Surface Fire Intensity Influences Simulated Crown Fire Behavior in Lodgepole Pine Forests with Recent Mountain Pine Beetle-Caused Tree Mortality

Chad M. Hoffman, Penelope Morgan, William Mell, Russell Parsons, Eva Strand, and Steve Cook

Abstract: Recent bark beetle outbreaks have had a significant impact on forests throughout western North America and have generated concerns about interactions and feedbacks between beetle attacks and fire. However, research has been hindered by a lack of experimental studies and the use of fire behavior models incapable of accounting for the heterogeneous fuel complexes. We populated the Wildland-Urban Interface Fire Dynamics Simulator with data from 11 field sites to investigate the effect of mountain pine beetle (MPB)-caused tree mortality on simulated crown fire behavior across a range of surface fire intensities. Simulations addressed fire behavior during a 1- to 2-year period after the initiation of the outbreak in which some proportion of the trees have been killed but no foliage has yet fallen. The effect of MPB-caused tree mortality on simulated crown fire behavior significantly changed as a function of surface fire intensity. The largest effects of mortality on crown fire behavior occurred at moderate levels of surface fire intensity, whereas diminished effects occurred at low and high levels of surface fire intensities. Our results suggest that increased crown fire potential immediately after bark beetle infestations is dependent on the fire intensity generated by the preoutbreak surface fuels complex. FOR. SCI. 59(4):390–399.

Keywords: fire hazard, computational fluid dynamics, spatial heterogeneity

WIDESPREAD MORTALITY OF LODGEPOLE PINE (*Pinus contorta* Dougl. Ex Loud.) caused by drought and mountain pine beetle (MPB) (*Dendroctonus ponderosae* Hopkins) has raised concern about potential increases in crown fire hazard in stands dominated by lodgepole pine (Kaufmann et al. 2008). Although historical fire regimes within lodgepole pine ecosystems included high-severity crown fires (Brown 1975, Arno 1980, Lotan et al. 1985), increased crown fire behavior in these systems poses a challenge for fire suppression operations. Crown fires burn with high intensity and spread rapidly, with increased potential for long-distance spotting and a high risk for losses to people and homes (Cohen and Butler 1998, Scott and Reinhardt 2001). Understanding and predicting crown fire behavior is challenging (Van Wagner 1977) due in part to the interactions between the surface fuel, canopy fuel, environment, and topography, all of which influence combustion. In MPB-infested forests, there are additional challenges and factors to consider in predicting and understanding crown fires as a result of changes in the fuels complex across spatial and temporal scales.

MPB-caused tree mortality is thought to influence potential fire behavior both directly and indirectly (Page and Jenkins 2007, Jenkins et al. 2008, Klutsch et al. 2011, Simard et al. 2011). Direct influences occur primarily through changes in the arrangement and composition of the fuels complex, whereas indirect changes occur through alterations to the within-stand environmental conditions such as increased wind flow and incoming solar radiation. Direct changes to the fuels complex and the associated indirect effects on within-stand environmental conditions vary through time and emerge as four distinct stages after MPB outbreaks, each with a different fuels complex (Jenkins et al. 2008, Simard et al. 2011). These stages are known as (1) the green stage (preoutbreak fuels), (2) the red stage (immediately after the outbreak), (3) the gray stage (several years after bark beetle-caused tree mortality), and (4) the old stage (several years to decades after tree mortality). These stages are used to classify the transient nature of the fuels complex after MPB outbreaks that has been described for lodgepole pine-dominated ecosystems (Brown 1975, Romme et al. 1986, Jenkins et al. 2008, Klutsch et al. 2009, 2011, Simard et al. 2011).

However, effects of alterations to the fuels complex after MPB outbreaks on fire behavior have been challenging to quantify because of a lack of empirical field studies and

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limitations in many of the modeling approaches used. Fire behavior modeling systems used operationally in the United States, such as Fire and Fuels Extension-Forest Vegetation Simulator (Reinhardt and Crookston 2003), Nexus (Scott and Reinhardt 2001), and BehavePlus (Andrews et al. 2008) are based on the integration of Rothermel's (1972, 1991) surface and crown fire spread models with Van Wagner's (1977) crown fire transition and propagation models. These modeling systems are based on the assumptions that surface fuels are spatially homogeneous and continuous and that crown fuels are a homogeneous layer at uniform height above the ground, with uniform bulk density, depth, and foliar moisture content. Neither differences in heat transfer mechanisms nor transient fire behavior is predicted by these models (Parsons et al. 2011). The inability of these systems to address fuel heterogeneity or the interactions of different heat transfer mechanisms significantly limits their application in evaluations of fire behavior after MPB outbreaks (Jolly et al. 2012). Despite these limitations, researchers have used these systems to examine fire behavior in beetle-killed stands, often with conflicting results. For example, using the modeling systems described above, Page and Jenkins (2007) and Jenkins et al. (2008) found that bark beetle-induced fuels changes probably increase crown fire intensity during the red stage, whereas Simard et al. (2011) found decreases in crown fire behavior during the red stage. Using similar modeling methodologies, Klutsch et al. (2011) found decreased potential for active crown fire spread, but no differences in the potential for torching, between the green stage and 7 years after the start of a bark beetle outbreak in Colorado. In contrast, Hoffman et al. (2012) used the Wildland-Urban Interface Fire Dynamics Simulator (WFDS) (Mell et al. 2007, 2009), a physics-based fire model, to investigate the effect of different levels of MPB-caused tree mortality on simulated crown fire behavior across a range of stand compositions, levels of tree mortality, and spatial arrangements during the red stage. They concluded that the level of tree mortality, along with stand characteristics and the spatial arrangement of trees, influenced the amount of crown fuel consumption and the intensity of crown fires and that there were significant increases in crown fire behavior during the red stage when at least 10% of the susceptible trees were killed by MPB.

Hoffman et al. (2012) only considered variations in the overstory fuels complex, because they held surface fire behavior, including intensity, heat release rate, and rate of spread, constant across the 11 sites they simulated. Thus, they only considered alterations in the canopy fuels complex, and they did not consider the potential effect that different preoutbreak surface fire intensities might have had on crown fire behavior. Here, we expand the work of Hoffman et al. (2012) to investigate how MPB-caused tree mortality influences simulated crown fire behavior across a range of surface fire intensities and mortality levels. By altering surface fire intensity as a proxy for surface fuel changes we were able to further investigate the role that MPB-caused morality has on crown fire behavior.

Objectives

Our overall objective was to use a physics-based fire model, WFDS, to examine the interaction of fire intensity and different levels of beetle-killed mortality for the 11 sites described in Hoffman et al. (2012). Our consideration of the beetle attack is constrained to the early attack stage in which some proportion of trees has been killed, but no trees have yet lost their needles. The period of time simulated in this study probably only represents a 1- to 2-year window after the initiation of an outbreak; however, few published data that quantify the temporal progression of needle drop after an outbreak exist. We investigated two main questions in this study: How does the effect of increasing MPB-caused tree mortality on simulated canopy fuel consumption and crown fire intensity vary depending on the surface fire intensity? and Are there thresholds of MPB-caused mortality at which there is increased crown fire intensity and canopy fuel consumption compared with the no mortality simulations and how do these thresholds vary as a result of different surface fire intensities?

WFDS Description

WFDS is a computational fluid dynamics model for simulating fire spread through vegetative fuels or a mixture of vegetative (i.e., trees, shrubs, and grass) and structural fuels (i.e., houses or other buildings). It is an extension of the Fire Dynamics Simulator (FDS) (McGrattan et al. 2010a) developed by the National Institute of Standards and Technology in cooperation with VTT Technical Research Centre of Finland, Industry, and Academics. WFDS numerically solves the Navier-Stokes equations appropriate for low Mach number flow, and models subgrid turbulent dissipation using a large-eddy simulation approach (McGrattan et al. 2010a). This approach results in both a space- and time-dependent prediction of fire behavior characterized by transient heat flux (radiative and convective), which considers heterogeneous fuel complexes and fuel- and fire-atmosphere interactions. Verification and validation studies for FDS, the parent model of WFDS, have been described by McGrattan et al. (2010a) and McDermott et al. (2010), whereas validation for WFDS was reported by Mell et al. (2007, 2009). McGrattan et al. (2010b) and Mell et al. (2009) described the mathematical formulation of WFDS more completely.

Methods

We sampled 11 sites that were predominately lodgepole pine on the Deschutes National Forest in central Oregon and on the Salmon-Challis National Forest in central Idaho (Table 1). Sampling locations were chosen in consultation with US Forest Service personnel to represent a wide range of typical stand structures in terms of tree density, species composition, and the size and number of canopy layers found in lodgepole pine-dominated stands on each National Forest. All sites sampled had recently experienced MPB-caused tree mortality and were similar in tree composition and structure to nearby stands with high levels of tree mortality from bark beetles.

Table 1. Mean stand-level characteristics of lodgepole pine sites used in WFDS simulations.

Site no.	Trees ha^{-1}	BA (m^2 ha^{-1})	QMD (cm)	Height (m)	CBH (m)	Species composition*
1	997	26.6	18.2	10.8	3.8	LPP 100%
2	775	28.6	21.4	11.6	3.5	LPP 80%, GF 20%
3	2825	42.3	13.6	9.5	3.7	LPP 100%
4	1118	33.7	19.4	14.0	6.0	LPP 74%, MH 15%, SF 11%
5	1137	27.7	17.4	10.3	2.7	LPP 100%
6	751	34.7	24.1	14.8	4.1	LPP 52%, SF 47%, ES 1%
7	1647	33.1	15.8	12.1	5.5	LPP 91%, SF 9%
8	1378	38.0	18.5	14.2	6.2	LPP 91%, SF 9%
9	1442	47.7	20.3	13.6	5.9	LPP 93%, SF 4%, ES 3%
10	1112	28.0	17.7	10.5	3.4	LPP 58%, WBP 28%, SF 14%
11	1406	36.5	17.9	14.0	5.8	LPP 60%, DF 31%, ES 6%, SF 2%

Measurements include stand density (trees ha^{-1}), basal area (BA), quadratic mean diameter (QMD), mean tree height (Height), height to base of live crown (CBH), and species composition as the percent of tree stems by species. LPP, lodgepole pine, GF, grand fir, MH, mountain hemlock, SF, subalpine fir, ES, Engelmann spruce, WBP, whitebark pine, DF, Douglas-fir.

As described by Hoffman et al. (2012), within each site, four fixed-radius 0.04-ha plots were sampled in a clustered design. Within each cluster, we measured dbh (1.37 m above the ground), total height, height to lowest branch with foliage (live or dead), tree status (live or dead), canopy position (dominant, codominant, intermediate, or suppressed), and crown width for all trees with a dbh of at least 5 cm. For each of the 11 sites, all tree data recorded on each of the 4 subplots within a cluster were combined to produce a single tree list representing that site for fire simulations with the WFDS model.

The 11 sites sampled varied in both tree composition and forest structure (Table 1). Three sites were composed entirely of lodgepole pine, and 8 sites were composed of a mix of other tree species dominated by lodgepole pine (Table 1). The mixed lodgepole pine sites included grand fir (*Abies grandis* [Douglas ex D. Don] Lindl.), mountain hemlock (*Tsuga mertensiana* [Bong.] Carrier), subalpine fir (*Abies lasiocarpa* [Hook.] Nutt.), Engelmann spruce (*Picea engelmannii* Parry ex Engelm.), whitebark pine (*Pinus albicaulis* Engelm.) and/or Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco).

Simulation Experiment

We used a completely randomized experimental design in which five levels of MPB-caused tree mortality (0, 25, 55, 70, and 100%) were the treatments and three levels of surface fire intensity (Table 2) were used as a covariate; the 11 sites acted as replications of each level of MPB-caused tree mortality and surface fire intensity. This resulted in a total of 165 simulations (11 sites × 5 levels of MPB-caused tree mortality × 3 surface fire intensities). These experiments were developed to represent a wide range of overstory fuel complexes and surface fire intensities. Observed tree mortality levels after MPB outbreaks have been reported to range from 5.5 to 100% across a 1- to 7-year time frame (Klutsch et al. 2009). Although our range of tree mortality covers the spectrum reported in the literature, it is not clear at what rate these levels of mortality occur across spatial scales. Thus, our simulated levels of mortality may not be realistic at all spatial scales of concern to fire managers, particularly when the rate of mortality is low and occurs over extended time frames. The variations in surface fire intensity simulated in these experiments could have been caused by a number of interacting factors such as fuel loading, distribution of fuel loading by size class, fuel moisture, and packing ratio. Regardless of the specific mechanism driving the change in surface fire intensity among the different scenarios, the altered surface fire intensities resulted in different levels of heat flux exposure for the overstory trees.

The simulated spatial domain was identical for all simulations, measuring 120 m × 48 m × 35 m in the x, y, and z dimensions, respectively, and discretized as 0.5-m cubical cells. All simulations ran for a total of 1,250 s (~20.4 min) of simulated time, with a time step of 0.1 s. The domain consisted of five parts (Figure 1): a wind entry field along the left-hand side of the domain, an exiting wind field along the right-hand side of the domain, a fire development zone (zone A), a zone representing the experimental section (zone B), and the preoutflow boundary (zone C). The boundary conditions along the top and bottom ($x = 0$, $y = 0–48$ and $x = 120$, $y = 0–48$, respectively) were simulated as an open domain, which acts as a passive boundary, allowing air to enter and exit without obstruction, whereas the boundaries along the sides ($x = 0–120$, $y = 0$ and $x = 0–120$, $y = 48$, respectively) were simulated as "mirrors" that act essentially as free-slip, no-flux boundaries.

Table 2. Summary of surface fire properties used to investigate the influence of surface fire intensity on the relationship between the level of mortality and fire behavior properties in WFDS simulation experiments.

	Rate of spread ($m\ s^{-1}$)	Heat release per unit area ($kW\ m^{-2}$)	Surface fireline intensity ($kW\ m^{-1}$)	Residence time (s)	Flame depth (m)
Low surface fire intensity	0.1	125	313	25	2.5
Moderate surface fire intensity	0.1	250	625	25	2.5
High surface fire intensity	0.1	500	1250	25	2.5

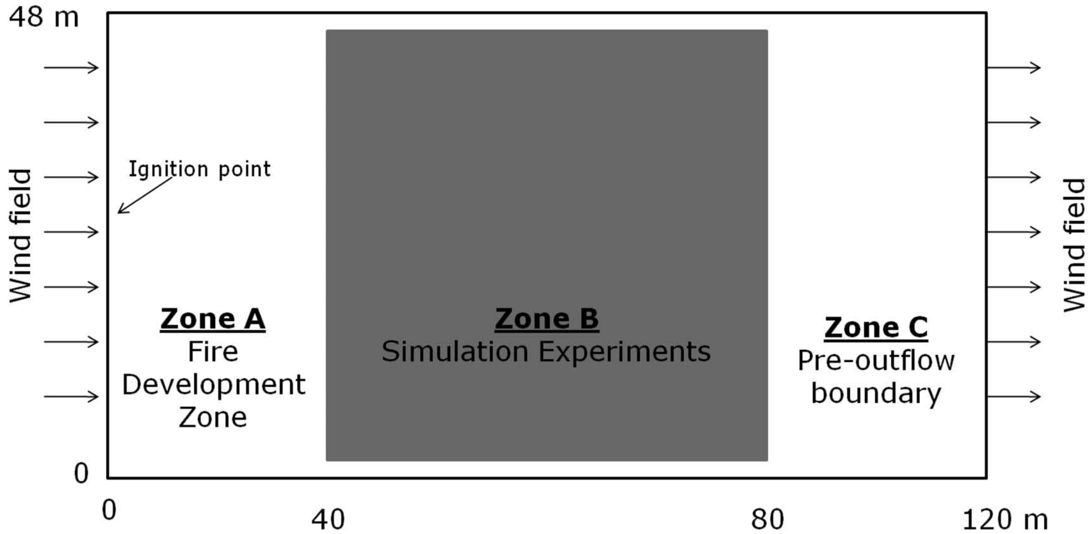

Figure 1. WFDS simulation layout showing the overall spatial domain measuring 120 × 48 × 35 m, with a predeveloped wind field entering the domain along the left-hand side, the ignition point, a fire development zone (zone A), the simulation experiments (zone B), the preoutflow boundary zone (zone C), and the exiting wind field along the right-hand side.

For all simulations, the wind entering the domain at $x = 0$ m varied with height above the ground after a vertical power-law profile (Morvan and Dupuy 2001, 2004) with a constant speed of 2 m s^{-1} at 6.1 m above the ground. The power law is of the form

$$U_x = U_r(Z_x/Z_r)^{\alpha},$$

where U_x is the wind speed at height Z_x, U_r is a known wind speed at height Z_r, Z_x is the height at which wind speed U_x will be predicted, and α is a constant value of 1⁄7. The entering windflow was allowed to interact with the fuels for 60 s before ignition, which allowed for a predeveloped windflow before surface fire ignition.

We modeled the surface fire as a steady-state fire with a known spread rate, heat release rate, and residence time. The surface fire spread radially from a point ignition at ($x = 1$, $y = 24$) and burned through the entire domain. Thus, instead of relying on WFDS to predict the surface fire behavior from a given surface fuel complex, we assumed that the surface fire behavior was known and that the fire propagated as a steady-state fire with homogeneous properties through both time and space. This modeling simplifies the dynamic nature of surface and crown fire interaction into a one-way interaction, in which crown fires are affected by the surface fire, but surface fire behavior is not influenced by the combustion of crown fuels. Although this assumption simplifies fire dynamics, it provides a conceptual framework for testing our hypotheses. By eliminating feedbacks from the crown fire on the surface fire, we ensured that differences in fire behavior between simulations were due to changes in surface fire intensities and the canopy fuels complex (caused by differences in sites, point patterns of tree locations, and level of MPB-caused tree mortality).

We simulated three different surface fire intensities (Table 2). The rate of spread and residence time were held constant for all three surface fires at 0.1 m s^{-1} and 25 s, respectively, and heat release rate was set at 125, 250, or 500 kW m^{-2}. The change in heat release rate resulted in three different levels of surface fire intensity hereafter referred to as low (313 kW m^{-1}), moderate (625 kW m^{-1}), and high (1,250 kW m^{-1}) intensity scenarios. The heat release rates and surface fire line intensities used in this study would result from 0.14, 0.28, and 0.57 kg m^{-2} of fuel combusting in the flaming front over the 25-s residence time we used for the low, moderate, and high surface fire intensity scenarios, respectively. According to the fire characteristics chart (Andrews and Rothermel 1982), both the moderate and high surface fire intensity values are higher than could be suppressed directly by firefighters using hand tools, whereas a fire burning at the low surface fire intensity could be suppressed by firefighters using hand tools. We chose these three scenarios to represent the wide range of potential surface fire intensities that might be encountered in lodgepole pine forests.

Individual tree crowns were modeled with crown fuels constrained to a cone with the height, crown width, and crown base height measured for each tree in the field. Fuels within the cone were represented as a homogeneous, thermally thin fuel with surface area/volume ratio of 6470 m^2 m^{-3} (Brown 1970) and bulk density of 0.7 kg m^{-3}. We simulated five levels of MPB-caused tree mortality (0, 25, 55, 70, and 100%) in the domain following Hoffman et al. (2012). In our simulations, we assumed that MPB-caused tree mortality was limited to susceptible tree species (lodgepole pine and whitebark pine) and to trees with a dbh of at least 10 cm. This method resulted in a clumpy pattern of tree mortality within stands. Because our focus here was on a single point in time rather than on a sequence over time, we assumed that tree mortality occurred as a synchronous event, which is a reasonable assumption considering the spatial extent of the simulations (0.2 ha) (zone B in Figure 1). This assumption resulted in our simulated forests having greater canopy fuel loadings, and horizontal and vertical canopy fuel continuity and lower mean canopy fuel moistures compared with the assumption of a nonsynchronous mortality event. Thus, our simulations represent a worst-case scenario in terms of canopy fuel hazard as indicated by canopy bulk density, total canopy biomass, and dead canopy biomass.

The level of tree mortality was measured as the percentage of MPB-susceptible trees killed rather than the percentage of all stems in the stand. Thus, even in the 100% mortality scenario, total stand mortality may have been less than 100% if nonsusceptible species and/or smaller (<10 cm dbh) trees were present. Live canopy fuels were set with a moisture content equal to 100% of dry weight. Keyes (2006) recommended this value for living trees as a prudently conservative value. The dead foliage within crowns of trees killed by MPB was represented with a foliar moisture content of 10% of dry weight; this is within the range of measured values by Jolly et al. (2011). The individual trees and the spatial arrangement of those trees in zones A and C were selected randomly from a master tree list consisting of all trees from each of the 11 sites such that the stand density was equal to 800 trees ha^{-1}. The trees in zone B consisted of the specific measured trees from each site. The overstory tree structure within zones A and C were held constant between simulations to ensure that the wind flow that entered zone B and the drag imposed by the downwind vegetation on air entrainment were consistent for all simulations. All tree spatial locations were simulated by generating random *x* and *y* locations using SpPack (Perry 2004). The simulated spatial patterns resulted in a random point pattern of tree locations in the domain.

We used two model outputs to quantify crown fire behavior. First, we used the mass loss of crown fuels, a global quantity tracked at each 0.1-s time step, that describes the consumption of total canopy fuel over time. We calculated the mean percent consumption for each simulation by the following equation:

$$\text{Percent canopy fuel consumption} = \left(\frac{\text{Canopy biomass}_{tend}}{\text{Canopy biomass}_{t0}}\right) \times 100,$$

where Canopy biomass$_{tend}$ is the biomass in kg remaining at the end of the simulation and Canopy biomass$_{t0}$ is the biomass in kg at the start of the simulation. Both the start and end canopy biomass were directly output from WFDS.

Second, we calculated the mean crown fire intensity. The crown fire intensity provides a measure of the energy output per unit time per unit length of fire front regardless of the depth and is commonly reported as kW m^{-1} (Byram 1959). We calculated the mean crown fire intensity as the average crown fire intensity for the period of time in which the fire was in zone B using the following equation:

$$\text{Mean crown fire intensity} = \frac{\sum_{n=400}^{n=850} ((Q_n - Qf_n)/\text{FL}_n)}{450},$$

where Q_n is the total heat release rate per unit area at time *n* (kW), Qf_n is the heat release rate of the surface fire at time *n* (kW), FL_n is the length of fire line at time *n* (m), and 450 is the total time for which there was a fire within zone B in seconds.

The total heat release (Q_n) is estimated in WFDS by

$$Q_n = (Mc \times Hc) + Qf_n,$$

where Q_n is the total heat release rate at time *n* (kW), M_c is the rate of gas fuel consumed due to canopy fuel gas (kg s^{-1}), H_c is the heat of combustion (kJ kg^{-1}), and Qf_n is the heat release rate due to the surface fire.

We tested the effect of the level of tree mortality on percent canopy fuel consumption and crown fire intensity across a range of surface fire intensities using an analysis of covariance with the five levels of tree mortality as the independent variable and the three levels of surface fire intensity as covariates. We then looked for differences of slope and intercept between surface fire intensity classes using Tukey's least significant difference multiple comparison procedure. We identified differences in percent canopy fuel consumption and crown fire intensity across percent tree mortality classes using a one-way analysis of variance and a Dunnett's test with the no tree mortality group as a control within each level of surface fire intensity. We used Bartlett's test and a Lillifors test to ensure that assumptions of homogeneous variance and normality were met before analyses were conducted.

Results

The effect of MPB-caused tree mortality on the percent canopy fuel consumption was significantly ($P < 0.05$) affected by the surface fire line intensity (Figure 2). The slope of the regression between the percent canopy fuel consumption and the level of MPB-caused tree mortality was greatest for the moderate surface fire intensity with the smallest slopes in the high surface fire intensity simulations. For a 10% increase in the level of tree mortality, there was a 1.4, 7.6, and 5.5% increase in the percent canopy fuel consumption for the high, moderate, and low levels of surface fire line intensity, respectively. There were also significant differences ($P < 0.05$) in the intercepts of the regression equations with near-zero percent fuel consumption in the no tree mortality category for both moderate and low surface fire intensities and >80% fuel consumption for the high surface fire intensity (Figure 2). The proportion of MPB-caused tree mortality explained a large amount of the predicted canopy fuel consumption, as measured by the R^2 statistic. At moderate surface fire intensities, the proportion of MPB-caused mortality accounted for 84% of the total variation in the percent canopy fuel consumption (Figure 2). At low surface fire intensities, the level of MPB-caused tree mortality explained approximately 49% of the variation in canopy fuel consumption, whereas at high surface fire intensities it only explained 22% of the variation (Figure 2).

At low surface fire intensity, the three highest tree mortality classes (55, 70, and 100% of susceptible trees) showed a significant increase in the percent canopy fuel consumed compared with the no tree mortality simulations ($P < 0.05$) (Table 3). For moderate surface fire intensities, all simulated stands with at least 25% MPB-caused tree mortality had significantly higher ($P < 0.010$) levels of canopy fuel

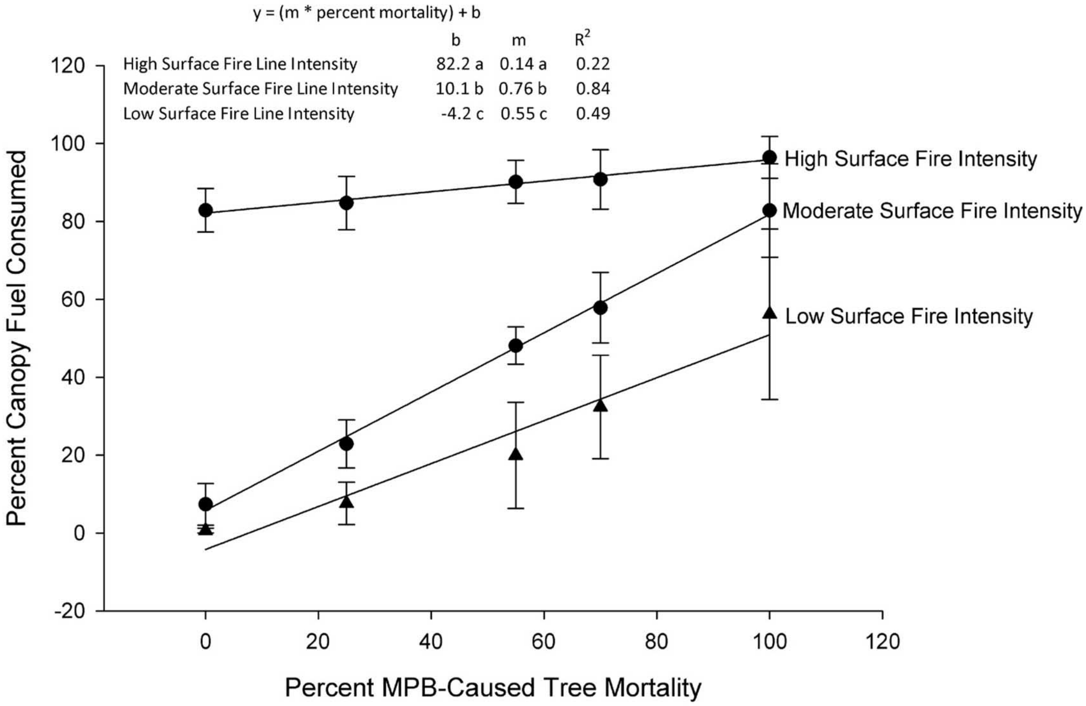

Figure 2. Simulated percent tree canopy fuel consumed as a function of the percent tree mortality for three different surface fire intensities. The mean canopy fuel consumed (lines) and 95% confidence intervals (vertical bars) are shown. The regression equation and parameters for each surface fire intensity are given in the table; parameter estimates followed by a different letter in a column are significantly different ($\alpha = 0.05$).

Table 3. Threshold values for the level of MPB-caused tree mortality at which significant ($\alpha = 0.05$) increases in the percent canopy fuel consumption and crown fire intensity were found compared with the no tree mortality scenario for three different surface fire intensities.

Surface fireline intensity	Threshold values of tree mortality required for an increase in fire behavior compared with the no mortality simulations: Percent canopy fuel consumed	Crown fireline intensity
High surface fireline intensity	70% mortality	No significant differences
Moderate surface fireline intensity	25% mortality	55% mortality
Low surface fireline intensity	55% mortality	100% mortality

Level of mortality is expressed as a percentage of susceptible trees killed, not as a percentage of total stems killed.

consumption compared with the same stands with no tree mortality (Table 3). At high surface fire intensities, all simulated stands with MPB-caused tree mortality greater than 70% experienced significantly higher canopy fuel consumption compared with the same stands with no tree mortality (Table 3). Overall, 20 and 65% less canopy fuel was consumed, respectively, with low surface fire intensity compared with the same stand conditions with moderate and high surface fire intensity, whereas those burned with moderate surface fire intensity had approximately 45% less canopy consumption compared with simulations with high surface fire intensity.

The influence of MPB-caused tree mortality on mean crown fire intensity was also significantly affected by surface fire intensity (Figure 3). There were significant differences in the slope of the regression between the high surface fire line intensity and both the moderate and low surface fire line intensity ($P < 0.05$) (Figure 3). However, no significant differences in slope were found between the low and moderate levels of surface fire intensity ($P = 0.437$) (Figure 3). An increase of 10% in bark beetle-caused tree mortality resulted in an average increase of 3, 25, and 36% in the crown fire intensity for the high, moderate, and low surface fire line intensity scenarios, respectively. The intercepts of the regression equations for each of the three levels of surface fire intensity decreased significantly ($P < 0.05$) from high to low surface fire intensity (Figure 3). The level of MPB-caused mortality was a significant ($\alpha = 0.05$) explanatory variable for crown fire intensity for both the low and moderate surface fire intensities with R^2 values of 0.38 and 0.56, respectively (Figure 3). At high levels of surface fire intensity, the level of MPB-caused mortality was not a significant explanatory variable for predicted crown fire intensity.

At low surface fire intensities, there were no significant differences between the predicted crown fire intensity for no mortality and all levels of tree mortality less than 100% of susceptible trees (Table 3). At moderate levels of

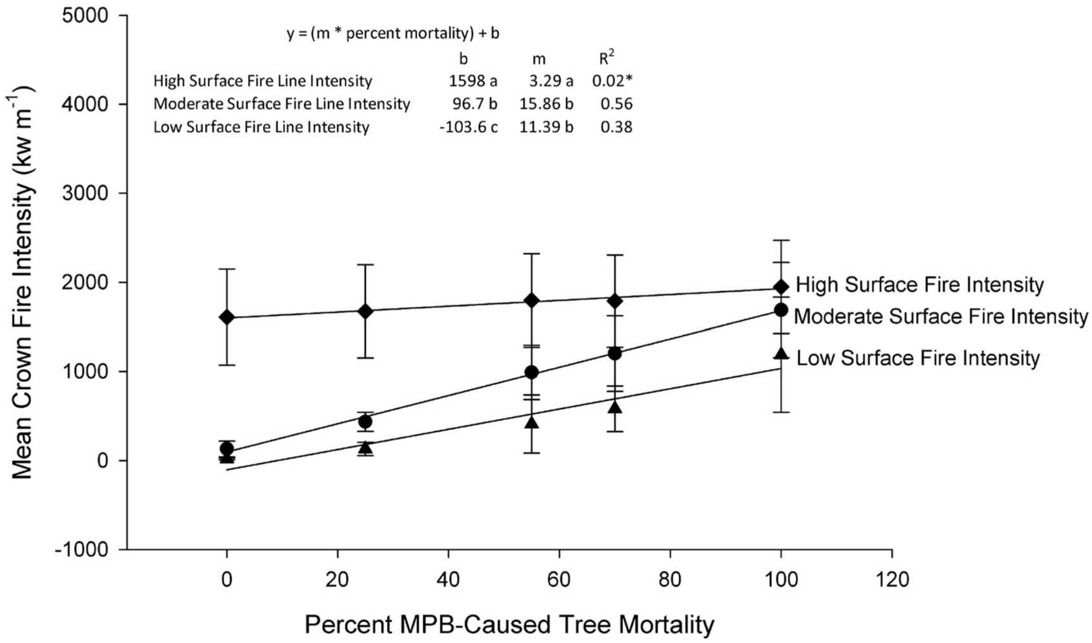

Figure 3. Simulated crown fire intensity as a function of the percent tree mortality for three different surface fire intensities. The mean and 95% confidence intervals for each level of MPB-caused tree mortality are indicated by vertical lines. The regression equation and parameters for each surface fire intensity tested are given in the table; parameter estimates followed by a different letter in a column are significantly different ($\alpha = 0.05$).

MPB-caused mortality, predicted crown fire intensity was significantly higher relative to no tree mortality for simulations with greater than 55% MPB-caused mortality (Table 3). Overall, the moderate levels of surface fire intensity had a predicted mean crown fire intensity that was 424 kW m^{-1} or approximately 90% higher than the low levels of surface fire intensity. The high surface fire intensity group was on average 270 and 98% higher than the low and moderate surface fire intensity simulations, respectively. However, we found no significant differences in crown fire line intensity between the different levels of MPB-caused mortality, so no threshold values were identified for the high surface fire intensity.

Discussion

Crown Fire Hazard Depends on Both the Level Tree Mortality and the Surface Fire Intensity

The effect of a given level of MPB-caused tree mortality on crown consumption was dependent on the heat exposure of crown fuels created by different surface fire intensities. In our low and moderate surface fire intensity scenarios, we saw increased crown consumption and crown fire intensity compared with those for preoutbreak simulations. These findings agree with the results reported in Hoffman et al. (2012) and with the conceptual model proposed by Jenkins et al. (2008). However, under our highest surface fire intensity simulations, we found that the level of MPB-caused mortality did not influence canopy fuel consumption or crown fire intensity to the same extent as in the low and moderate levels of surface fire intensity simulations.

The nonlinear relationship between the amount of heat energy released by the surface fire and the amount of overstory killed by MPB affected the amount of canopy fuel consumed. Increased simulated crown fire behavior in stands with MPB-caused tree mortality was greatest when the thermal energy produced by a surface fire was nearly, but not quite, intense enough to initiate crown fire in a given fuels complex with no overstory tree mortality. In simulations for which the thermal energy from a surface fire either surpassed or was far below the threshold for crown fire initiation, MPB-caused tree mortality played only a small role in determining the simulated canopy fuel consumption. In the case for low surface fire intensities, the reduction in foliar moisture content due to tree mortality did not reduce the thermal energy required for ignition enough to promote the onset of crowning. For high surface fire intensities, any reductions in heat required for ignition in the overstory was negligible, given that the heat flux exposure of the crown fuels resulted in crown ignition regardless of tree mortality. The diminishing effect of MPB-caused tree mortality was evident in both the decreasing slope in the regression equations between crown fuel consumption and level of MPB-caused tree mortality and decreased explanatory power of MPB-caused tree mortality on low and high surface fire intensity as measured by the R^2 statistic (Figures 2 and 3).

In our moderate surface fire line intensity simulations, we found significant increases in the percent canopy fuel consumption at the lowest level of tree mortality (25%). However, for the low and moderate surface fire line intensity, tree mortality levels less than 55 and 70%, respectively, were not significantly different from the no-mortality simulations, whereas canopy fuel consumption was significantly higher at greater levels of tree mortality. Thus, for a particular fuels complex, there were thresholds at which MPB-caused tree mortality significantly increased canopy fuel consumption. In terms of simulated crown fire intensity, tree mortality level had to be at least 100 and 55% for the low and moderate surface fire intensities before significant increases were detected compared with the no mortality scenario. Further, we found that, regardless of tree mortality level, there was no significant increase in crown fire intensity for the high surface fire intensity scenario. At larger spatial extents than those simulated here (0.2 ha), high levels of tree mortality during the red stage may not be a common occurrence. Thus, some of our identified thresholds may be limited to small spatial scales for which these conditions could exist. These findings suggest that increased fire behavior was not necessarily an outcome immediately after MPB outbreaks.

The potential effects of bark beetle mortality on subsequent fire behavior have been debated recently in the scientific literature with several authors suggesting that bark beetle outbreaks will lead to catastrophic wildfires (Brown 1975, Geiszler et al. 1980), whereas others have suggested that such increases may only occur during the red stage (Gara et al. 1985, Romme et al. 2006). Although studies investigating the effect of bark beetle outbreaks on subsequent fire behavior are still few, there is a growing body of both retrospective (i.e., Kulakowski and Veblen 2007, Bond et al. 2009) and modeling studies (Page and Jenkins 2007, Jenkins et al. 2008, DeRose and Long 2009, Simard et al. 2011). However, a clear picture of bark beetle-caused mortality effects on fire behavior immediately after an outbreak has yet to emerge (Hicke et al. 2012). Kulakowski and Veblen (2007), Bond et al. (2009), and Simard et al. (2011) reported no significant change in subsequent wildfire behavior during the red stage compared with that in forests not affected by bark beetles, whereas Page and Jenkins (2007), Jenkins et al. (2008), and Hoffman et al. (2012) have suggested that there is an increase in fire behavior during the red stage. The dependence of red stage fire behavior on the relationship between the level of mortality and the surface fire intensity may provide some explanation as to why such discrepancies may exist between studies. Future studies that evaluate the effects of bark beetle mortality on subsequent fire behavior should include descriptions of the level of tree mortality and adequate information regarding the stand conditions and fire behavior such that cross-experimental comparisons can be made.

Assumptions and Limitations of the Modeling Approach Used

Our fire behavior was not modeled in a fully coupled fire environment. We assumed that the rate of spread and intensity of the surface fire were constant and not influenced by radiative heat transfer or convective flow induced by the combustion of canopy fuel. Thus, we were unable to assess any effects that crown fire activity may have had on surface fire behavior. The assumption of a steady-state surface fire decoupled from the crown fire resulted in a constant intensity and arrival time of the surface fire through space. This assumption also probably dampened the range of outcomes that could have occurred in a fully coupled approach by eliminating far-field entrainment effects due to crown fuel combustion and radiative heat transfer effects from the canopy. The implications of this assumption on simulation results need to be further explored.

The main focus of this study was to explore interactions among different levels of mortality and surface fire intensity for the simple case in which there is a mix of red- and green-stage trees in the stand. We did not intend in this study to capture the full range of fuel changes that occur in a beetle-attacked stand over time, and our simplifications may not accurately represent fuel conditions in beetle-attacked stands in which the outbreak unfolded over several years, leaving a stand comprised of a mix of green-stage, red-attacked, and gray-stage trees. In scenarios in which mortality occurred over several years, resulting in a mix of green-, red-, and gray-stage trees, our assumption of synchronous mortality would have resulted in increased canopy fuel biomass, canopy bulk density, horizontal and vertical fuel continuity, and decreased mean canopy fuel moisture contents compared with a nonsynchronous simulation. Thus, our assumption represented a limiting worst-case scenario in terms of crown fuel hazard. Because crown fire behavior is generally thought to increase as canopy bulk density, canopy fuel loadings, and crown fuel continuity increase and as canopy fuel moisture decreases we would expect that that our simulations probably overestimated rates of canopy fuel consumption and crown fire intensities and that our threshold estimates are conservative compared with simulations that included a nonsynchronous representation of bark beetle mortality that resulted in a mix of green-, red-, and gray-stage trees. However, more studies are needed to better understand the effects of the canopy and surface fuels when there are mixes of green-, red-, and gray-stage trees and the effects of these distributions on fire behavior. Future studies investigating this topic should consider the spatial variability in overstory tree patterns, the spatial alterations to surface fuels, and the spatial relationship between the surface and canopy fuels.

Along with further investigation of the assumptions we made in this study, studies are needed in other forest types that have also had bark beetle-caused tree mortality. Investigations at larger spatial scales are also needed. The thresholds we identified in this study were simulated with a relatively small spatial extent (0.2 ha) and may not be a common occurrence at larger spatial scales. Future studies using physics-based models to investigate postoutbreak time periods across a range of environmental and topographical conditions could help identify fuel and weather conditions in which MPB-caused tree mortality influences crown fire behavior. Simulations that account for a range of topographical and environmental conditions may reveal conditions under which operational and physics-based models differ. In addition, both laboratory and field experiments are needed to help validate the results from physics-based simulations such as those performed here.

Conclusions

Surface fire behavior played a significant role in determining the effect of MPB-caused tree mortality on simulated crown fire behavior by altering the heat flux exposure of the canopy fuels. When simulated surface fire intensity was high, the degree of tree mortality did not affect crown fire intensity or consumption, but with moderate and low surface fire intensity, simulated canopy fuel consumption and crown fire intensity increased as the percentage of MPB-caused tree mortality increased. For a given surface fire intensity, there are thresholds in the level of MPB-caused tree mortality during the early red stage over which increased crown fire hazards exist compared with the same stands with no mortality. Our study demonstrated that mountain pine beetle-caused tree mortality increased crown fire and crown consumption, with the greatest effects shown at moderate, rather than very low or very high, levels of surface fire intensities. This work highlights the importance of the interaction between surface fire intensity and canopy fuels on crown fire behavior and provides a possible mechanism for disparate results of previous studies investigating MPB-caused mortality effects on fire behavior.

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