CHAPTER 13.

Conventional Fire Behavior Modeling Systems are Inadequate for Predicting Fire Behavior in Bark Beetle-Impacted Forests

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INTRODUCTION

Understanding the impacts of mountain pine beetle (MPB; *Dendroctonus ponderosae* Hopkins) on fire behavior is important from both an ecological and land management viewpoint. However, numerous uncertainties exist in the linkages of MPB-caused tree mortality to changes in canopy and surface fuels (e.g., fuel loading, arrangement, and availability) and the effects on simulated and observed fire behavior in MPB-attacked forests. Current fuel inputs to fire behavior models may be poorly suited to predict fire behavior in these disturbed forests because of inappropriate assumptions, resolutions, and design. Spatial patterns of recent beetle mortality are difficult to realistically represent in fire models, and it is virtually impossible to determine model output accuracy in a planning scenario. The numerous stages of tree condition (green-infested, red, and gray phases) due to time since attack further complicate modeling. MPB-killed foliage is more flammable than green needles (Jolly and others 2012); however, it is unknown if this increase in flammability scales up to entire canopies to result in higher-intensity crown fires (Alexander and Cruz 2013).

In spite of the complexities in predicting fire in MPB-killed stands discussed above, the greatest limitation likely lies in our ability to accurately describe the fuel complex for simulating resultant fire behavior because of model reliance on fire behavior fuel models (FBFMs) (Anderson 1982, Scott and Burgan 2005). Most fire behavior prediction systems are point models using the Rothermel (1972) surface fire spread model applied at the stand or landscape levels with generalized surface fuel inputs or FBFMs. These surface fuel classifications are often insensitive to fine-scale changes in fuels after MPB outbreaks (Keane 2013). FBFMs are chosen to match a set of observed or expected fire behavior under a range of environmental conditions rather than to actually describe surface fuel characteristics (Burgan 1987). As a result, we are constrained in accurately representing the true tree-to-stand-level heterogeneity of fuels over the spatial scales used by fire behavior modeling systems because the FBFMs in Scott and Burgan (2005) or Anderson (1982) are too coarse to represent the subtle changes in fuels resulting from MPB outbreaks, leading to inaccuracies in model outputs.

We simulated fire behavior before, during, and after a hypothetical MPB outbreak using an intensively sampled subalpine lodgepole pine-dominated (*Pinus contorta* Douglas ex Loudon) landscape in central Montana to determine if FuelCalc (Reinhardt and others 2006) and the fire behavior modeling system FlamMap (Finney 2006) are sensitive to changes in forest structure during the red stage of a MPB outbreak. Previous studies have used plot data to assess fire hazard using non-spatial fire behavior models (see Hicke and others 2012 for review, Schoennagel and others 2012) or used simulated input values based on broad, stand-level mapping to predict spatially explicit fire behavior (McMahan and others 2008). This study is one of the first to model potential fire behavior spatially across a MPB-affected landscape using an extensive plot-level fuel and tree data grid as model inputs. Results of this study are intended to highlight how model inputs change predicted fire behavior in MPB-affected stands to increase understanding of appropriate model applications and limitations.

MATERIALS AND METHODS

Field Methods

The Tenderfoot Creek Experimental Forest (TCEF) is a high-elevation (1850 to 2441 m) lodgepole pine-dominated forest in the Little Belt Mountains of central Montana (Hood and others 2012). We used a network of permanent plots established in 1997 on a 330-m^2 grid across the entire TCEF to sample vegetation and fuel loading. We collected surface and canopy fuel data on three hundred 0.04-ha circular plots during the summers of 2011 and 2012, which appeared to be the start of a MPB outbreak. We estimated fine downed, dead woody surface fuel loading using the planar-intercept method (Brown 1974). Duff and litter depths were measured at two points along each transect (Lutes and others 2006). For coarse woody fuel (> 8 cm diameter), we measured small- and large-end diameter, length, and numerical decay classification (Maser and others 1979) of every log within the 0.04-ha plot. We used FIREMON sampling methods and classes (Lutes and others 2006) to collect vegetation data. We visually estimated canopy cover class and height of each plant species or genera, if species was unknown on eight 1-m^2 microplots placed along each fuel transect. We tallied tree seedlings (< 1.37 m) by height class and species on a 0.01-ha plot nested in the larger 0.04-ha plot. Saplings [< 12.7 cm diameter at breast height (d.b.h., measured at 1.37 m above ground)] and trees (≥ 12.7 cm d.b.h) were recorded individually on the 0.04-ha circular plot. For each sapling, we recorded diameter class, species, height, and crown base height. For each living tree, we recorded d.b.h., species, height, crown base height, and crown class (dominant, codominant, intermediate, and suppressed). For *Pinus* species, we also assessed each tree for signs of MPB attack and assigned an estimated attack year. For standing dead snags, we recorded diameter, species, and height. For standing dead *Pinus*, we also assigned a snag class.

Mountain Pine Beetle Severity Scenarios

We first created three MPB attack scenarios to compare effects of bark beetle severity on potential fire behavior at endemic, incipient, and epidemic population stages. We used the field-measured tree and attack data to represent the incipient scenario and created the other scenarios by changing sampled tree characteristics in the input data. To create the endemic scenario, we changed the status of trees recorded as recently attacked to alive and unattacked and assigned crown base height (CrBH) and crown class using estimates obtained from regression modeling of live trees. To create the epidemic scenario, we used the MPB rate-of-loss model by Cole and McGregor (1983) over a 10-year period, using our actual field data of recently attacked trees to initialize the model. This model predicts the probability of a tree being attacked within a given time based on host tree characteristics, stand conditions, and MPB population pressure.

Currently, most fuel and fire behavior modeling system inputs do not explicitly include dead trees with needles remaining in the crown (Hicke and others 2012). We addressed this possible shortcoming by creating two additional scenarios based on the incipient and epidemic scenarios (red-incipient and red-epidemic). For these scenarios we changed tree status for currently attacked trees from dead to healthy to allow crown base height values. Red needles have lower foliar moisture contents and ignite more easily than green needles (Jolly and others 2012), which can increase crown flammability and affect the likelihood of torching and crown initiation (Jolly and others 2012, Scott and Reinhardt 2001). To reflect potential increased flammability of recently attacked trees, we used a recently proposed method (USDA Forest Service 2011) that substitutes an effective crown base height ($\mathrm{CrBH}_{\mathrm{effective}}$) for the measured CrBH value. The $\mathrm{CrBH}_{\mathrm{effective}}$ lowers the crown base height of trees based on foliar moisture content of green and red needles. For green needles we used a foliar moisture content ($\mathrm{FMC}_{\mathrm{green}}$) of 108.5 percent and a $\mathrm{FMC}_{\mathrm{red}}$ of 11.7 percent for red needles as suggested by Jolly and others (2012) to calculate $\mathrm{CrBH}_{\mathrm{effective}}$. For example, a tree with a pre-attacked live CrBH of 6 m has a $\mathrm{CrBH}_{\mathrm{effective}}$ of 1.3 m to reflect the increased flammability of the red or fading needles due to bark beetle attack. We reduced tree height by the same amount as crown base height to keep crown bulk density estimates unchanged.

Crown class and CrBH were not recorded for dead trees. Therefore, for the endemic, red-incipient, and red-epidemic scenarios, we estimated CrBH for dead trees based on regression analysis of healthy lodgepole pine trees ≥ 12.7 cm d.b.h. We assigned crown classes for dead trees using the crown class distribution of living pine trees and then assigned a class using a random number generator. These changes were made to individual trees prior to any estimation of canopy fuel variables.

Fuel Calculations and Fire Behavior Simulation

We used FuelCalc v. 1.1.0 (Reinhardt and others 2006) to calculate canopy fuel characteristics and FBFM by plot for each of the bark beetle attack scenarios. FuelCalc computes canopy bulk density, canopy base height, and stand height based on species-specific allometric equations relating individual tree, sapling, and seedling diameter; crown base height; tree height; and crown class to crown biomass and keys these values to a FBFM (Lutes 2014). Ground fuel and woody surface fuel loadings were calculated in FIREMON v. 2.1.2 (Lutes and others 2006).

We used FlamMap v. 5.0.1.3 (Finney 2006) to simulate fire behavior at 30 x 30-m pixel resolution for the five scenarios across the entire TCEF. FlamMap computes rate of spread, fire line intensity, and flame length using constant weather and live fuel moisture conditions to assess potential fire behavior for a given scenario on a landscape. We used the Scott and Reinhardt (2001) crown fire calculation method. For non-spatial inputs to FlamMap, we applied the following parameters: initial fuel moisture scenario of 1-hour = 4 percent, 10-hour = 5 percent, 100-hour = 7 percent, herbaceous = 60 percent, live woody = 90 percent, and live crown fuels = 80 percent. We conditioned fuels based on topography and weather from nearby weather stations (Finney 2006). The conditioning period was 12 August 2007 at 1300 to 16 August 2007 at 1500, and elevation was modified to 2134 m to reflect the lower elevation at TCEF compared to the weather station location. We assumed no cloud cover during the conditioning period. We chose this conditioning period because it was when recent fires in the area had experienced large growth and therefore represented realistic extreme burning conditions. We used a wind speed of 32 km/hour at 227^{o} based on August wind speed gusts and average direction recorded at the Onion Park SNOTEL station (#1008).

We compared FuelCalc average stand characteristics by attack scenario using general linear mixed model analysis with plot as a random factor (SAS® v. 9.4, SAS Institute, Cary, NC, USA). Predicted fire behavior response from FlamMap (fire line intensity, rate of spread, and flame length) for each pixel by attack scenario was modeled as a generalized additive model (GAM) with a northing x easting interaction component included using a thin plate regression spline basis (R v. 3.0.1 packages mgcv, multcomp, and gstat), followed by multiple comparisons adjusted for family-wise Type I error. The lack of effect of spatial dependence on the standard errors of parameter estimates was confirmed by increasing the number of spline knots until the residual variograms indicated no spatial correlation.

RESULTS

Bark Beetle Severity

Recent MPB activity was generally low across TCEF in 2012 based on field evaluations, with only 4 percent of host trees (pines ≥ 12.7 cm d.b.h.) recorded as recently attacked. However, 36 percent of the plots contained at least one recently attacked tree suggesting the potential for increased MPB activity in the future. Attacks were more concentrated along portions of the TCEF boundary, with up to 50 percent of the host trees attacked in these areas. The simulated epidemic scenario dramatically increased recent MPB attacks to 47 percent of host trees and 56 percent total host mortality (lodgepole pine and whitebark pine only).

Surface Fuel Characteristics

TCEF litter loadings ranged from 0 to 4.3 kg/m^2 (mean = 0.7 kg/m^2; median = 0.5 kg/m^2), while duff loadings ranged from 0 to 13 kg/m^2 (mean = 2.7 kg/m^2; median = 2.3 kg/m^2). Herbaceous and shrub loadings were quite low across the study area with maximum loads of 0.06 and 0.08 kg/m^2, respectively. Mean and median seedling loadings were also low, with values of 0.07 and 0.03 kg/m^2, respectively, and were fairly uniform across the experimental forest. Fine woody fuels (1-, 10-, and 100-hour size classes) ranged from 0 to 13.7 kg/m^2 (mean = 3.2 kg/m^2; median = 2.9 kg/m^2). Coarse woody fuels (1,000-hour sound and rotten) ranged from 0 to 9.4 kg/m^2, with the maximum for sound wood being 7.1 kg/m^2 and that for rotten wood being 5.7 kg/m^2. Total surface fuel load ranged from 0.3 to 21.1 kg/m^2 (mean = 6.1 kg/m^2; median = 5.7 kg/m^2).

FuelCalc assigned 10 FBFMs, and these did not change with scenario. Over 62 percent of the plots were assigned to the Timber Litter (TL) group. The majority of these (77 percent) were TL6, which represents a moderate fuel load with a less compacted fuelbed, moderate spread rate, and low flame length. The next most common FBFM category (22 percent) was Slash-Blowdown (SB) with SB2 being predominant. Fires burning in SB FBFMs are predicted to have high spread rates and flame lengths. Ten percent of the remaining plots were defined as Timber-Understory (TU), which is represented by low grass and/or shrub loading with litter. Low spread rates and flame lengths are predicted in the TU1 FBFM, which comprised 9 percent of the landscape. The FBFMs associated with more intense fire behavior (e.g., TU4, 10, SB2, and SB3) were concentrated in the steeper slopes of the Tenderfoot Creek drainage, while fuels represented by the TL6 FBFM were generally on the flatter portions of the forest.

Canopy Fuel Characteristics

Based on our field measurements (incipient scenario), average canopy fuel loading was 1.06 kg/m^2, canopy base height was 1.7 m, canopy bulk density was 0.12 kg/m^3, and canopy cover was 66 percent. Average overstory tree (≥ 12.7 cm d.b.h.) density was 813 trees/ha. Average stand density (seedlings, saplings, and trees) was 1,972 trees/ha, reflecting the many areas of dense seedlings and saplings. Most stand attributes among the endemic, red-incipient, and red-epidemic scenarios were identical due to the assumptions used to create these scenarios. Increasing beetle-killed trees with red needles using the $\text{CrBH}_{\text{effective}}$ values decreased canopy base height, but did not affect predicted torching and crowning indices in the FuelCalc predictions, as fuel moisture is not an input into this model. The epidemic scenario lowered canopy base height, canopy bulk density, tree density, quadratic mean diameter, and basal area.

Simulated Fire Behavior

There was relatively little difference in median simulated fire behavior variables among scenarios (fig. 13.1), but the epidemic and red-epidemic had more variability and higher flame lengths, fire line intensities, and rates of spread in some areas. Flame length values for the majority of the TCEF ranged from 0.5 m to 1.3 m (1st to 3rd quantiles) for the endemic, incipient, and red-incipient scenarios, but

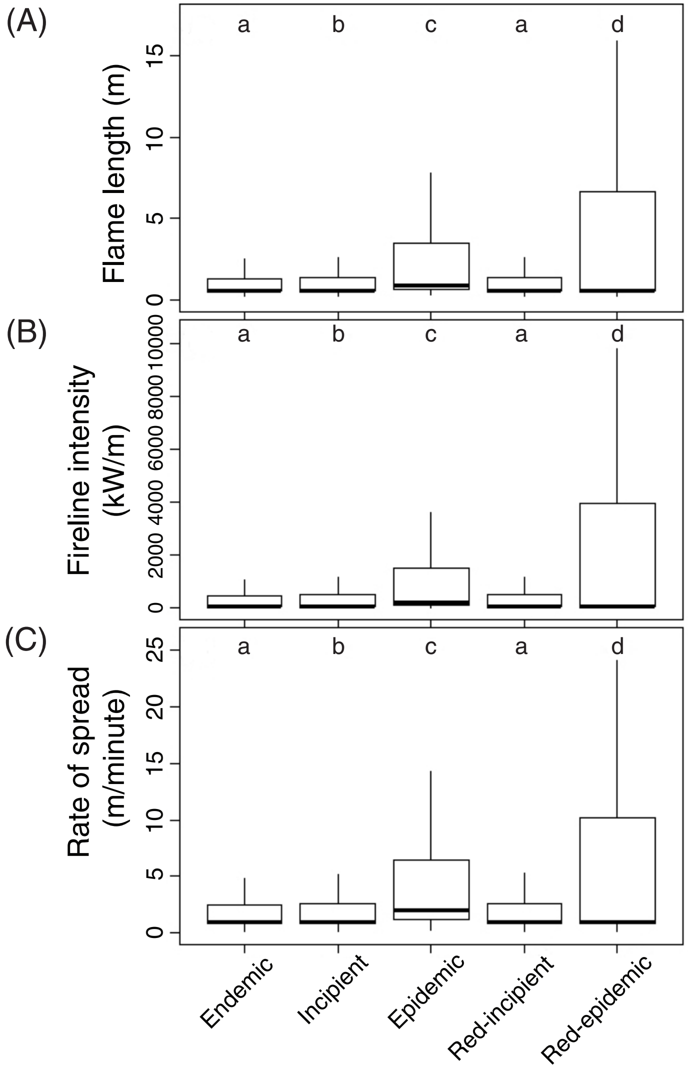

Figure 13.1—Results of the fire behavior FlamMap simulation showing the range of predicted (A) flame length, (B) fire line intensity, and (C) surface fire rate of spread by the five scenarios. Boxes denote 1st and 3rd quartiles, with lines inside boxes showing median values, and bars showing ±1.5 interquartile range (IQR). Data points outside of 1.5 IQR not shown. Different letters denote differences between scenarios ($\alpha = 0.05$).

ranged up to 3.5 m for the epidemic scenario and 6.7 m for the red-epidemic scenario. Fire line intensity variability was greatest for the red-epidemic scenario, ranging from 68 kW/m to almost 4000 kW/m. Median rate of spread was double for the epidemic scenario at 2 m/minute compared to 1 m/minute for the other scenarios.

Surface fire was the dominant fire type simulated for all scenarios (51–78 percent of total area; fig. 13.2). Passive crown fire was highest for the epidemic (49 percent) and red-epidemic (33 percent) scenarios, compared to 20–23 percent for the other scenarios (fig. 13.2). This increased passive crown fire activity was driven by reduced canopy base height and canopy cover values, especially in the epidemic scenario, which increased midflame windspeeds, thereby fostering more crown fire activity. This was also reflected in the torching index for the epidemic scenario, which was lower (52 km/hour) than all other scenarios (79–87 km/hour). Active crown fire activity increased slightly for the red-epidemic scenario to 5 percent of the area, compared to approximately 1 percent for the other scenarios, but crowning index was the same for all scenarios except the epidemic scenario (65 km/hour vs. 101 km/hour). Unlike the red-epidemic scenario, the epidemic scenario did not increase active crown fire due to the reduction in canopy bulk density and canopy fuel load after trees died from beetle attack and no needles were left in the tree crowns, making it much more difficult for active crown fire to propagate.

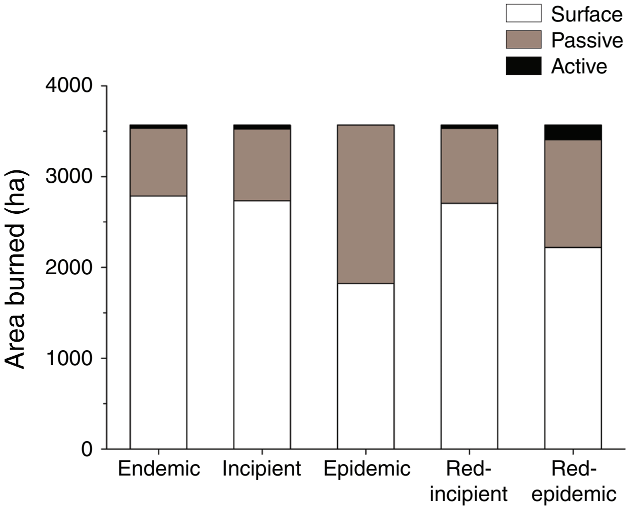

Figure13.2—Simulated area of Tenderfoot Creek Experimental Forest burned by fire type (surface fire, passive crown fire, active crown fire) by bark beetle scenario.

DISCUSSION

Our results highlight the limitations of predicting fire hazard in red-stage MPB-affected forests due to a mismatch of scales and resolution between canopy fuels, surface fuel FBFMs, and fire behavior prediction systems. We show that large changes in crown fuels due to a simulated MPB outbreak did not translate into large changes in predicted fire behavior. This is likely because the surface fuel model did not change. Moreover, MPB-mediated differences were not detected by FuelCalc to change fire behavior fuel models, and FlamMap's 30-m^2 resolution was not sufficient to capture the subtle changes in canopy fuel characteristics during the simulated MPB outbreak.

Increased efforts to collect tree and fuel data at finer scales will likely not improve efforts to simulate fire behavior in MPB-affected forests with the current suite of models. Fire behavior fuel models were originally developed to help managers predict fire behavior based on a current fire incident. They were designed as a guide to match current fire behavior observations with predicted fire behavior, rather than to describe actual fuel characteristics. Modeling fire behavior in bark beetle outbreaks will undoubtedly continue to be challenging because there is limited opportunity to validate model predictions with actual fire behavior. Therefore, we rarely can know accuracy levels of these models.

Our goal was to evaluate the differences in fuels and fire behavior across MPB scenarios, but the design of the fuel and fire behavior modeling systems did not have the sensitivity to detect the subtle differences across bark beetle scenarios. We feel that the fire behavior predictions simulated in this study likely do not reflect expected fire behavior in the event the TCEF burns. In reality, wildfires burning in lodgepole pine forests in the red stage will likely have higher intensities, rates of spread, and crown fire activity compared to unattacked lodgepole pine (Hicke and others 2012, Jenkins and others 2014, Page and others 2014, Perrakis and others 2014). Current fire behavior models have shown a consistent under-prediction of surface and crown fire rate of spread in unattacked forests (Cruz and Alexander 2010); therefore, it is not surprising that attempting to use these models outside of their originally intended use may lead to dubious predictions. It will always be difficult to address all the factors that impact fire hazard after MPB outbreaks because of the complex biophysical feedbacks that influence the fire and fuel environment at multiple scales. Even so, improving fire behavior simulation accuracy will continue to be limited without a better understanding of the basic physical processes of fire ignition and spread.

CONTACT INFORMATION

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