*

In addition to the rothermel() and cfis() functions, we also included the option to calculate several fire danger indices. Fire danger indices provide a method to gauge relative fire danger based on changing weather and/or fuel conditions. fireIndex() function calculates static indices including the Angstrom, Chandler Burning, Hot-dry-windy, Fuel Moisture, Fosberg Fire Weather, and MacArthur Grassland Mark IV and V indices (Sharples et al., 2009). These indices require the user to supply estimates of the air temperature, wind speed, and relative humidity. The MacArthur indices also require the available fuel load and percent grass curing in the case of Mark IV. In contrast, the fire danger indices estimated with fireIndexKBDI() are dynamic; these indices are updated daily based on the prior day's value and the current day's conditions. Most of these indices rely on the Keetch–Byram Drought Index (KBDI) or the drought factor (DF), a component of KBDI (Keetch and Byram, 1968). In addition to KBDI and DF, this function yields the Forest Mark V, the Fosberg Fire Weather Index modified with KBDI, the Fuel Moisture Index modified with KBDI, the Nesterov Index, a modified Nesterov Index, and the Zdenko Index (Goodrick, 2002; Groisman et al., 2005; Skvarenina et al., 2003). Inputs for fire danger ratings vary but often include air temperature, precipitation amount, mean annual precipitation, wind speed, and relative humidity.

firebehavioR is available on the Comprehensive R Archive Network (https://cran.r-project.org/web/packages/firebehavioR/). Alternatively, you can install the development version from GitHub (https://github.com/EcoFire/firebehavioR). Additional resources regarding firebehavioR can be found in Ziegler et al. (2019) and through the reference manual and vignette available at https://cran.r-project.org/web/packages/firebehavioR/.

WFDS-LS Overview and Development

The wildland-Urban Interface Fire Dynamics Simulator (WFDS) is an extension of the Fire Dynamics Simulator, developed at the National Institute of Standards and Technology to predict fire spread and smoke transport (McGrattan et al., 2016a). WFDS has both a physics-based (WFDS-PB) model for fire behavior simulations (Mell et al. 2007) and an approach for fire front propagation based on the level set method (WFDS-LS). We have abbreviated the physics-based model to WFDS-PB, and the level set based model to WFDS-LS. WFDS-PB simulates fire dynamics through vegetative fuels by explicitly representing the known and assumed processes and their interactions with each other and the environment (Hoffman et al., 2020). More details about WFDS-PB are provided by (Mell et al. (2007) and Mell et al. (2009). Verification and validation of the Fire Dynamics Simulator are presented in (McGrattan et al. (2016b, 2019). Further evaluation of the use of WFDS-PB for vegetative fuels can be found in Mell et al. (2007, 2009), Castle et al. (2013), Mueller et al. (2014), Overholt et al. (2014), Hoffman et al. (2016), Perez-Ramirez et al. (2017), Sánchez-Monroy et al. (2019).

Fire front propagation in WFDS-LS is based on a Eulerian based level set approach. The level-set method is a commonly used technique to track a propagating fire front (Coen et al., 2013; Lautenberger, 2013; Rehm and Mcdermott, 2009; Rochoux et al., 2014). The level set function (Φ_{ls}= f(x(t), y(t), t= 0) defines the area that separates the unburned areas (Φ_{ls} > 0) from the burned area (Φ_{ls} <0) and the fire front (Φ_{ls} = 0). To find the rate of change of the level set function at a fixed point along the fire line is estimated as follows:

$$\frac{d\emptyset_{ls}}{dt} = \frac{\partial\emptyset_{ls}}{\partial t} + R_u\frac{\partial\emptyset_{ls}}{\partial x} + R_v\frac{\partial\emptyset_{ls}}{\partial y} = 0$$

where Ru and Rv are the rates of fire spread in the x- and y-directions, respectively. Equation x is solved numerically given the initial conditions in the simulation domain and an estimate, or a model, of fire spread rates. Further details of the numerical solution of the level set equation can be found in Bova et al. (2016) and Rehm and Mcdermott (2009).

The surface fire ROS is estimated based on the Rothermel (1972) spread rate formula. Currently, WFDS-LS does not contain the Rothermel equation for the calculation of no-wind, no-slope spread rate (R_0). Therefore, users must estimate R_0 and enter this value in the input file. This can be carried out using other fire behavior software such as firebehavioR (Ziegler et al., 2019b). Modification of R_0 to account for non-zero wind and slope is accomplished by estimating vector forms of the wind and slope coefficients based on data from Wilson (1980) following Finney (1998)and Andrews (2012). The local surface fire spread rate, R, is than estimated following Rothermel (1972) using the magnitude of the combined mid flame wind and slope vectors (Andrews, 2012):

$$R_s = R_o\left(\sqrt{(\emptyset_w + \emptyset_s)\cdot(\emptyset_w + \emptyset_s)}\right)$$

Rates of spread of the flanking and backing portions of the front are estimated using the same equations found in Finney (1998), where it is assumed that the fire front has an elliptical shape. The length-to-breadth ratio, LB, of the elliptical fire front is estimated following (Anderson, 1983):

$$LB = 0.93\ exp(0.2566U) + 0.461\ exp(-0.15481) - 0.397$$

The maximum length to breadth ratio is set to match that used by Finney (1998).

$$LB = max\ (1, (LB, 8))$$

To account for the effect of slope in the Anderson (1983) we use Finney's (1998) assumption that the effect of slope may be accounted for by creating a virtual midflame wind speed:

$$U_{virtual} = 0.3048\left[\frac{1}{C}\left(\frac{\beta}{\beta_{op}}\right)^{E}\right]^{1/B}(\emptyset_{s,x}, \emptyset_{s,y})$$

The ‘effective’ wind vector is then calculated as the sum of the midflame wind vector and the virtual wind vector and substituted into the length to breadth ratio equation. The heading-to-backing fire spread rate ratio, HB, and spread rates that determine the elliptical axes are calculated following the methods of Richards (1990) and Finney (1998). Additional details in the level set method can be found in Bova et al. (2016).

WFDS-LS can account for the ignition and spread of crown fires on ROS and FLI using either the approach outlined in Scott and Reinhardt (2001) or Cruz et al. (2006). Regardless of the approach chosen, there are three steps in the model. First, the potential for crown fire initiation is estimated, then the type of fire (i.e., passive or active) is estimated, and finally the ROS and FLI are estimated.

The Scott and Reinhardt (2001) approach allows users to simulate the fire across surface, passive, and active crown fires by linking Van Wagner's (1977, 1993) crown fire transition criteria to Rothermel's surface and crown fire spread models (1972, 1991). Crown fire transition is determined by comparing the predicted surface fireline intensity (I_s) to a threshold surface fireline intensity (I_i). The threshold fireline intensity is estimated following Van Wagner (1977):

$$I_i = [0.01\ CBH(460 + 25.9\ MC)]^{\frac{3}{2}}$$

where the CBH is the canopy base height (m), and the MC is the moisture content (%) on a dry mass basis of the available canopy fuel. If crown fire ignition is possible, that is $I_S > I_i$, we then determine if the crown fire would be classified as either a passive or active crown fire; otherwise, the surface fire ROS is used. Following the procedure outlined in Scott and Reinhardt (2001), we first estimate the active crown fire rate of spread (R_A) based on Rothermel (1991).

$$R_A = 3.34 R_{S,10}^{0.4}$$

where $R_{S,10}^{0.4}$is the surface fire ROS for standard fire behavior fuel model 10 (Anderson, 1982) with a wind reduction factor of 0.4. The critical minimum rate of spread (RAC) required to sustain active crowning is estimated as:

$$RAC = \frac{3.0}{CBD}$$

where the CBD is the canopy bulk density. If I_S is greater than I_i and R_A is greater than or equal to RAC the fire is classified as an active crown fire. If I_S is greater than I_i and R_A is less than RAC the fire is classified as a passive crown fire. The crown fraction burned (CFB) ranges from 0 for surface fires to 1 for active crown fires. CFB is estimated as is estimated as:

$$CFB\ =\ (R_S - R_i)\ /\ (R'_{SA} - R_i)$$

where $R_i$is the critical rate of spread for crown fire initiation, and $R'_{SA}$is the surface fire rate of spread that corresponds to the environmental conditions where there is complete crown consumption. R_i and $R'_{SA}$are calculated as described in Scott and Reinhardt (2001).

The final rate of spread (R_f) can be estimated using one of two approaches. The first approach SR follows Soctt and Reinhardt et al. 2001 and estimates the final rate of spread as:

$$R_f = R_s + CFB(R_A - R_s)$$

Alternatively, users can specify the FS model which is based on Finney (1998) and estimates the final rate of spread as follows:

$$\text{If } R_A < \ RAC \text{ then } R_f = R_S$$

$$\text{If } R_A \geq RAC \text{ then } \ R_f = R_A$$

Users can also estimate the likelihood and rate of spread of a crown fire using equations outlined in Cruz et al., (2005, 2004). The probability of a crown fire occurring (P_C)is estimated:

$$P_C = e^g/(1 + e^g)$$

where g depends upon the surface fuel consumption (SFC), which is commonly estimated as the amount of available fuel and was coded as a categorical variable.

$$4.236 + 0.357U_{10} - 0.71FSG - 4.613 - 0.331EFFM,\ SFC <= 1\ kg\ m^{-2}$$

$$g = 4.236 + 0.357U_{10} - 0.71FSG - 1.856 - 0.331EFFM,\ 1 < SFC <= 2\ kg\ m^{-2}$$

$$4.236 + 0.357U_{10} - 0.71FSG + 0.000 - 0.331EFFM, SFC >= 2 \text{ kg m}^{-2}$$

where U_{10} (km/hr) is the wind speed 10 m above canopy, FSG (m) is the fuel strata gap, and EFFM (%) is the estimated fine fuel moisture content.

To date, the type of crown fire (i.e., passive, or active) has not been linked to the predicted crown fire probability level. To overcome this, Cruz et al., (2005) developed an approach to distinguish the various types of fire based on Van Wagner's (1977, 1993) criterion for active crowning (CAC):

$$CAC = CROS_A / R_o$$

Where the $CROS_A$ is the predicted active crown fire rate of spread, R_o is the critical spread rate needed to achieve a crown fire. R_o can be estimated by dividing the critical mass flux (MFR_o) of 3.0, which was determined experimentally by Van Wagner (1977) by the estimated canopy bulk density (CBD) for a continuous active crown fire. To determine the type of crown fire in WFDS, the user selects a probability of crown fire below which all fires are assumed to be a surface fire and above which the fires are assumed to be either a passive or active crown fire. Passive crown fires occur when the estimated CAC is < 1, active crown fires are predicted to occur when the estimated CAC is ≥ 1.

For active crown fires (i.e., where CAC ≥ 1) the rate of spread is estimated as:

$$CROS_A = 11.02 \, (U_{10})^{0.9} \, CBD^{0.19} \, e^{-0.17EFFM}$$

where U10 is the open 10-meter wind velocity, CBD is the estimated canopy bulk density and EFFM is the estimated fine fuel moisture. For passive crown fires the rate of spread is estimated as:

$$CROS_P = CROS_A \, e^{-CAC}$$

The level set methods described in this document along with example input files are available in the Wildland Urban Interface Fire Dynamics Simulator version 9977 which can be downloaded at (https://github.com/ruddymell/wfds9977). Future work will integrate these approaches into the Fire Dynamics Simulator (https://pages.nist.gov/fds-smv/downloads.html).

Surface fire spread comparisons between WFDS level set and FARSITE

To assess the ability of WFDS-LS to simulate an advancing fire front, we made a series of comparisons between WFDS-LS and the marker-based approach used in FARSITE (Finney, 1998). All simulations were conducted using a 1 square kilometer simulation domain discretized as a mesh forming 10- x 10-m cells with a vertical resolution of 1 m. We simulated five scenarios on flat ground and two scenarios with complex terrain. The flat ground scenarios include 1) a single point ignition in grass fuels, 2) two point ignitions in grass fuels, 3) a simulation domain consisting of a random mix of 100x100m grass and chamise patches, 4) a domain with a 300 x 300 m non-burnable patch found in the center of the domain and 5) a domain consisting of 50 x 50 m array of unburnable patches. The complex terrain scenarios consisted of a single terrain, generated using a '1/f' filter to the fast Fourier transform of a random noise field. For the first complex topographic scenario, we placed the grass fuel model in every cell. In the 2nd scenario we placed the same random pattern of grass and chamise fuels used in the flat ground scenario. All simulations had an unburnable 100 m wide perimeter around the domain to ensure constant boundary conditions during the simulation. The open wind speed was set at 18 km h^{-1} in all simulations. The two surface fuel models used in the comparisons, a grassland fuel model, and a chamise fuel model are described in Table 2. We estimated the no-wind, no-slope rates of spread, R_0, using the Rothermel (1972) ROS model for each fuel model (Table 2). No fire acceleration (i.e., no change in rate between ignition and steady-state spread) was implemented in either model, or the default minmod flux limiter was used unless noted.

To compare the respective LS and FS simulations, we compared isochrones of the time of arrival (TOA) of fire lines. The isochrones (TOA contours) were compared using a custom Matlab (Mathworks, Inc., v. 2010, Natick, MA) script that estimates the lengths of fire perimeters and burned areas at periodic intervals.

Table 2. Fuel properties for grassland and chamise fuel models used in WFDS-ls and FARSITE comparisons.

Fuel Model	Chamise Fuel Model	Grassland Fuel Model
Packing Ratio	0.0041	0.0012
Surface area to volume ratio (m^{-1})	3344	11400
Fuel Height (m)	0.91	0.51
1-h fuel moisture (%)	2	6
10-h fuel moisture (%)	4	n/a
100-h fuel moisture (%)	5	n/a
Live herbaceous fuel moisture (%)	90	n/a
Live woody fuel moisture (%)	70	n/a
No-wind, No-slope ROS ($m\ s^{-1}$)	0.007	0.04

Influence of topographic complexity on landscape scale fuel treatment effectiveness.

The overall objective of this study is to assess the effect of the proportions of landscape treatment on landscape scale fire behavior across a range of topography complexities. We represented a range of topographic complexity using rugged and dissected landscapes containing a mixture of topographic features including V-shaped valleys, plateaus, and flatlands. We selected three different representative 5 km x 3 km landscapes termed Landscapes A, B, and C (Figure 1). Landscape A had a median slope of 34%, and an elevation range of 432 m; the prominent feature was a modest ridge oriented in the streamwise X axis and could be described as hilly. Landscape B had a median slope of 33% and ranged up to 443 m; the topographic variation in Landscape B included larger swaths of flat lands and a more defined central valley spanning the streamwise direction. Landscape C was the most mountainous with a median slope of 87% and ranged up to 1447 m in elevation; this landscape featured the most incised canyon, also oriented in the streamwise direction.

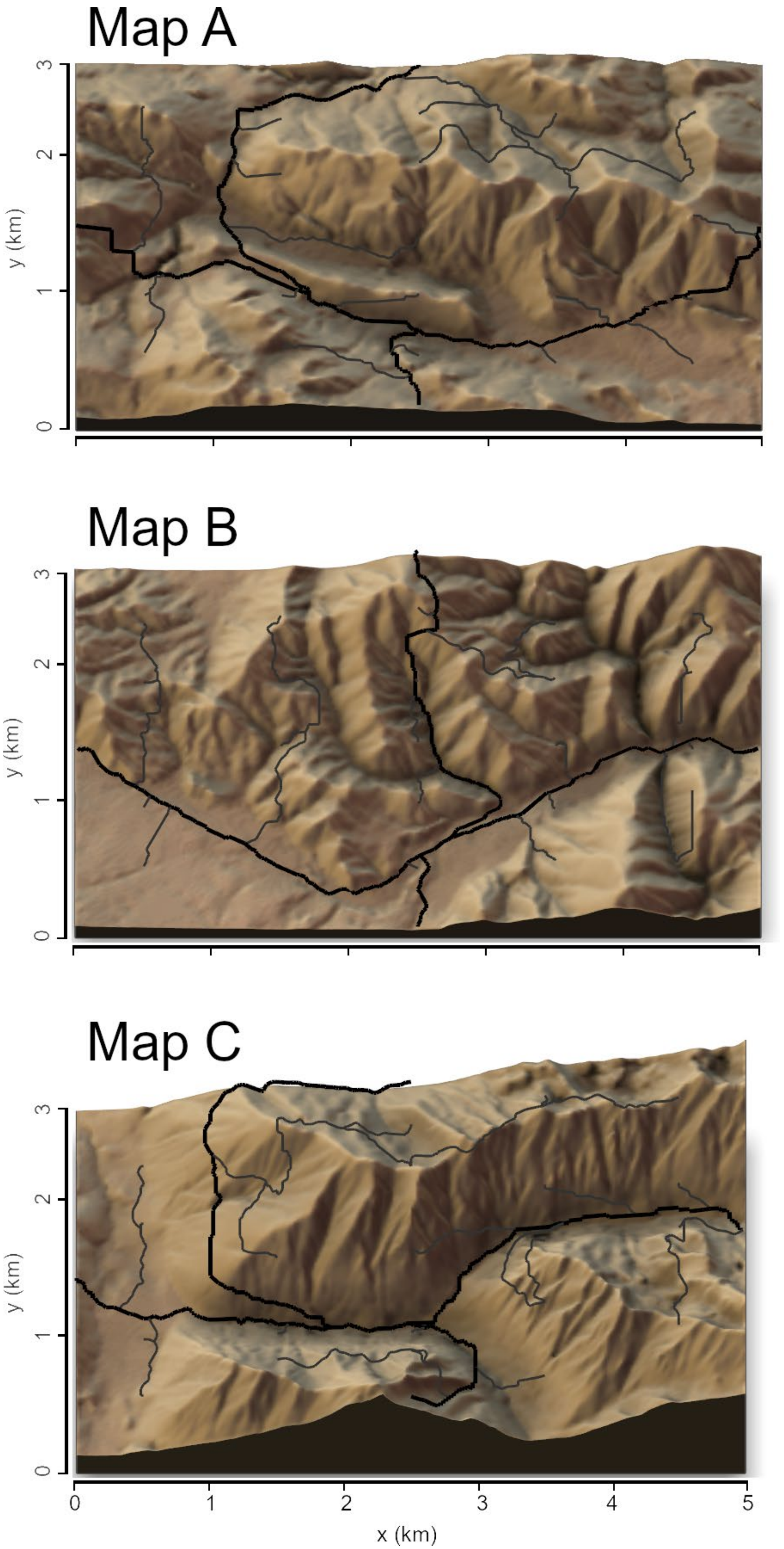

Figure 1. Oblique visualizations of simulation landscapes, with simulated major roads (black lines) and minor roads (dark grey lines).

We simulated three levels of fuel treatments: 0, 5, 10 or 15% of landscape proportion treated. The locations for these treatments were determined based on three factors designed to emulate real-world constraints. These included: road network density, allowable distance from roads, and whether a treatment could be placed on steep slopes. First, we constructed a sparse and dense road network. First, we constructed a sparse network of two major roads connecting the mid-points along each four sides for each Map. The dense road network was constructed by forming a ½ km x ½ km grid over each landscape and adding minor roads connecting these grid points to the major roads. The layout of these roads was determined by Dijkstra's algorithm using the gdistance software package (van Etten, 2017) in R v3.6.3 (R Core Team, 2019); this least-cost algorithm seeks the shortest distance between points, weighted by 'resistance', a parameter derived by slope. In practice, this algorithm creates topographically contouring road layouts, suited for road layouts in mountainous environments. Second, treatments were, or were not, allowed to be placed on ground with 40%+ slope. Third, we applied a narrow or a wide buffer from roads, permitting treatments to be placed either 200m or 400m from any road.

Our study design used a full factorial approach to assess the effect of treatment proportion and the effects of placement constraints on fire behavior. Each simulation of landscape fire had either 5%, 10% or 15% of the landscape treated, a sparse or dense road network, a wide or narrow buffer in which to place treatments, and slope was or was not limiting placement. This led to 40 different combinations of factors that determine the random placement of treatments. For each combination of factors, we created 5 realizations of treatment placements, leading to 480 total simulations, 160 for each map. Because Map C was so rugged, there were 15 instances in which we could not place treatments given the slope constraint; these simulations were not considered in any further analysis.

All simulations were conducted with the level set formulation (Bova et al., 2016) of the Wildland Fire Dynamics Simulator (WFDS) version 9977. All WFDS-LS simulations were conducted using a domain that measured 5000 m × 3000 m × 480 m that was discretized as a mesh of 20 × 20 m cells. To account for the effect of terrain on the wind speed and direction we developed gridded data of wind direction and velocity for each topography. Gridded wind data was developed for each simulation by initializing the domain with an inflow wind field described with an atmospheric power law profile with neutral boundary conditions and a u-velocity of 22 m/s at 20 meters above the ground. We ran the wind field for 3000 seconds after which time we saved out the open wind velocity and direction for each 20 x 20m cell. The wind fields for each topography were used to initialize the fire simulations. The open wind speeds were converted to midflame wind speeds for surface fire spread rate predictions using a wind adjustment factor of 0.18 for untreated stands and 0.09 for treated stands. Fire was ignited in all simulations as an approximately 1 ha rectangular fire located from 20 to 100 m in the dx dimension and from 1440 to 1560 m in the dy dimension.

We assigned a single set of canopy fuel parameters to all untreated areas and another set of parameters within treatments. These parameters correspond to ponderosa pine/Douglas-fir stands sampled by Scott and Reinhardt (2005). The simulated treatment was designed to replicate a thin form below with whole tree harvesting. Canopies were 23 m tall in both conditions with a foliar moisture of 100%. Treated stands had a canopy base height of 11 meters and a canopy bulk density of 0.037 m. The untreated stands had a canopy base height of less than 1 m and a canopy bulk density of 0.089 kg m-3. We assumed a standard fire behavior fuel model 10 in all stands, with the dead fuel moisture scenario 'D1L1' (i.e., 3%, 4%, 5%, 30% and 60% fuel moistures for 1 hour downed dead wood (DWD), 10 hr DWD, 100 DWD, live herbaceous, and live woody fuels, respectively).

After fire simulations were completed, we extracted the median ROS, FLI, and CFB within each 20 × 20 m cell of each fire simulation's burned area. We then fit regressions with the following form to examine the impact of treatment proportions and constraints on fire behavior metrics,

$$y = PT + SC + RD + RB + LS\times PT + LS\times SC + LS\times RD + LS\times RB$$

where: y was the response, either ROS, FLI, or CFB; PT was proportion of the landscape treated, either 5%, 10%, or 15%; slope constraint (SC) was where treatments are constrained to slopes of less than 40% or now; RD was road density, either high or low; RB was the road buffer limiting treatment placement, either 200 m or 400 m from a road; and landscape (LS) referred to one three landscapes simulated, A, B or C. We added the two-way interactions to separate how the impacts of each independent variables might have varied by individual landscape.

Long-Term Impacts of Fuel Treatment Placement with Respect to Forest Cover Type on Potential Fire Behavior across a Mountainous Landscape

We designed this study to examine how treatment placement among different cover types with differential productivity rates impacted the initial effectiveness and duration of fuels treatments in mountainous landscapes. We distributed cover types with low and high productivity rates over a real-world landscape, populating stands using forest inventory data, applied treatments to these stands, and then simulated forest growth as well as landscape fires. We hypothesized that treatments in more productive stands would be more effective than less productive stands as the former have greater fuel loads. Secondly, we supposed that treatment effects would have a longer duration on the less productive stands owing to lower recovery rates.

Study landscape

We created a realistic but idealized landscape of undisturbed forests to investigate the impact of treatment configuration, treatment age, and topography on landscape fire behavior. We selected an 8 km by 6 km landscape within the Arapaho-Roosevelt National Forest, Colorado, USA (Figure 2a). This mountainous landscape had mostly northern and southern facing aspects (Figure 2b), which are commonly differentiated by ponderosa pine and Douglas-fir forests on each respective aspect. Slope ranged from 1% to 66% and averaged 20%. We divided this landscape into fictional stands. First, we classified land into northerly (270–90°) and southerly (90–270°) aspects, and then we superimposed a 400 m by 400 m grid onto our landscape to split up areas of contiguous aspects. This resulted in 1187 stands which ranged in size from 1–16 ha, averaging 4 ha (Figure 2c).

Next, we populated the stands within the landscape using plots in the Forest Inventory & Analysis (FIA) database (USFS FIA DataMart; https://apps.fs.usda.gov/fia/datamart/). We drew FIA plots found within the Arapaho-Roosevelt National Forest, with no recent disturbance, and a stand age of at least 80 years. We then classified these plots as ponderosa pine or Douglas-fir forest type based on whether the respective species accounted for at least half of the plot's basal area and stem density. We subsequently filtered these plots based on productivity as estimated by the growth and yield model, Forest Vegetation Simulator (FVS; Crookston and Dixon, 2005). We selected 18 Douglas fir-dominated plots producing at least 0.0168 kg m^{-2} yr^{-1} and 26 ponderosa pine-dominated plots producing less than 0.0168 kg m^{-2} yr^{-1}. We then randomly attributed these ponderosa pine and Douglas-fir plots to southerly and northerly stands, respectively, in our landscape.

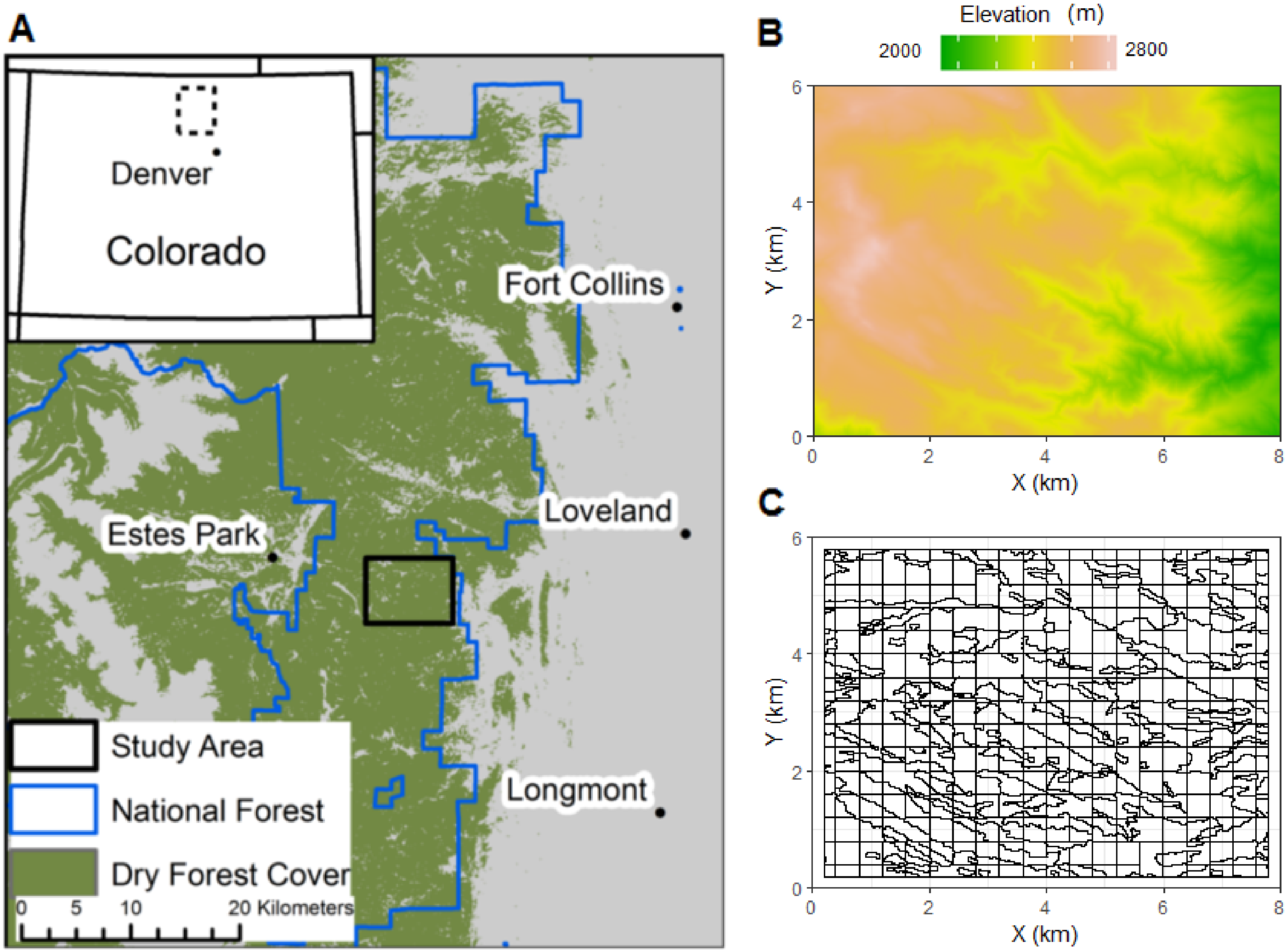

Figure 2. The (a) location, (b) elevation and (c) stand delineations used in Ex. et al. 2019 simulations.

Simulation of fuel treatments

We simulated three scenarios of hazardous fuel treatment placements: a scenario with no treatments, a scenario with treatments only within southerly (ponderosa pine-dominated) stands, and a scenario with treatments only within stands on northerly aspects (Douglas-fir-dominated). In the latter two scenarios, the areal footprints of treatments were 20% (9.6 km2) of the total landscape and stands to be treated were chosen randomly with regard only to aspect and not by stand conditions (e.g., CBH, CBD, stand basal area, etc.).

We simulated immediate effects and fuel dynamics of hazardous fuel reduction treatments over 50 years using the FVS variant parameterized for the central Rocky Mountains. The following details for treatments emulated current silvicultural specified within the Colorado Front Range (Underhill et al., 2014). Treated stands were thinned using a two-step process. First, we simulated a tin-from below for all trees under 10 cm, followed by a free thinning of trees with a DBH above 10 cm until a residual basal area of 11.5 m^2 ha^{-1} was reached. Treatments preferentially removed late seral, shade-tolerant tree species at an 80% harvesting efficiency on southern aspects, and preferentially removed early seral, shade-intolerant species at a 90% harvesting efficiency on northern aspects. In the case of stands within southerly aspects, 14 of the 26 FIA plots used to represent stands already met fuel treatment specifications and were thus excluded for potential treatment. We assumed additional tree regeneration in modeling dynamics of stands over 50 years. Informed by prior studies on tree regeneration rates within similar Colorado Front Range forests (Francis et al., 2018), we specified that fuel treatments would result in 432 ponderosa pine and 123 Douglas-fir seedlings per hectare in southerly stands and 385 ponderosa pine and 553 Douglas-fir seedlings per hectare on northerly stands. Seedlings had an initial height of 0.30 m and no mortality over the initial decade, after which mortality rates were assumed by FVS. Within untreated stands, we assumed these more densely stocked stands had no available growing space for regeneration. While we allowed FVS to dynamically alter canopy fuel conditions over the fifty simulated years, we held surface fuel parameters constant. We assigned Fuel Model 9 (medium hazard timber litter;) with a dead fuel moisture of 9% and live fuel moisture of 30% to southerly stands and Fuel Model 10 (high hazard timber litter) with 9% dead, and 30% live fuel moistures to northerly aspects.

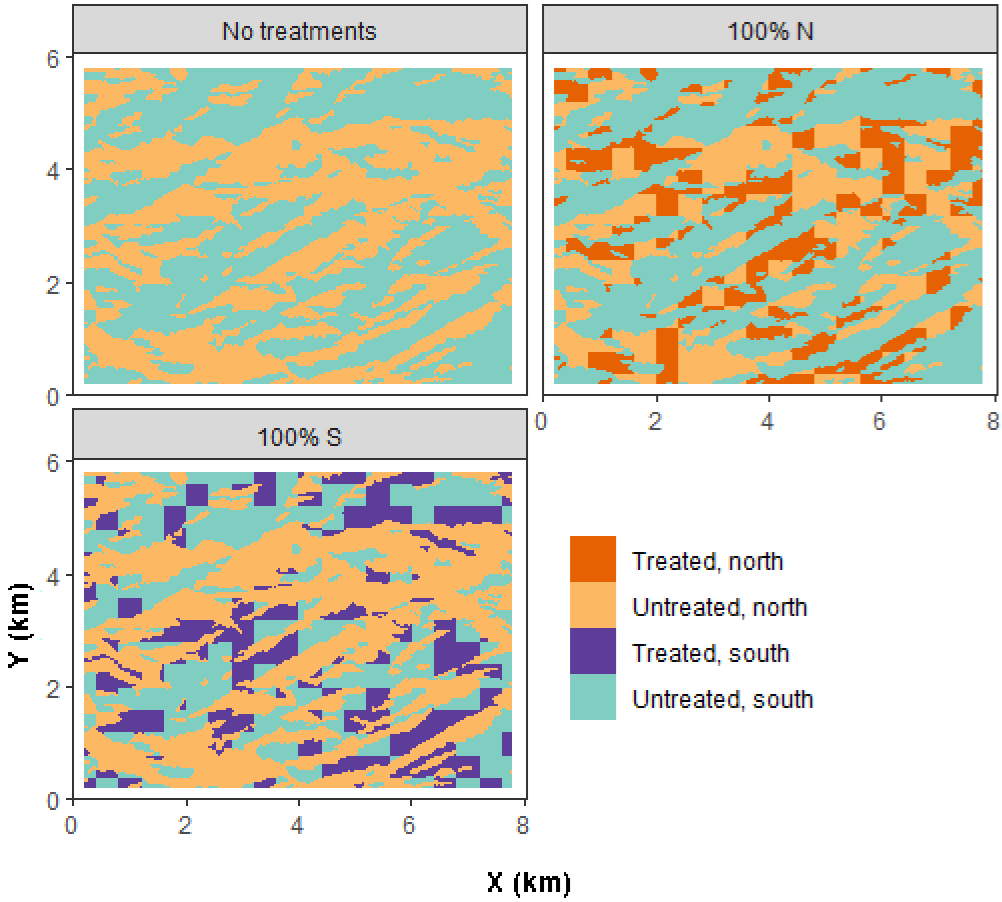

Figure 3. Aspect delineation and location of treatments for each of the three scenarios in Ex. et al. 2019.

FVS-FFE incorporates predefined fuel loadings to represent surface fuels (Rebain, 2010). Surface fuel models in FVS-FFE change over time depending on stand conditions, which can strongly influence model predictions of fire behavior. These changes can obscure the effects of tree regeneration and growth. As this work was specifically focused on tree regeneration and growth impacts to potential fire behavior, surface fuels for southerly aspects dominated by ponderosa pine were simulated as a fuel model 9 (medium hazard timber litter) with a dead fuel moisture of 6%. In comparison, surface fuels on the Douglas-fir dominated northerly aspects were simulated as a fuel model 10 (high hazard timber litter) with dead fuel moisture of 9% and a live fuel moisture of 30%. Surface fuel model assignments were then held constant throughout all simulations. Crown fuels were modeled to be dynamic, with stand-specific parameters: FVS-FFE estimates initial crown fuel quantities (e.g., CBH, CBD) from inventory data using allometric models and then uses parameters that are species- and site-specific to model subsequent change.

Wildfire simulation

To simulate the effect of treatments on fire spread across the analysis landscape, we used a level-set-based fire propagation model in WFDS. All WFDS-LS simulations were conducted using a domain that measured 8000 m × 6000 m × 920 m that was discretized as a mesh of 20 × 20 m cells. WFDS-LS requires the user to provide gridded ASCII data that describe the topography, fuels, fuel moisture, and wind velocity and direction. In our simulations, we used the default relative humidity (40%), temperature (20 °C), and pressure (101325 Pascal). However, it is important to recognize that these values are independent of the fuel moistures prescribed in WFDS. Slope and aspect were described in WFDS-LS by first extracting the slope and aspect from the 10 m digital elevation model (The National Map. Available online: https://nationalmap.gov) using base tools in ArcGIS 10.3 (ESRI, Redlands, CA, USA) and then reclassifying this data using a majority filter to a 20 m × 20 m resolution. Surface fuels were simulated as described in Section 2.3 above. Canopy fuel properties (i.e., CBH and CBD) were populated in each time step based on the FFE-FVS predictions described in Section 2.3, with a foliar moisture content of 100% as suggested by Agee et al. (2002). To generate the wind velocity and direction datasets, we developed a "wind-only' simulation based on our 20 × 20 m gridded topographic data. Wind flow was entered into the simulation along the x = 0 plane following an atmospheric power-law profile with a velocity of 12 m s−1 at 10 m above ground. We allowed the wind to flow across the domain for 0.8 h, at which time we extracted gridded wind velocity data 20 m above the terrain. We adjusted the open wind speeds to the midflame wind speeds following Andrews (2012). All other values in the simulation were set at the defaults for WFDS.

Metrics from our fire spread simulations included fire size, mean ROS, and the proportion of area burned with surface, passive, and active fire behavior. The fastest spreading of the scenarios reached the end of the simulation domain in 7.5 h. We extracted potential fire behavior measures from all scenarios at 7.5 h of simulated time to facilitate comparisons across scenarios. We used the spatial extent of burned grid cells to characterize fire size and the average rate of fire spread. Following typology used by the Canadian Forest Fire Behavior Prediction System (Forestry Canada Fire Danger Group, 1992), we classified fire behavior for grid cells as 'surface', 'active crown', or 'passive crown' according to whether CFB was <10%, >90%, or between breakpoints, respectively. Then, we tabulated the relative frequency of each fire type within each simulated fire footprint.

Results and Discussion

Surface fire spread comparisons between WFDS-LS and FARSITE

This study used a series of surface fire spread simulations in two different fuel types and over domains of increasing topographical complexity to evaluate the difference in fire front propagation between a level set (WFDS-LS) and marker method (FARSITE) model. The differences between the two models were minor, especially compared to the inherent uncertainties associated with modeling fire spread. Comparisons of fire spread for the flat ground simulations indicated differences in the burned area ranged from less than 2 to 12 percent. The differences in the final burned area between the two models for the flat ground with one fuel type, flat ground with multiple ignition points, and flat ground with two fuel types were 2% or less (Figure 4).

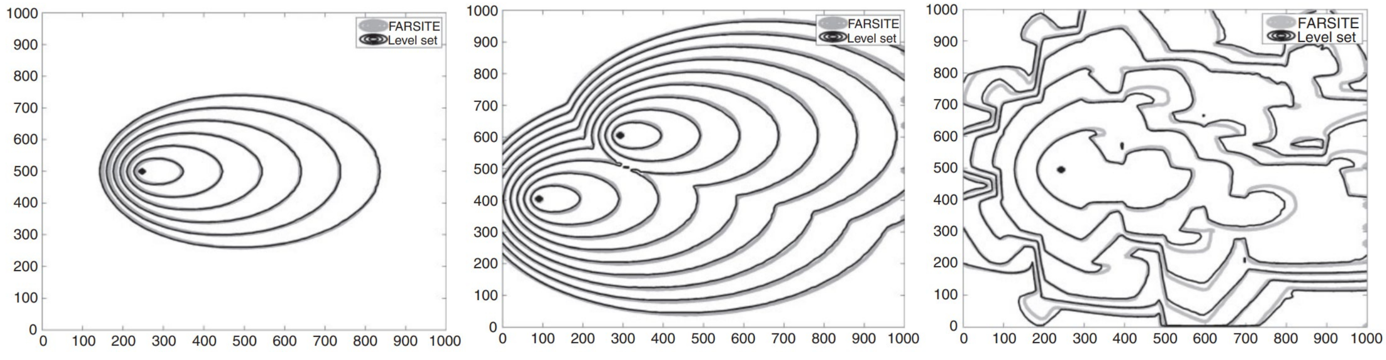

Figure 4. Expansion of fire perimeters for WFDS-LS (Black), and Farsite (Grey) for flat ground with grass fuels, flat ground with grass fuels and multiple ignition points and flat ground with a random pattern of grass and chamise fuels. Contours are separated by 180s for flat ground with grass fuel and a single or multiple ignition points and 600s for flat ground with random patches of fuels.

Differences in the final fire perimeter in WFDS-LS and FARSITE were greater for the two flat ground simulations that incorporated unburnable patches. The presence of unburnable patches presents a special challenge for the level set approach due to the sharp gradient associated with the unburnable areas. In the simulation with a single 300x300m unburnable patch (Figure 5) the difference in the final area burned between the two models was approximately 5%. For the more complex unburnable case, which consists of an array of 50x50 m unburnable patches surrounded by grass, WFDS-LS produces slower spread rates along the flank fires resulting in a reduction in the area burned by 11-12% compared to FARSITE (Figure 5). Interestingly, the difference between the two models decreased to 3% when the superbee flux limiter was used instead of the default minmod limiter.

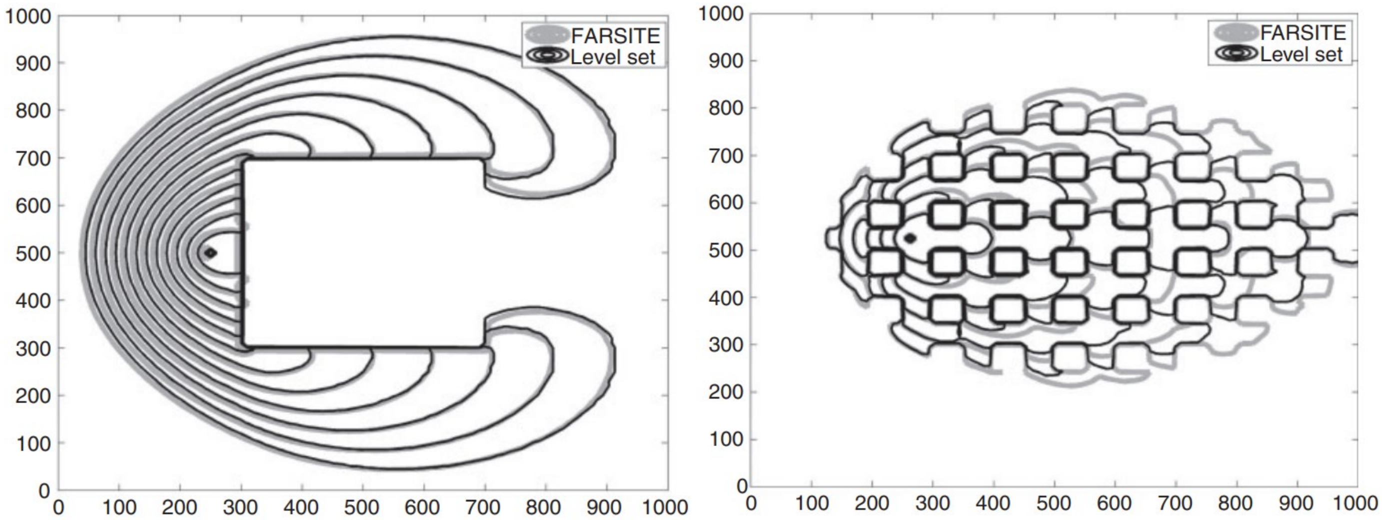

Figure 5. Comparison of fire perimeters for WFDS-LS (Black), and Farsite (Grey) for flat ground with grass fuel and a single 300x300m unburnable area, and for flat ground with grass fuels and an array of 50x50m unburnable areas.

The corresponding contours of the two models for the complex terrain case with grass fuels match closely with each other. The WFDS-LS contours tend to have more curvature than those generated by FARSITE, resulting in a final burned area that is 2% smaller than the FARSITE predictions. Comparisons between the two models for the complex terrain scenario with two fuel types are more complicated than those with a single fuel type in complex terrain. The largest differences in the burned area (16%) between the two models occur partway through the simulation for the multiple fuel type simulations. As simulation time increases, there is a greater agreement between the two models (Figure 6). In general, WFDS-LS tended to lag the FARSITE simulation for this case.

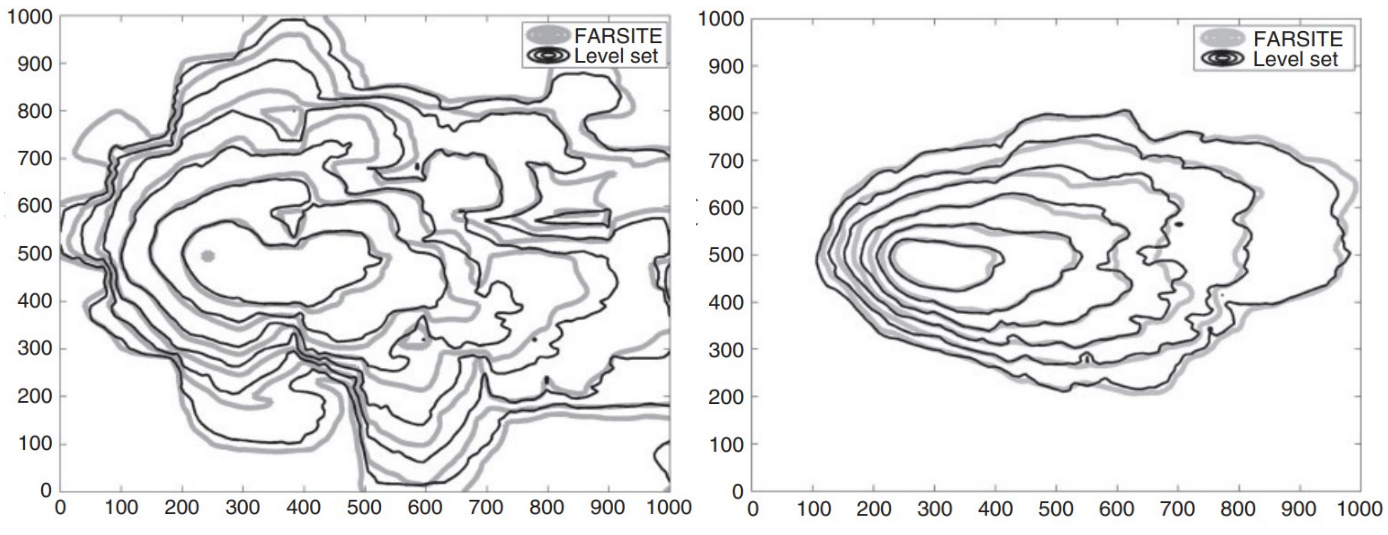

Figure 6. Comparison of fire perimeters for WFDS-LS (Black), and Farsite (Grey) for complex topography with grass fuel, and for complex topography with a random patchwork of grass and chemise fuels.

Although our results show that WFDS-LS can produce similar fire perimeters to FARSITE for simple cases, more complex cases resulted in differences in area burned of up to 16%. These differences occur as relatively small dissimilarities at the initial stages of the simulation that become exaggerated as time progresses. Other simulations (not shown) indicate that significant improvement in model agreement occurs when the superbee flux limiter is used rather than the default minmod limiter. Furthermore, increasing the mesh resolution can also reduce model disagreement, suggesting that level set simulations of fire spread might be improved by incorporating adaptable mesh capabilities. Our results suggest that although the level set and Lagrangian marker approach used in FARSITE are often regarded as different models, they are similar enough in most cases to be considered interchangeable for wildland fire spread.

Influence of topographic complexity on landscape scale fuel treatment effectiveness.

Predicted fire behavior was influenced by the proportion treated, landscape, slope constraint, road density and road buffer constraint as well as interactions between landscape and the other predictor variables. Our regression analyses described the variation in fire behavior metrics well with a coefficient of determination of 0.98, 0.68, and 0.96 for ROS, FLI, and CFB (Table 3). Although all the independent variables we investigated were significantly related to predicted fire behavior, their importance in our models varied greatly. Variability in fire behavior was most closely tied to differences in the topography, followed by proportion treated and the interaction between a slope constraint and landscape ruggedness (Figure 7). The effect of proportion treated on ROS and FLI was 2.5 to 3 times greater in the more rugged landscapes (Landscape B and C) then on our least rugged landscape (Figure 8). Although we also found that the proportion of landscape treatment was negatively correlated with CFB, this effect did not depend upon landscape ruggedness (Figure 7). These results suggest that treatment effectiveness is dependent upon a host of complex interactions. With treatments in complex or more rugged topographies being more effective (i.e., greater reductions in ROS and FLI and similar reductions in CFB) then those in less rugged topographies.

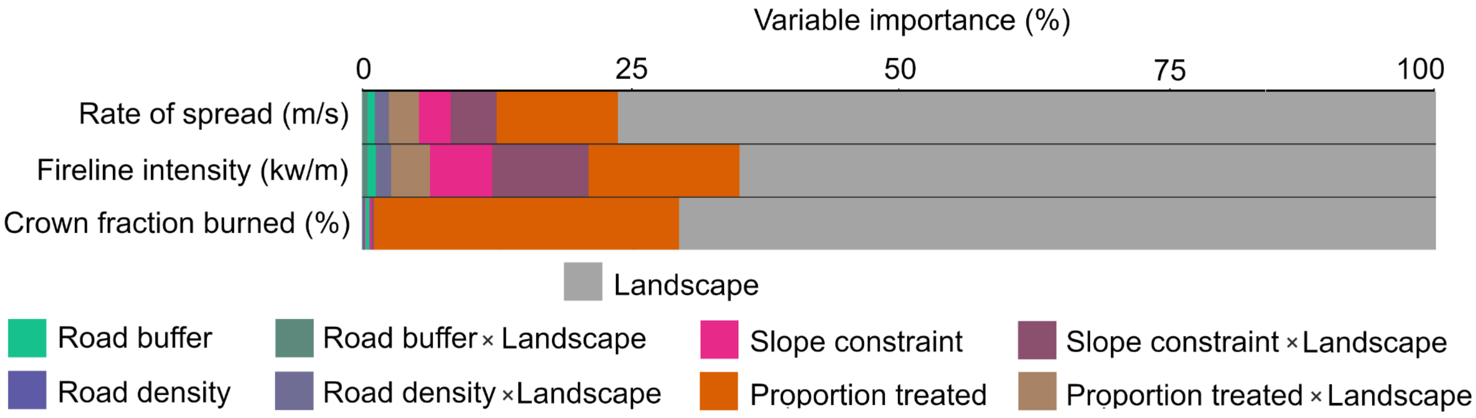

Figure 7. Relative variable importance of independent factors fitted to fire behavior across mountainous landscapes.

While ROS and FLI were primarily related to differences in the topographic scenarios and the proportion of landscape treated, our result also showed a significant effect of treatment constraints on predicted fire behavior (Figure 7, Table 3). We found that removing the slope constraint and allowing treatments to be placed on slopes greater than 40% resulted in significant reductions in ROS and FLI and that these reductions were greater for the most rugged landscape scenario. For example, removing the slope constraint resulted in a reduction of 4, to 6percnet reduction in Landscapes A and B and a 35-36% reduction in Landscape C for the ROS and FLI (Figure 8). Interestingly we found no effect of removing a slope constraint on CFB for any of our landscape scenarios. Last, we found that the effects of road density and the buffer from roads in which to place treatments were the least impactful (Figure 7). Comparing across landscapes, adding more roads led either to a slight decrease in ROS and FLI (Landscape A), no change (Landscape B), or a slight increase (Landscape C). In these cases, the road layouts may have favored the placement of treatments nearer to or further from the direction of fire spread, depending on the topography. Finally, increasing our road buffer resulted in slightly greater reductions in ROS and FLI in Landscapes A and C, though no effect was found in Landscape B (Figure 8). This suggests that moderate dispersion of treatments, rather than linear clusters, may be more effective within some landscapes.

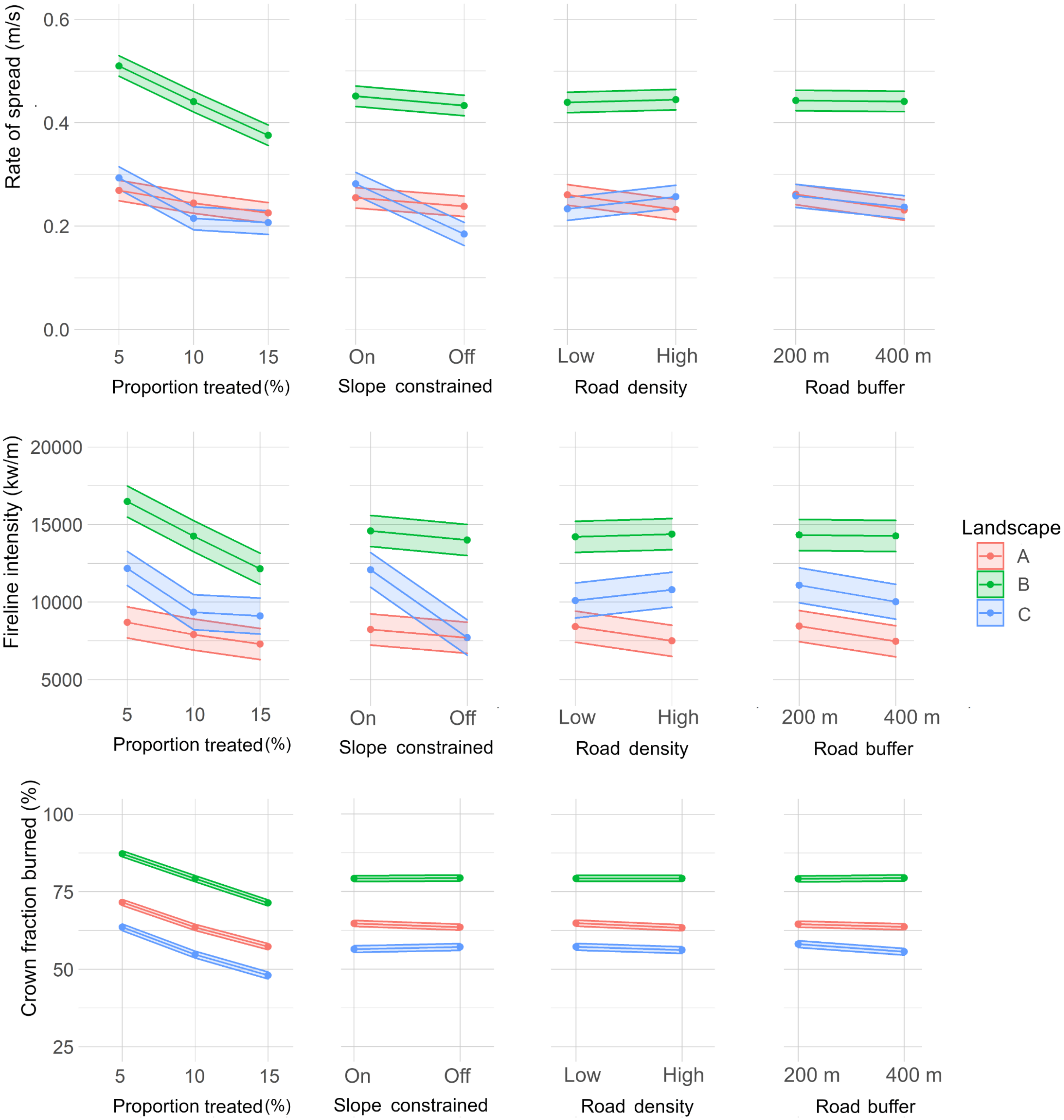

Figure 8. Marginal plots of predicted fire behavior across three landscapes; each plot examines levels of a given independent variable, averaged over levels of other variables.

Simulation studies such as this allow scientist to investigate the numerous factors believed to influence treatment efficacy such as treatment placement, and proportion of landscape treated in ways that our impossible in the real world (Hoffman et al. 2018). Similar to other studies (Bahro et al., 2007; Finney, 2001; Loehle, 2004), our results indicate that the proportion of landscape treated is negatively related to reductions in landscape scale fire behavior. This relationship is primarily based on the idea that as the proportion of treated area increases there is also an increased likelihood that the treated area intercepts a spreading head fire. Where a head fire encounters a treatment, treatments reduce the spread rate, FLI and CFB, altering the alignment of the wind direction and fire front resulting in increased flanking and backing fire (Finney, 2001; Loehle, 2004). Similar to previous studies this process resulted in reductions in fire behavior outside of treatment areas. However, further work is needed to better understand if and how treatment placement can effectively redistribute landscape fire behavior and risk.

Table 3. Categorical regressions of slope constraint (SC), road density (RD), proportion of landscape treated (PT) and their interactions with landscape (LS) on fire behavior simulated in WFDS-LS.

Fire behavior output	Regressor	β	SE	t	p
Rate of spread (m/s)	Intercept	0.31	0.01	30.33	< 0.01
	SC(off)	-0.02	0.008	-2.00	0.05
	RD(high)	-0.03	0.008	-3.44	< 0.01
	RB(400m)	-0.03	0.008	-3.66	< 0.01
	PT(10%)	-0.02	0.01	-2.41	0.02
	PT(15%)	-0.04	0.01	-4.28	< 0.01
	LS(B)	0.21	0.014	14.75	< 0.01
	LS(C)	0.03	0.014	1.75	0.08
	SC(off)×LS(B)	0.00	0.012	-0.14	0.89
	SC(off)×LS(C)	-0.12	0.013	-8.9	< 0.01
	RD(high)×LS(B)	0.03	0.012	2.89	< 0.01
	RD(high)×LS(C)	0.07	0.012	5.34	< 0.01
	RB(400m)×LS(B)	0.03	0.012	2.42	0.02
	RB(400m)×LS(C)	0.05	0.013	3.81	< 0.01
	PT(10%)×LS(B)	-0.04	0.014	-3.13	< 0.01
	PT(15%)×LS(B)	-0.09	0.014	-6.36	< 0.01
	PT(10%)×LS(C)	-0.08	0.015	-5.25	< 0.01
	PT(15%)×LS(C)	-0.09	0.016	-5.64	< 0.01
Fireline intensity (kW/m)	Intercept	9908.41	511.84	19.36	< 0.01
	SC(off)	-534.73	417.91	-1.28	0.2
	RD(high)	-917.61	417.91	-2.2	0.03
	RB(400m)	-976.43	417.91	-2.34	0.02
	PT(10%)	-786.82	511.84	-1.54	0.13
	PT(15%)	-1399.72	511.84	-2.73	0.01
	LS(B)	6816.88	723.85	9.42	< 0.01
	LS(C)	4164.42	731.02	5.7	< 0.01
	SC(off)×LS(B)	-52.8	591.02	-0.09	0.93
	SC(off)×LS(C)	-5179.27	668.15	-7.75	< 0.01
	RD(high)×LS(B)	1091.78	591.02	1.85	0.07
	RD(high)×LS(C)	2225.8	632.12	3.52	< 0.01
	RB(400m)×LS(B)	911.67	591.02	1.54	0.12
	RB(400m)×LS(C)	1572.51	648.74	2.42	0.02
	PT(10%)×LS(B)	-1447.1	723.85	-2	0.05
	PT(15%)×LS(B)	-2938.51	723.85	-4.06	< 0.01

	PT(10%)×LS(C)	-3083.84	765.19	-4.03	< 0.01
	PT(15%)×LS(C)	-3569.27	797.89	-4.47	< 0.01
Crown fraction burned (%)	Intercept	73.36	0.49	149.69	< 0.01
	SC(off)	-1.19	0.4	-2.98	< 0.01
	RD(high)	-1.5	0.4	-3.76	< 0.01
	RB(400m)	-0.86	0.4	-2.14	0.03
	PT(10%)	-8.05	0.49	-16.42	< 0.01
	PT(15%)	-14.27	0.49	-29.12	< 0.01
	LS(B)	13.66	0.69	19.71	< 0.01
	LS(C)	-8.2	0.7	-11.72	< 0.01
	SC(off)×LS(B)	1.36	0.57	2.4	0.02
	SC(off)×LS(C)	-1.58	0.64	-2.47	0.01
	RD(high)×LS(B)	1.51	0.57	2.68	0.01
	RD(high)×LS(C)	1.62	0.61	2.67	0.01
	RB(400m)×LS(B)	1.15	0.57	2.03	0.04
	RB(400m)×LS(C)	0.34	0.62	0.56	0.58
	PT(10%)×LS(B)	0.02	0.69	0.03	0.98
	PT(15%)×LS(B)	-1.57	0.69	-2.27	0.02
	PT(10%)×LS(C)	-1.14	0.73	-1.56	0.12
	PT(15%)×LS(C)	-2.05	0.76	-2.68	0.01

Given that landscape fire behavior is modified, not just by vegetation and weather, but also by topography (Turner and Romme, 1994), the topographic context of landscape fuel treatment networks are important considerations when conducting quantitative analyses of potential fire behavior (Finney, 2005). Although fire simulation studies are often performed in topographically diverse landscapes, we found differentiated sensitivities of fuel treatments on fire behavior across landscapes with a range of topographic ruggedness. Incremental additions of treatments yielded outsized reductions in ROS and FLI within more mountainous landscapes. This presents an offset in the context of fire suppression; on the one hand, rugged terrain decreases the production rate of fireline construction (Fried and Gilless, 1989; Smith, 1986). However, these reductions may be countervailed by decreased rates of spread, which increases the probability of fire containment (Smith, 1986). Further simulation studies incorporating fire suppression resources, may further elucidate benefits of fuels treatment networks—both the size of treatments and their placement.

Multiple barriers limit the placement and extent of fuels treatments, such as land designation (e.g., wilderness, stream buffers, and designated roadless areas), and operability (e.g., slope gradient and access) (Lydersen et al., 2019). In our simulations we were sometimes not able to meet assigned targets for the proportion of landscape treated in our most rugged scenario (Landscape C) when treatments were not allowed on slopes over 40%. In these cases, there is a substantial effect of treatment constraints on the potential to reduce the overall fire behavior within the landscape. However, placing treatments of steeper slopes, can significantly increase the cost of treatments (Buckley et al., 2014). Where public officials evaluate fuels treatments programs based on acres treated (Dale and Gerlak, 2007), constraints on the extent of fuels treatments may severely lower perceived effectiveness and incentivize cost efficiency (ha/USD). However, our study suggests treatments on slopes yield reductions in landscape ROS and FLI commensurate with additions of 5% landscape treated. Under an evaluation scheme based on risk analysis of fire behavior, rather than hectares treated, (Rideout et al., 2019), there may be a potential exchangeability between additional hectares and treatment placement targeted to topography. And though, treatments on steeper slopes may cost more, these placements may generate indirect monetary benefits including avoided costs associated with erosion and water quality degradation (Jones et al., 2017).

Beyond placing treatments on steeper slopes, designs of fuel treatment networks must integrate spatially varying fire hazard (e.g., fuel load and arrangement), fire risk (e.g., ignition likelihood), and sociocultural and ecological values (e.g., built infrastructure, wildlife habitat, watersheds). In consideration of these values, road density and the distance from roads where treatments are placed may be an important consideration during the planning phase. Further studies that link fire behavior, fire effects, and econometrics, may help elucidate how topographic variation influences the efficacy of fuel treatment networks and ultimately maximize managers ability to achieve the desired landscape impacts of fire while treating just a fraction of a landscape (Bahro et al., 2007).

Long-Term Impacts of Fuel Treatment Placement with Respect to Forest Cover Type on Potential Fire Behavior across a Mountainous Landscape

Simulated silvicultural treatments reduced stand density, basal area, and CBD, while increasing CBH relative to pretreatment stand conditions on both southerly and northerly aspects (Table 4). Pre- to post-treatment changes in stand structure metrics were greater for stands on northerly aspects compared to stands on southerly aspects apart from QMD, which increased by 2% and 6%, respectively (Table 4).

Table 4. Mean and (standard deviation) of stand structural attributes for Northerly and Southerly aspects used in Ex et al. (2019). SI_{100} is site index base age 100, TPH is trees per hectare, BA is basal area per hectare, QMD quadratic mean diameter, CBH canopy base height, CBD is canopy bulk density.

Aspect	Status	SI_{100} (m)	TPH	BA (m2/ha)	QMD (cm)	CBH (m)	CBD (kg/m3)
Northerly	Untreated (n = 18)	15.7 (2.9)	730 (398)	36.5 (17.7)	26.3 (4.5)	1.90 (1.01)	0.174 (0.060)
	Treated (n = 18)	15.7 (2.9)	218 (73)	11.6 (9.1)	26.9 (4.0)	3.25 (0.94)	0.092 (0.047)
Southerly	Untreated (n = 12)	13.9 (1.9)	755 (549)	24.1 (10.1)	22.7 (5.9)	2.31 (0.91)	0.042 (0.008)
	Treated (n = 12)	13.9 (1.9)	287 (114)	11.9 (0.3)	24.2 (4.8)	3.81 (1.27)	0.037 (0.013)
	Untreatable (n = 14)	14.3 (2.0)	280 (171)	12.6 (3.7)	25.9 (5.7)	3.86 (2.46)	0.037 (0.013)

The south treatment scenario resulted in a ~25% reduction in both simulated fire size and mean ROS immediately following treatment relative to the no treatment scenario. In contrast, the north treatment scenario resulted in little to no difference in simulated fire size (Figures 9, 10). Compared to the no treatment scenario, the proportion of both active and surface fire behavior types were decreased in favor of increased passive crown fire in the north treatment scenario. In the south treatment scenario, the proportion of active and passive crown fire was reduced, while surface fire increased proportionally (Figure 10).

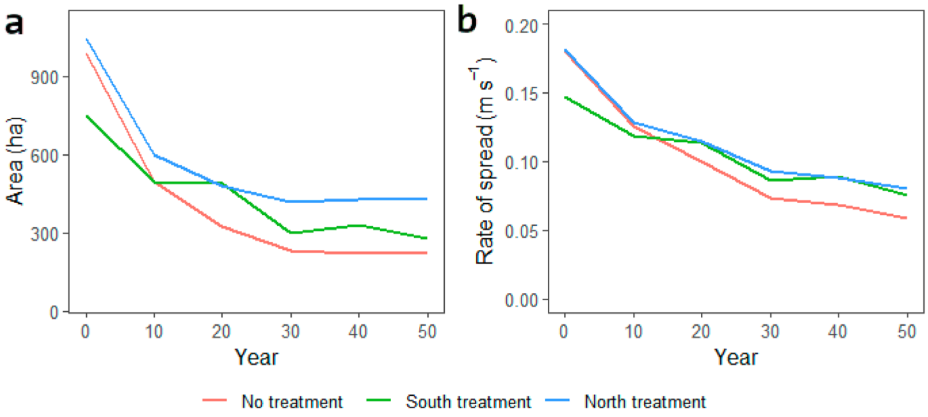

Figure 9. Changes in fire size after 7.5 hr of spread, and the mean rate of fire spread for the untreated scenario (red line), and the southerly (green line) and northerly (blue line) treatment placement scenarios.

In untreated stands, CBH increased from approximately 2–3 m over the first 30 years, at which time CBH was predicted to stabilize for the remaining 20 years. The canopy Bulk density in untreated stands was predicted to either slightly increase or decrease through time. Treated stands on both southerly and northerly aspects had greater CBHs than untreated stands for the decade following treatment. After the first decade, CBH rapidly declined, reaching a low point of ~1 m 30 years after treatment due to regeneration response to the treatment. Following this low point, the CBH increased through time as the regeneration grew. As in untreated stands, CBD was stable through time for treated stands on southerly aspects. In contrast, CBD increased by ~10% during each decade of the simulation for stands on northerly aspects. Midflame wind speeds remained elevated in treated stands relative to untreated stands throughout the simulation period.

Placing treatments on southerly aspects resulted in a decrease in fire size and mean ROS for the first decade compared to the other scenarios. In contrast, limiting treatment placement to northerly aspects resulted in similar rates of fire spread and a slight increase in fire size compared to the no-treatment scenario during the same period (Figures 9, 10). Following the first decade, both treatment scenarios resulted in larger fires and greater rates of spread than the no-treatment scenario. Compared to the north treatment scenario, the south treatment scenario tended to result in similar rates of spread, but ultimately smaller fire sizes. Regardless of treatments or treatment placement, the proportion of passive crown fire decreased while the proportion of surface fire increased through time due to crown recession in untreated stands. Placing treatment on southern aspects resulted in less passive crown fire behavior relative to surface fire behavior compared to the north treatment scenario for the first 20 years following treatment. After this time, there was no discernable difference in the effect of treatment placement on the proportion of fire types (Figure 10).

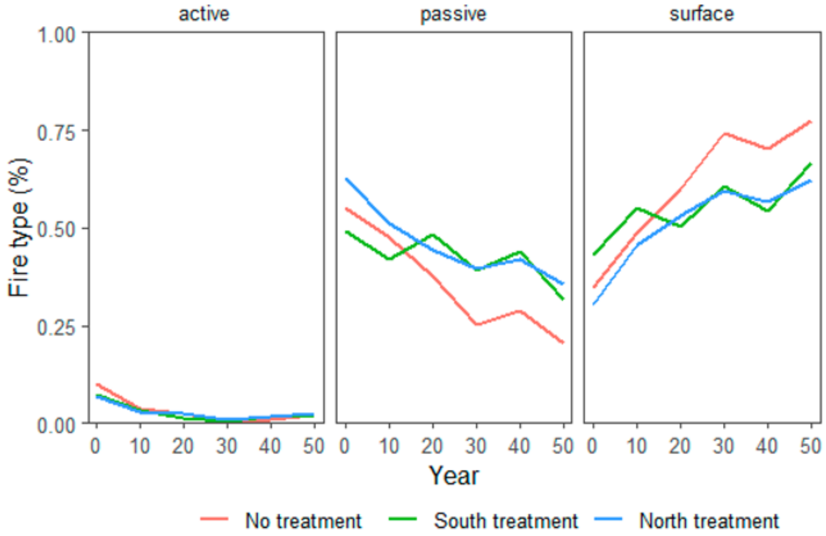

Figure 10. Percentage of surface, passive, and active crown fire for the untreated scenario (red line), and the southerly (green line) and northerly (blue line) treatment placement scenarios.

We expected that treatments would result in greater reductions in fuel hazard and fire behavior (i.e., fire type, fire size, and spread rate) on the denser Douglas-fir-dominated forests associated with northerly aspects compared to the sparser ponderosa pine-dominated stands on southerly aspects. Comparison of pre-and post-treatment stand structure shows that treatment on northerly aspects resulted in greater reductions in CBD than those on southerly aspects. While this finding partially supports our expectation, we did not see concomitant reductions in fire size nor the ROS when treatments were concentrated on northerly aspects (Figure 9). The lack of reduction in fire behavior was in part due to a proportional increase in passive crown fire, and a decrease in surface fires (Figure 10). This increase in passive crown fire behavior in the north treatment scenario effectively canceled out the decrease in active fire behavior, resulting in similar rates of fire spread and fire size to the no treatment scenario. Treatments in the Douglas-fir type were less effective at reducing active and passive crown fire because of increased midflame wind speeds associated with overstory canopy reduction, combined with greater surface fuel loads in these stands. Several previous studies have also demonstrated that increased midflame wind speeds following the removal of overstory trees can increase the possibility for passive crown fires following overstory removal (Agee and Lolley, 2006; Crotteau et al., 2016; Johnson et al., 2011). In contrast to our original expectation, we found that the south treatment scenario, not the north treatment scenario, resulted in the largest decreases in the proportion of active and passive crown fires, mean rate of fire spread, and fire size.

Fuel complex recovery occurred at a greater rate in Douglas-fir-dominated stands associated with the northerly aspects than on the ponderosa pine forests associated with the southern aspects. Even 50 years post-treatment, our simulations showed that the CBD in treated areas was lower than pretreatment levels, indicating long-lived resistance to active crown fire. These findings are consistent with recent work that also showed a long-lived reduction in CBD following treatments such as those simulated here, translating to prolonged reductions in the potential for active crown fire (Tinkham et al., 2016). Treated stands in the Douglas-fir cover type did experience an ~10% increase in CBD per decade compared to only a slight increase over the simulation period for ponderosa pine-dominated stands, which we attribute to the systematic differences in composition, productivity, and tree regeneration rates between cover types in this study. Although CBD reductions were persistent throughout our simulations, initial increases in CBH lasted for only a single decade following treatment regardless of cover type. After the first decade, we found CBH rapidly decreased over a 20-year period as post-treatment regeneration grew sufficiently tall to be incorporated into CBH estimates for stands. CBH increased over the final 20 years of the simulation, reflecting crown recession at increasing stand densities. Although the treatment scenarios resulted in similar trajectories of CBH over time, conditions were more hazardous in treated Douglas-fir-dominated stands for two reasons. First, these stands reached a much lower minimum CBH over the simulation period. In addition to lower minimum CBHs, treated Douglas-fir-dominated stands also showed a slower rate of CBH increase compared to ponderosa pine-dominated stands on southerly aspects (0.34 vs. 0.43 meters per decade, respectively. These differences are likely to affect increased regeneration rates and Douglas-fir seedlings' ability to maintain a longer crown at a given level of stand density than ponderosa pine (Oliver and Leroy Dolph, 1992). The differences in regeneration rates and crown recession reduced the duration of stand-level treatment effectiveness in these locations.

Although there were clear differences in CBD and CBH dynamics between treated stands in the two cover types, differences among treatment scenarios in fire spread across the analysis landscape were less pronounced. Our results indicate that the south treatment scenario resulted in decreased fire behavior for approximately two decades relative to the north treatment scenario. After the first two decades following treatment there were no discernable differences in ROS or distribution of surface fire and passive and active crown fire between cover types (Figure 10). The lack of long-term treatment effects on fire behavior was driven by tree regeneration and forest growth which worked in concert with each other to homogenize stand structure in the absence of further disturbance. However, our results did suggest a small decrease in fire size through time associated with treatment placement on southerly aspects (except for 20 years post-treatment, Figure 9). Visual assessment of the simulated fire perimeters suggests that the decreased fire growth was associated with differences in the spatial pattern of fire perimeters relative to the other scenarios. These differences may reflect localized, terrain-related variations in fire spread rate and direction (Parisien et al., 2010). Terrain directly influences components of the fire environment like midflame wind speed and indirectly influences fuels via its effect on characteristic composition and structure of forest cover types, which develop at variable rates due to variation in forest dynamics (Taylor and Skinner, 2003). These complex interactions underlie the development of potential fire behavior over time in forests (Finney et al., 2005). Disentangling these interactions and how they manifest in different forest types is critical to developing our understanding and ability to design fuel treatments capable of influencing fire spread across landscapes composed of complex topography. To account for the high degree of entanglement between topography, fire weather and patterns of vegetation structure and dynamics, future studies will likely need to make use of numerical experiments where the various factors are highly controlled, and interactions can be investigated using a methodical approach (Hoffman et al., 2018; Parisien et al., 2010).

Our results indicate that CBH dynamics were driven by crown recession and the establishment and growth of regenerating trees. We used the default crown recession model in FFE-FVS, which resulted in increasing CBH through time in all untreated stands. Because most of the simulated landscape was untreated, this resulted in all simulations showing a decrease in fire size, mean ROS, and active and passive crown fire proportions through time. These findings are consistent with the outcomes of similar studies conducted in dry forest types in California and contribute to a growing body of literature that suggests a better understanding of crown recession is critical for improving our ability to predict the longevity of fuel treatment effects (Collins et al., 2013, 2011; Tinkham et al., 2016). These studies also highlight the importance of accounting for stand dynamics in untreated areas when assessing the longevity of landscape scale fuel treatments. In addition to assumptions regarding fuel dynamics, our study also made several important assumptions regarding fuel treatment design and placement.

Our results indicate that placing treatments in drier ponderosa pine-dominated stands on southerly aspects was initially more effective than placing treatments in wetter Douglas-fir-dominated stands on northerly aspects at reducing fire spread rate, size, and crown fire activity. This disparity in treatment effects lasted approximately 20 years, at which point the scenarios displayed similar fire behavior. Despite this, stand-level fuel hazards (CBD, CBH) develop more slowly in ponderosa pine-dominated stands. Ultimately, we conclude that the placement of treatments with respect to systematic variation in composition, productivity, and tree regeneration rates among cover types calls for consideration when designating areas for treatment in forests characterized by strong contrasts in these factors among cover types. However, locating treatments such that they target stands with the greatest fuel hazards and creating treatment patches of sufficient size to disrupt fire spread may be of equal or greater importance.

Conclusions

The ongoing implementation of stand-scale fuels treatments raise several questions on how landscape fire behavior is altered across a range of topographic complexity through both space and time. The myriad interactions among the fire, fuels, atmosphere, and topography (Hoffman et al., 2020; Linn et al., 2013; O'Brien et al., 2018) that drive fire behavior and effects pose a computational burden which hinders the ability to produce predictions in a timeframe that is useful for fire management (Hilton et al., 2018; Linn et al., 2020). In this JFSP project, we addressed this burden by developing two different open-source fire behavior models, and then applying these models to investigate how landscape fire spread can be reduced by several factors including the proportion of landscape treated, the placement of those treatments, and how constraints reduce or amplify treatment effectiveness.

First, we developed two open-source software packages for fire behavior prediction. The first, firebehavioR, packages multiple fire behavior prediction models with functions to assess fuel and fire weather hazard. Verification efforts against CFIS, NEXUS and BEHAVEPlus (Andrews, 2018; Cruz et al., 2004; Scott and Reinhardt, 2001), showed high agreement. For some fire analysts the implementation of these models in the R programming language is advantageous: first, the code is free-and-open-source which increases transparency and promotes advances in the code; second, users can interface via a read-evaluate-print-loop console that increases interactivity and facilitates teaching and research; third, the inputs and outputs can be easily linked with other programs or functions thus improving analytical workflows, supporting more complex analyses. Second, we developed the WFDS-LS model to project fire spread across complex fuels and landscapes. Fire behavior models have typically relied on using either a Eulerian, as implemented in WFDS-LS, or Lagrangian approach, as implemented in FARSITE (Finney, 1998). Although there is a mathematical equivalence between the Eulerian and Lagrangian methods, there has been a lingering question of whether equivalent fire spread models will give the same results when numerically implemented within these two frameworks. Our suite of simulations demonstrated similarities between the WFDS-LS and FARSITE models, with deviations of predicted area burned within 15% of each other with the greatest deviations occurring in more complex scenarios. These deviations could be reduced by either the choice of solvers or resolution used in the WFDS-LS model. Future developments of the WFDS-LS model will focus on inclusion of added physical mechanisms such as fire-atmospheric interactions, which will further expand the suit of modeling capabilities available.

Following our development of WFDS-LS, we applied this model to address outstanding research questions relevant to landscape treatment planning. In our first study, we found that the impacts of landscape treatment design decisions differentially affect landscapes of varying terrain. Specifically, we found that reductions of fire spread rates and intensity associated with a given level of treatment (e.g., 15% of the landscape) were greater when treatments could be placed on steeper slopes and in scenarios with more complex topography. These results imply that the greater operational difficulty associated with placing treatments in complex landscapes and steep slopes may be offset by greater fire behavior reductions. Meanwhile, factors associated with treatment dispersion such as the access and proximity to roads were not as significant in terms of their effects on reducing landscape fire behavior. It is worth noting our study considered randomized treatment placements and future studies that look to optimize treatment placement within a landscape are needed.

We designed our second study to examine the treatment longevity over complex landscapes with differential fuel loads and rates of fuel recovery. We expected landscape treatment effectiveness to be higher when only stands in more productive stands were treated, but that the duration of effectiveness would be longer when stands in less productive stands were treated. However, our results were counterintuitive and showed little differentiation between these two treatment placement scenarios, aside from a relative advantage of treating on the less productive stands over the more productive stands for a period of two decades. These results show that landscape fire behaviors exhibit dynamics more complex than assumptions gleaned from studies on fire behavior performed at the stand-scale. Expectations of landscape fire behavior were complicated not only from the patterns of fuel recovery, nor just how fire behavior responds at landscape scales due to perturbations in fuel hazard within individual stands, but also from dynamics simultaneously occurring within untreated stands.

Wildland fire managers are faced with a three-pronged challenge including the rise of the built infrastructure in the wildland urban interface, an increase in the length and severity of wildland fire seasons, and a growing deficit of forest that require treatment. While this project has offered new insights into landscape scale fuel treatment planning, we have also highlighted the complexity driving fire behavior in complex landscapes that needs to be considered when designed landscape fuel treatments. Although this study focused on landscape scale fire spread, there is a need to link fine scale variability in fuels and weather to fire behavior and effects. This understanding will be especially important for future research which seeks to include not just mechanical treatments but the use of managed wildfire, and prescribed fire. In addition, further work which develops 3D fuel characterization methods that can span across spatial scales and can incorporate temporal changes in the fuels complex are needed. Finally novel approaches that link fire behavior and effects with fire suppression effectiveness and costs would be useful to help mangers develop more effective landscape treatments.

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Appendix A: Contact information for key project personnel

Dr Chad H. Hoffman
Department of Forest & Rangeland Stewardship
Colorado State University
C.Hoffman@colostate.edu

Dr Yvette L. Dickinson
Department of Forest & Rangeland Stewardship
Michigan Technological University
yldickin@mtu.edu

Dr Seth A. Ex
Department of Forest & Rangeland Stewardship
Colorado State University
Seth.Ex@colostate.edu

Dr Russell A. Parsons
Rocky Mountain Research Station
US Forest Service
russell.a.parsons@usda.gov

Dr William E. Mell
Pacific Northwest Research Station
US Forest Service
william.mell@usda.gov

Justin Ziegler
Department of Forest & Rangeland Stewardship
Colorado State University
Justin.Ziegler@colostate.edu

Appendix B: List of Completed/Planned Scientific/Technical Publications/Science Delivery Products

Software

1) Ziegler, J. P. 2019. firebehavioR: Prediction of Wildland Fire Behavior and Hazard. The Comprehensive R Archive Network. Accessible at: https://cran.r-project.org/web/packages/firebehavioR/index.html
2) Mell, W.E. Wildland Fire Dynamics Simulator Version 9977 repository. Accessible at: https://github.com/ruddymell/wfds9977

Scientific Publications

1) Ex, S.A., Ziegler, J.P., Tinkham, W.T., Hoffman, C.M. 2019. Long-term impacts of fuel treatment placement with respect to forest cover type on potential fire behavior across a mountainous landscape. Forests 10 (5), 438.
2) Ziegler, J.P., Hoffman, C.M., Mell, W.E. 2019. firebehavioR: An R Package for Fire Behavior and Danger Analysis. Fire 2 (3), 41.
3) Tinkham, W.T., Dickinson, Y., Hoffman, C.M., Battaglia, M.A., Ex, S., Ziegler, J.P., Underhill, 2017. Visualization of heterogeneous forest structures following treatment in the southern Rocky Mountains. USDA Forest Service Rocky Mountain Research Station General Technical Report RMRS-GTR-365. Fort Collins, CO. (Recipient of the 2017 USDA FS RMRS Technology Transfer Award)
4) Tinkham, W.T., Hoffman, C.M., Ex, S.A., Battaglia, M.A. and Saralecos, J.D., 2016. Ponderosa pine forest restoration treatment longevity: implications of regeneration on fire hazard. *Forests*, *7*(7), p.137.
5) Bova, A.S., Mell, W.E., Hoffman, C.M. 2016. A comparison of level set and marker methods for the simulation of wildland fire front propagation. International Journal of Wildland Fire, 25(2), 229-241.

Presentations

1. Ziegler, J. P., Hoffman, C. M., Mell, W. 2020. Open-source software as a force multiplier in research: Examples using fire modeling. 73rd Annual Meeting – Society for Range Management, Feb 17, Denver, CO. (invited)
2. Mell, W., Perez-Ramirez, Y., Santoni, P., Hoffman, C., Monroy, X., Mueller, E., Hadden, R., Simeoni, A., The promise and challenges of CFD physics-based wildland fire behavior modeling, University of Corsica, France. October 2019. (invited)
3. Mell, W., Hoffman, C.M., Ziegler, J. 2019. A reduced fire-physics fire behavior model: Development and evaluation. 6th International Fire Behavior and Fuels Conference, April 29-May 3, Albuquerque, NM.
4. Mell, W., Hoffman C.M., Ziegler, J. 2018. The state of physics-based modeling and an example of a reduced-physics model. VIII International Conference of Forest Fire Research. November 9-16, Coimbra, Portugal.
5. Mell, W.E.2017. FDS for Fires in Vegetation, NIST WUI Day, NIST, January 17, 2017
6. Hoffman, C.M., Ziegler, J., Battaglia, M., Mell, W. 2016. How are Front Range CFLR treatments altering structure and fire behavior? An assessment. Front Range Roundtable, Landscape Restoration Monitoring Team, May 23, Golden, CO. (Invited)
7. Hoffman, C.M., Ziegler, J., Battaglia, M., Mell, W. 2016. Assessing restoration treatment effectiveness

in the southern Rocky Mountains. WESTFIRE Center Spring Seminar Series, Colorado State University, March 2, Fort Collins, CO. (Invited)

8. Hoffman, C.M., Linn, R.R., Mell, W., Battaglia, M., Sieg, C., Winterkamp, J., Canfield, J., Ziegler, J. 2016. Predicting the spread of wildland fires: The importance of fire interactions with the atmosphere, ecosystems and topography. Colorado State University Department of Atmospheric Sciences Colloquia. Feb. 5th, Fort Collins, CO. (Invited)
9. Mell, W.E., Linn, R.R. 2013. Future of coupled fire-atmosphere modeling. INTERNATIONAL SMOKE SYMPOSIUM. The University of Maryland University College October 21-24, 2013

Appendix C: Metadata

This project relied on a combination of open data sets and previously published data. Tinkham et al. (2016, 2017) and Ziegler et al. (2019b) utilized data collected in a previous JFSP funded project (#13-01-04-53) which was published in Ziegler et al. (2019a). Ex et al (2019) utilized USDA Forest Service Forest Inventory and Analysis (FIA) data available at https://apps.fs.usda.gov/fia/datamart/ and a 10 m digital elevation model which can be found at https://nationalmap.gov. The WFDS level set input files used in Ex et al. (2019) and Bova et al. (2016) are available at https://github.com/ruddymell/wfds9977.