Evaluating Potential Fire Behavior in Lodgepole Pine-Dominated Forests after a Mountain Pine Beetle Epidemic in North-Central Colorado

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ABSTRACT

A mountain pine beetle outbreak in Colorado lodgepole pine forests has altered stand and fuel characteristics that affect potential fire behavior. Using the Fire and Fuels Extension to the Forest Vegetation Simulator, potential fire behavior was modeled for uninfested and mountain pine beetle-affected plots 7 years after outbreak initiation and 10 and 80% projected tree fall using measured and projected fuel and stand characteristics. Under 90th percentile weather conditions, uninfested plots exhibited proportionally more crown fire than infested plots. Plots predicted to have crown fire were composed mainly of nonhost conifer species and had a lower and more continuous canopy than infested plots. Where surface fire was predicted to occur, live lodgepole pine was the only conifer present, and plots had significantly lower tree mortality from fire than plots predicted to have crown fire. Mountain pine beetle-induced changes in stand and fuel characteristics resulted in increased intensity of surface fire behavior. Furthermore, with 80% infested tree fall, potential smoke production was predicted to be higher. Tree species composition of stands pre and postbark beetle outbreak is important when identifying mountain pine beetle-caused changes to potential fire behavior.

Keywords: bark beetles, *Dendroctonus ponderosae*, fire types, species composition, *Pinus contorta*

Mountain pine beetle (*Dendroctonus ponderosae* Hopkins) has infested more than 2 million ac of lodgepole pine (*Pinus contorta* Dougl. ex Loud.) forest since an outbreak began approximately in 2000 in north-central Colorado (US Forest Service). As the stand characteristics and fuel complexes of affected stands are altered, there is a pressing need for forest managers, researchers, and the general public to understand the potential effects associated with the mountain pine beetle epidemic, including changes in fire behavior. It is generally thought that mountain pine beetle outbreaks in lodgepole pine forests increase the potential for high-intensity and severe fires (Arno 1980, Jenkins et al. 2008). It is also known that lodgepole pine fire regimes are characterized as having stand-replacing, high-severity fires driven by weather conditions, with low-intensity surface fires generally playing a less frequent role in lodgepole pine ecosystems (Arno 1980, Kipfmueller and Baker 2000).

In an associated study in north-central Colorado, Klutsch et al. (2009) reported that canopy characteristics and surface fuel loads have been significantly altered because of this recent mountain pine beetle outbreak. Mountain pine beetle-caused mortality in these lodgepole pine-dominated forests has reduced lodgepole pine density by 42%, resulting in an average density of 240 lodgepole pines/ac and 190 nonhost trees/ac, such as Engelmann spruce (*Picea engelmannii* [Parry]), subalpine fir (*Abies lasiocarpa* [Hook.] Nutt. var. *lasiocarpa*), and quaking aspen (*Populus tremuloides* Michx.) (Table 1). Mountain pine beetle selectively infested lodgepole pine with dbh (4.5 ft) greater than 8 in., resulting in a reduction of live lodgepole pine quadratic mean diameter of 34% in affected areas. Seven years after outbreak initiation, the median amount of downed woody debris (DWD) in affected stands was not significantly different from that in uninfested stands, with total fuel loads of 8.7 and 9.8 tons/ac, respectively (Table 2). Simulations in which 80% of affected trees were converted to surface fuels showed that projected DWD loads (total, fine, and coarse) were significantly greater than with no tree fall, resulting in an estimated 22.8 tons/ac increase in total fuel load. The amount of coarse woody debris projected to accumulate with 80% tree fall could be considered within historical ranges found in lodgepole pine forests (Brown et al. 2003). Changes in fuel loads due to fall of mountain pine beetle-killed lodgepole pine was also shown by Page and Jenkins (2007a).

The changes in stand characteristics and fuel loads in lodgepole pine-dominated forests affected by the current mountain pine beetle epidemic in north-central Colorado could influence fire behavior and effects. Page and Jenkins (2007b) modeled potential fire behavior for lodgepole pine stands undergoing a mountain pine beetle outbreak, stands affected by an outbreak 20 years previously, and stands with endemic mountain pine beetle in Utah and Idaho. They reported increased surface fire rate of spread and fire line intensity in mountain pine beetle-affected stands compared with endemic stands. Characterizing potential fire behavior in lodgepole pine-dominated forest with

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Table 1. Mean (standard error) stand characteristics in plots with lodgepole pine (*Pinus contorta*) killed by epidemic levels of mountain pine beetle (MPB) and uninfested plots, Arapaho National Forest, Colorado, 2006–2007.

	Uninfested plots	Infested plots	*P* value[a]
Trees/ac total live	653.1 (42.6)	430.3 (22.1)	<0.0001
Trees/ac live *P. contorta*	365.3 (40.1)	239.9 (18.3)	0.0012
Trees/ac live nonhost trees	287.8 (39.8)	190.4 (20.4)	0.0071
Trees/ac *P. contorta* killed by MPB		141.4 (7.5)	
Basal area live total (ft^2/ac)	141.5 (9.4)	68.8 (3.8)	<0.0001
Basal area live *P. contorta* (ft^2/ac)	97.6 (9.8)	37.2 (2.7)	<0.0001
Basal area live nonhost trees (ft^2/ac)	43.9 (6.3)	31.6 (3.5)	0.0186
Basal area *P. contorta* killed by MPB (ft^2/ac)		78.4 (3.0)	
Canopy base height (ft)[b]	2.2 (0.4)	6.5 (0.8)[c]	0.0002
Canopy bulk density (lbs/ft^3)[b]	0.0078 (0.0004)	0.0042 (0.0002)	<0.0001

Modified from Klutsch et al. (2009). Numbers of uninfested and infested plots were 51 and 170, respectively. Nonhost species include *Picea engelmannii*, *Abies lasiocarpa*, and *Populus tremuloides*.
[a] *P* value from Wilcoxon rank sum test for stand characteristics.
[b] Calculated from the Fire and Fuels Extension to the Forest Vegetation Simulator.
[c] $n = 166$.

Table 2. Median (median absolute deviation) downed woody debris (DWD) fuel loads (tons/ac) in plots with lodgepole pine killed by epidemic levels of mountain pine beetle and plots without infested trees in the Arapaho National Forest, Colorado, 2006–2007.

DWD	Uninfested plots	7 years after outbreak initiation	10% infested tree fall	80% infested tree fall	P-value
≤0.25 in.	0.2 (0.1)[a]	0.2 (0.1)[a]	0.3 (0.1)[a]	0.9 (0.3)[b]	<0.0001
>0.25–1 in.	0.5 (0.3)[a]	0.6 (0.4)[a]	0.6 (0.3)[a]	1.3 (0.4)[b]	<0.0001
>1–3 in.	1.0 (0.5)[a]	1.0 (1.1)[a]	1.0 (0.9)[a]	1.2 (0.7)[a]	0.0442
>3 in.	6.4 (6.4)[a]	6.8 (6.8)[a]	9.1 (7.1)[a]	28.1 (12.2)[b]	<0.0001
Total	8.7 (8.0)[a]	9.8 (8.3)[a]	11.9 (8.6)[a]	32.6 (12.2)[b]	<0.0001

Modified from Klutsch et al. (2009). Numbers of uninfested and infested plots were 51 and 170, respectively.
[a,b] Different letters denote significance at $P < 0.05$. *P* value from a robust linear regression with a Bonferroni adjustment.

mountain pine beetle-caused mortality in north-central Colorado will help interested groups understand potential fire implications in areas with extensive lodgepole pine mortality. The objective of this study was to compare potential fire behavior modeled with the Fire and Fuels Extension to the Forest Vegetation Simulator (FFE-FVS) in uninfested stands, stands 7 years after mountain pine beetle outbreak initiation, and infested stands with projected fuel and stand characteristics that represent 10 and 80% tree fall.

Methods

Stand Structure and Downed Woody Debris Sampling

The study area consisted of lodgepole pine-dominated forests in the Sulfur Ranger District, Arapaho National Forest, Colorado (approximate central point: 40°4′N, 106°0′W), which covers approximately 45% of the 442,000-ac District, with an elevational range of 8,200–11,300 ft. Engelmann spruce, subalpine fir, and quaking aspen were also present in lodgepole pine-dominated forests. The understory in the study area consisted mainly of grouse whortleberry (*Vaccinium scoparium* Leiberg ex Coville), and common juniper (*Juniperus communis* L.).

Using a GIS, we randomly selected plot locations in areas uninfested and infested with mountain pine beetle in lodgepole pine-dominated forests. Plots were established within 0.25 miles of access roads, were at least 0.25 miles away from one another, and spanned an elevational range of 8,300–11,360 ft. In 2006–2007, 7 years after initiation of the outbreak, 221 fuel and stand assessment plots were measured: 170 infested and 51 uninfested (Klutsch et al. 2009). These plots were used in an analysis of the influence of the mountain pine beetle outbreak on stand characteristics and fuel complexes (Klutsch et al. 2009). Herein, we use the data to model potential surface and crown fire behavior in infested and uninfested stands. The infested plots had varying dates of initial infestation (2000–2006) and contained varying numbers of trees attacked by mountain pine beetle in any or all of the infestation years. Site, tree, and stand characteristics were measured within a 1/20th-ac stand assessment plot. For all trees greater than 1 in. dbh, we recorded the species condition (live, infested or killed by mountain pine beetle, or dead from other causes), year of mountain pine beetle infestation, dbh, total height, and height to base of live crown (lowest branch with living foliage). The year of infestation by mountain pine beetle was categorized by degradation classes of needles and branches (Klutsch et al. 2009). Tree height and height to base of live crown were used to calculate live crown ratio. Trees with dbh less than 1 in. were tallied by species and condition. Surface fuel loads were measured within each plot along three Brown's planar transects, each 24 ft in length and radiating from plot center at 120° from one another (Brown et al. 1982). Along each transect, surface fuel by size class was tallied at segments of 6 ft for DWD ≤1 in. in diameter, 10 ft for DWD >1–3 in. in diameter, and entire transect for DWD >3 in. in diameter. For DWD >3 in. in diameter, decay class (sound or rotten) and diameter were recorded. To calculate the surface fuel loads with 10 and 80% fall rate for mountain pine beetle-killed trees, trees were randomly chosen and converted to DWD. We used allometric equations for lodgepole pine (Brown 1978, Pearson et al. 1984) to predict DWD fuel loads by size class. These trees were removed from the list of standing trees and added to the surface fuel load.

Table 3. Median (median absolute deviation) potential surface fire behavior for plots with lodgepole pine killed by epidemic levels of mountain pine beetle and plots without infested trees in the Arapaho National Forest, Colorado, 2006–2007.

	Uninfested plots	7 years after outbreak initiation	10% infested tree fall	80% infested tree fall	*P* value
Surface flame length (ft)	4.3 (1.1)[a]	6.6 (2.2)[b]	7.1 (2.4)[b]	7.7 (2.5)[b]	<0.0001
Surface rate of spread (chains/hour)	8.0 (2.6)[a]	15.1 (7.3)[b]	15.8 (7.5)[b]	17.6 (8.4)[b]	<0.0001
Reaction intensity (BTU/ft^2/min)	4760.9 (1470.1)[a]	6476.0 (1879.9)[b]	6564.3 (1826.7)[b]	7114.4 (1946.7)[b]	<0.0001

Numbers of uninfested and infested plots were 51 and 170, respectively.
[a,b] Different letters denote significance at $P < 0.05$. *P* value from multiresponse permutation procedure analysis with a Bonferroni adjustment.

Fire Behavior Modeling

Potential surface and crown fire behavior, tree mortality from fire, and smoke production were modeled for uninfested plots and for infested plots at three points in time: 7 years after outbreak initiation, at projected 10% infested tree fall, and at projected 80% infested tree fall. Custom fuel models from measured fuel loads were used to calculate potential fire behavior for each plot using the Central Rockies variant (Suppose 2.02) (Edminster et al. 1991, Reinhardt and Crookston 2003) of FFE-FVS. Fuel bed depth was obtained from FFE-FVS to model surface fire behavior as it can estimate a reasonable value using total and fine fuel loads (Rebain 2010). FFE-FVS was developed with current fire science information and represents an adequate tool to assess potential fire behavior. Historic weather data were obtained from the Harbison Meadow National Oceanic and Atmospheric Administration Remote Automated Weather Station (RAWS) (40°12′N, 105°52′W, 8,500 ft), which was the closest to our study area. Data were summarized for the summer fire season (June to September 15) for the years 1964 to 2000, after which the station was moved. Plots were on average 16.6 miles (SEM = 0.6) from the weather station. The 90th percentile weather condition (i.e., high fire weather) was identified from historic fire weather using Fire Family Plus, a program with fire climatology analysis capabilities (Bradshaw and McCormick 2000). Under 90th percentile conditions, air temperature was 84°F, and the 20-ft windspeed for 1-minute gusts was 18 miles/hour (mph) as converted from the RAWS 10-minute windspeed with a windspeed conversion table (Crosby and Chandler 2004). On the basis of the Energy Release Component, fuel moisture was 4, 6, 11, and 14% for the DWD diameter classes ≤0.25, >0.25–1, >1–3, and >3 in., respectively.

Canopy bulk density (CBD) for trees greater than 6 ft in height was estimated in FFE-FVS, a practice that is standard because of the difficulty in measuring CBD in the field. This estimate of canopy bulk density is a relative value that was used to compare the different scenarios of uninfested and infested plots and not an actual value. For the calculation of CBD, crown biomass is assumed to be equally distributed along the entire length of tree crowns (Reinhardt and Crookston 2003). Within 1-ft height increments of individual crowns, FFE-FVS estimates the crown biomass. A 13-ft running mean of crown biomass for each section is calculated, and the maximum average value is the CBD of a stand. This method is thought to be more realistic than assuming a uniform vertical distribution of canopy fuel (Scott and Reinhardt 2001). An adjustment of 20-ft windspeed due to canopy sheltering was used in FFE-FVS (Albini and Baughman 1979).

Potential surface and canopy fire behavior were modeled in FFE-FVS using custom surface fuel models based on measured fuel loads from our fuel plots. Because of the short time period modeled and the slow growth of trees in subalpine environments, we excluded potential growth of residual trees in the 10 and 80% infested tree fall simulations. Regenerating trees did not reach the minimum tree height required (>6 ft) for FFE-FVS to incorporate trees into calculations of potential crown fire behavior (Reinhardt and Crookston 2003) and were not included in modeling potential canopy fire behavior.

Surface and canopy fire behavior outputs include surface rate of spread, fire reaction intensity, surface flame length, fire type, and torching and crowning indices (Reinhardt and Crookston 2003, 2007). Surface rate of spread is the rate that a fire moves through the surface fuels. Potential fire reaction intensity represents the rate of heat energy released per minute from a square foot section of the fuel bed in the flaming zone. Surface flame length is the expected fire intensity in the form of estimated flame length from surface fuels during a surface fire. Categories of fire type include surface, passive crown, conditional surface, and active crown fires. Surface fires are defined as those that burn surface fuels and do not transition into the canopy. Passive crown fires occur when the canopies of individual trees or groups of trees are burned. Conditional surface fire is defined as having either surface or active crown fire behavior in a given stand depending on where the fire originates (Scott and Reinhardt 2001). Active crown fires are defined as those in which flames move between crowns and the entire fuel complex is burned. Torching index is the 20-ft windspeed expected for surface fire to ignite crown fuel based on surface fuel characteristics and moisture contents, foliar moisture content, canopy base height, slope, and wind reduction by the canopy (Rothermel 1972, Van Wagner 1977, Scott and Reinhardt 2001). Crowning index is the 20-ft windspeed expected for active fire spread and is a function of canopy bulk density, slope, and needle fuel moisture content (Van Wagner 1977, Rothermel 1991, Scott and Reinhardt 2001). For both indices, a greater crown fire hazard is indicated by a lower index value.

Data Analysis

Most data were either nonnormally distributed, skewed by the presence of outliers, or both. The statistical techniques used to test significance of stand, fuel, and fire behavior characteristics between plot types or fire types did not have an assumption of normality and were chosen to deal with outliers in the data set. The median and the median absolute deviation (MAD) are reported where significant outliers were present. The MAD is the median absolute value of the difference between each observation and the median. The differences in stand characteristics between infested and uninfested plots were tested using the Wilcoxon rank sum test, and the mean and standard error of the mean are reported. To limit the influence of skewness and the presence of outliers, DWD loads were tested for significant differences between plot types with a robust regression

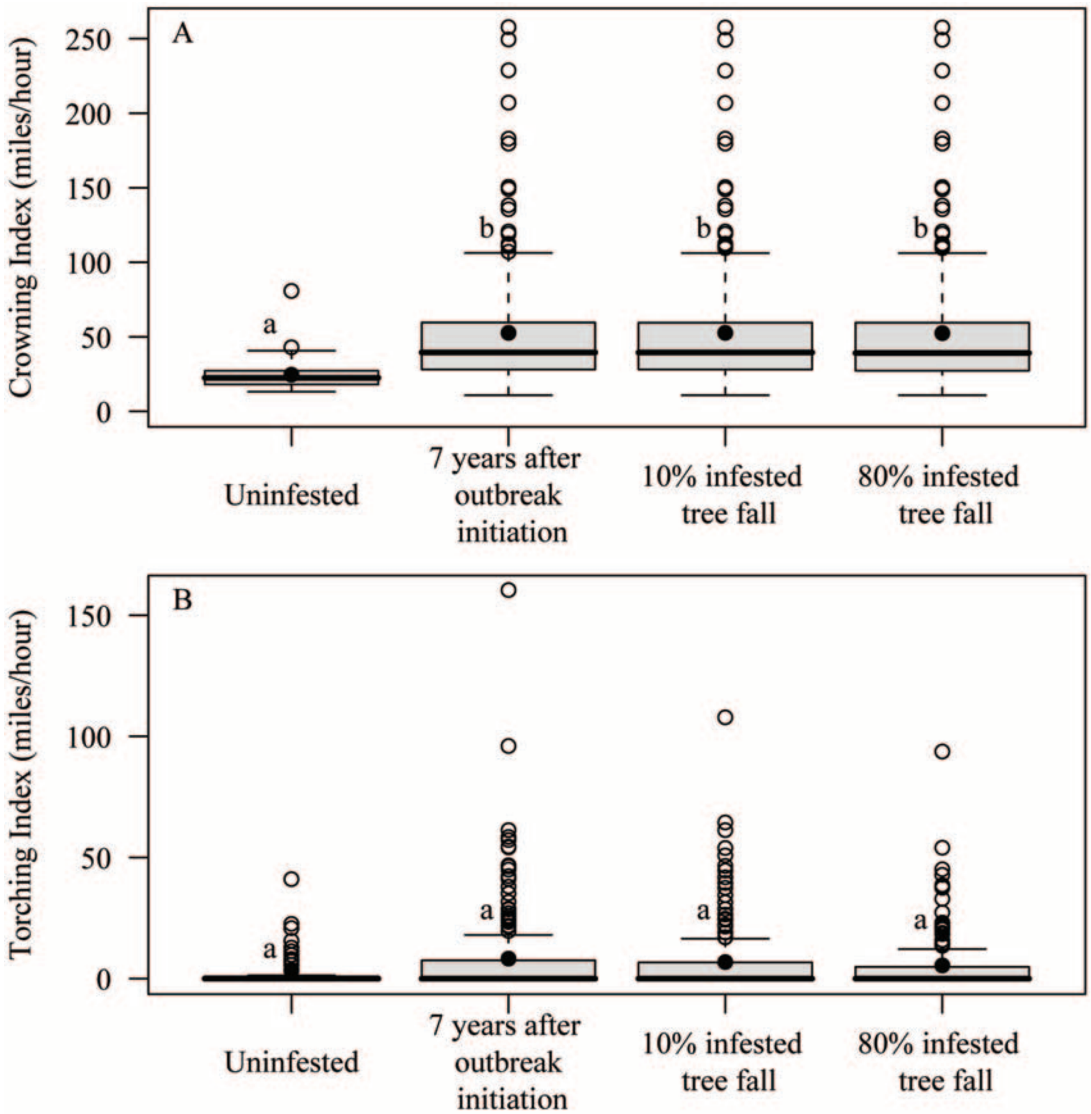

Figure 1. Crowning index (A) and torching index (B) under 90th percentile fire weather for uninfested plots, plots 7 years after epidemic mountain pine beetle infestation initiation, and plots with 10 and 80% infested tree fall in lodgepole pine forest, Arapaho National Forest, Colorado, 2006–2007. In each box plot, the filled circle indicates the mean, the heavy line is the median, the box represents the 1st and 3rd quartiles, whiskers are Tukey's 1.5 interquartile range, and the open circles indicate outliers. Different letters denote significance at $P < 0.05$ from multiresponse permutation procedure analysis with Bonferroni adjustment.

(PROC ROBUSTREG) (SAS Institute 1999). A test for equal proportionality of fire type for uninfested, 7 years after outbreak initiation, 10% tree fall, and 80% tree fall plots was performed with a chi-square test. Differences in potential surface and crown fire behavior variables among uninfested plots, plots 7 years after outbreak initiation, and 10 and 80% projected infested tree fall plots were tested with multiresponse permutation procedure (MRPP) based on Euclidean distance for a one-factor design (Mielke and Berry 2001) using a Microsoft Excel macro developed by R. King, US Forest Service (version 3/14/2008). The differences in stand characteristics and tree mortality from fire among predicted fire types were also tested using MRPP. Because the data included multiple simulations of potential fire behavior for a plot, the data were aligned by plot, which transforms each response as a difference from the median within each plot, minimizing the difference of plots with extreme differences from the median. Differences in fire behavior and stand structure between plot types or fire types were considered significant at $P < 0.05$ after a Bonferroni adjustment for multiple comparisons (Miller 1981).

Results

Stand Structure

Stand characteristics were different between uninfested plots and infested plots (Table 1). Both lodgepole pine density and basal area were lower in plots with mountain pine beetle-caused mortality compared with uninfested plots. The density and basal area of nonhost trees were also lower in infested plots compared with uninfested plots. Average live canopy base height in uninfested plots was lower than in infested plots. Uninfested plots had a greater canopy bulk density compared with infested plots.

Potential Fire Behavior and Tree Mortality

Mountain pine beetle-induced changes in stand and fuel characteristics were reflected in all three measures of fire behavior involving

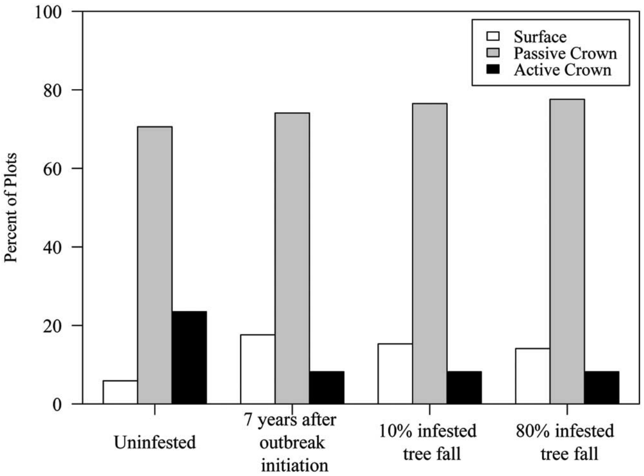

Figure 2. Percentage of plots within infestation class with surface, passive crown, and active crown fire types with 90th percentile fire weather for uninfested plots, plots 7 years after epidemic mountain pine beetle infestation initiation, and plots with 10 and 80% infested tree fall in lodgepole pine forest, Arapaho National Forest, Colorado, 2006–2007. Significantly different distribution (*P* < 0.0001) tested with a chi-square test (test statistic=53.5, degrees of freedom=9).

surface fuels. Surface flame length, surface rate of spread, and reaction intensity were lower in uninfested plots compared with plots 7 years after outbreak initiation and 10 and 80% projected infested tree fall plots (Table 3).

Windspeeds predicted to sustain an active crown fire (i.e., crowning index) were lower in uninfested plots than infested plots with and without tree fall (Figure 1A). The median crowning index for infested plots was 40 mph compared with 30 mph in uninfested plots. The risk of crown fire initiation, based on the average torching index, was not different in uninfested and infested plots (Figure 1B).

The distributions of fire types modeled to occur on uninfested and infested plots were significantly different (Figure 2). Uninfested plots contributed most to the difference in proportions of fire types between plot conditions. Crown fire was most predominant in uninfested plots (Figure 2). Uninfested and infested plots predicted to have active crown fires had higher basal area of nonhost tree species and greater canopy bulk density than plots predicted to have passive crown or surface fires (Table 4). Passive crown fire dominated uninfested plots, plots 7 years after outbreak initiation, plots with 10% tree fall, and plots with 80% tree fall. Conditional surface fire was not predicted to occur in any plots. A greater percentage of infested plots were predicted to have surface fire compared with uninfested plots. Plots predicted to have surface fire had an absence of nonhost conifer trees, lower canopy bulk density, and higher canopy base height compared with plots with crown fire (Table 4).

Potential tree mortality (percentage of basal area killed by fire) was not different in uninfested plots compared with plots 7 years after outbreak initiation, plots with 10% tree fall, and plots with 80% tree fall (Figure 3A). Median percentage of basal area killed by fire was 99% for uninfested plots and all categories of infested plots. Plots with less than 90% basal area mortality from fire were predicted to have surface fire. For infested plots, mortality from fire was significantly less for both lodgepole pine and nonhost species in plots with surface fire compared with plots with passive or active crown fires (Table 4). Smoke production was significantly greater in plots with 80% tree fall compared with uninfested plots, plots 7 years after outbreak initiation, and plots with 10% tree fall (Figure 3B).

Discussion

Effect of Mountain Pine Beetle Outbreak on Stand Characteristics and Fuel Complexes

Under a wildfire scenario, the mountain pine beetle outbreak in lodgepole pine-dominated forests in north-central Colorado will likely affect fire behavior. The live tree component in plots 7 years after outbreak initiation was significantly less dense and was on average composed of smaller diameter lodgepole pine and nonhost tree species. These changes in stand characteristics in infested plots have not led to altered surface fuel loads in the first 7 years after outbreak initiation. However, with projected 80% infested tree fall, surface fuel loads will be greater than in uninfested plots, recently infested plots, and plots with 10% tree fall. Mitchell and Preisler (1998), in a mountain pine beetle outbreak in Oregon, found that approximately 10% of infested trees fell in 6 years and approximately 80% fell in 12 years, although the rate of fall in our study area may be different and will be affected by stand density, wind patterns, and site conditions (Keen 1955). These differential surface fuel loads in combination with changes in stand structure influence potential surface fire behavior.

Potential Fire Behavior and Tree Mortality

Crown fire was predicted for a majority of uninfested plots and each category of infested plots; however, the potential for fire to move into the crown was more variable in the infested plots across our study area. Although 62% of infested plots were predicted to experience torching without wind, 12% of the infested plots required windspeeds exceeding 25 mph to initiate torching. This is in contrast to the 73% of uninfested plots that were predicted to have torching without wind. Infestation by mountain pine beetle also reduced the occurrence of active crown fire to 10% compared with 25% in the uninfested plots. Where active crown fire was expected to occur in the infested plots, there was a substantial component of nonhost trees (subalpine fir and Engelmann spruce) in the plot, with only 11% of basal area made up of live lodgepole pine. Even with lodgepole pine mortality from mountain pine beetle, a large component of nonhost conifer trees in these stands could still maintain torching and crown fire behavior because of lower canopy base heights and higher canopy bulk densities of nonhost trees. In contrast, infested plots without a significant component of nonhost conifer species had tall canopy base heights and lower canopy bulk densities, resulting in a reduction in canopy fuel continuity and increased occurrence of surface fire. In fact, species composition was, on average, 11% quaking aspen in plots with surface fire compared with 3% quaking aspen in plots with passive fire and 0.1% quaking aspen in plots with active fire. These results highlight the importance of identifying pre- and postmountain pine beetle infestation stand tree species composition when discussing the mountain pine beetle infestation and potential fire behavior.

Although we observed differences in crown fire type under a 90th percentile fire weather scenario between infested and uninfested plots, tree mortality exceeded 99% for both uninfested and infested plots, regardless of tree size. The main difference in mortality was observed in the infested plots that had a component of aspen, a low

Table 4. Median (median absolute deviation) stand characteristics and potential mortality from fire under predicted potential fire type for uninfested plots and plots 7 years after epidemic mountain pine beetle infestation initiation, Arapaho National Forest, Colorado, 2006–2007.

Plot type	Fire type			*P* value
	Surface	Passive Crown	Active Crown	
Live *Pinus contorta* ft^2/ac				
Uninfested		70.0 (34.8)	84.0 (39.8)	1.0000
Infested	48.1 (31.5)[a]	26.7 (20.3)[a]	2.7 (2.7)[b]	0.0002
Live nonhost ft^2/ac				
Uninfested		16.7 (16.5)[a]	65.6 (29.1)[b]	0.0058
Infested	0.0 (0.0)[a]	9.9 (9.9)[b]	119.2 (41.1)[c]	<0.0001
Canopy bulk density (lbs/ft^3)				
Uninfested		0.006 (0.002)[a]	0.012 (0.002)[b]	<0.0001
Infested	0.002 (0.001)[a]	0.003 (0.002)[b]	0.011 (0.001)[c]	<0.0001
Canopy base height (ft)				
Uninfested		1.0 (0.0)	1.0 (0.0)	0.1412
Infested	18.5 (6.5)[a]	1.5 (0.5)[b]	1.0 (0.0)[c]	<0.0001
Potential % basal area *P. contorta* killed by fire				
Uninfested		99.6 (0.05)[a]	99.7 (0.01)[b]	<0.0001
Infested	80.7 (12.3)[a]	99.6 (0.04)[b]	99.7 (0.01)[c]	<0.0001
Potential % basal area nonhost killed by fire				
Uninfested		99.6 (0.05)[a]	99.7 (0.01)[b]	<0.0001
Infested	76.2 (23.3)[a]	99.6 (0.07)[b]	99.7 (0.01)[c]	<0.0001

Nonhost species include *Picea engelmannii*, *Abies lasiocarpa*, and *Populus tremuloides*. Plots with 10 and 80% infested tree fall did not have different live canopy characteristics, and potential mortality from fire was not significantly different compared with plots 7 years after outbreak initiation. Surface fire was predicted for only three uninfested plots and is not included.
[a,b,c] Different letters denote significance at $P < 0.05$. *P* value from multiresponse permutation procedure analysis with Bonferroni adjustment.

density of lodgepole pines that were not infested by mountain pine beetle, and no component of nonhost conifer tree species. These plots experienced surface fire, and mortality of trees with dbh >10 in. was only 60%. Again, these results highlight the importance of acknowledging that this epidemic is occurring in a range of forest types that have a component of lodgepole pine rather than pure lodgepole pine forests.

Although the FFE-FVS model did not indicate that surface flame length or fire intensity would increase with tree fall, we suspect that the greater fuel load of DWD >3 in. in diameter in plots with 80% infested tree fall would have significant effects on ecosystem recovery if a fire occurred. Empirical data show that the high surface fuel loads from tree fall would influence a number of factors related to fire-induced changes in soil characteristics. Hartford and Frandsen (1992) found that maximum temperatures reached under burning or smoldering DWD and duff in a lodgepole pine forest reached levels that can cause significant negative effects to biological, physical, and chemical processes (Wells et al. 1979, Hungerford et al. 1991, Debano et al. 1998, Certini 2005). Water repellency in soil has been shown to be a consequence of burning lodgepole pine slash piles (Everett et al. 1995), which can lead to increased erosion and nutrient loss (Wells et al. 1979). The duration of time and spatial arrangement of high soil temperatures will be influenced by the amount of duff on the forest floor and placement of the extensive amount of downed woody material >3 in. in diameter that is projected to accumulate. Advances in simulation models and validation of these models are needed for better predictions of the impacts of large amounts of DWD added to the forest floor after infestation.

The potential crown fire behavior predictions from FFE-FVS likely represent a conservative estimate. The potential underprediction of crown fire behavior is due to a number of factors related to fire behavior models, including foliar moisture values and the use of custom surface fuel models (Cruz and Alexander 2010). We used custom surface fuel models instead of standardized surface fuel models (Anderson 1982). Standard fuel models, which are stylized and simplified descriptions of fuel bed characteristics (Albini 1976, Anderson 1982), limit the assessment of variability in surface fuel characteristics. However, standard fuel models are calibrated to potential fire behavior, whereas custom fuel models allow for the direct use of fuel characteristics but are uncalibrated (Cruz and Alexander 2010). We did a comparison of our custom fuel models to the standard Anderson fuel models 8 (closed timber with litter) and 10 (timber with litter and understory) that were identified to best portray surface fuel loads found in both uninfested and infested plots (personal communication, Paul Mintier, Fire Management Officer, Sulfur Ranger District, Arapaho-Roosevelt National Forest). Although most fire behavior results from our custom fuel models were comparable to results from standard fuel models, the ability to directly assess variability from surface fuel loads outweighed the potential underprediction of crown fire behavior.

There is limited ability to incorporate needle moisture of both live and dead trees into fire behavior calculations with the crown fire behavior models currently used to assess fire behavior. Most models, including FFE-FVS, do not incorporate needle moisture on dead trees into canopy fuel loads, nor do most of these models allow differences in percentage of foliar moisture among trees (Cruz et al. 2008). However, the height at which the canopy is resistant to ignition at certain flame lengths increases as needle moisture declines (Keyes 2006). Furthermore, the presence of and amount of dead needles varies across the landscape with time since tree death. The expected fire type, along with torching and crowning indices from FFE-FVS, could be conservative in the short term in mountain pine beetle-affected areas because reduced needle moistures on affected trees are not incorporated into the models.

A change from a closed to a more open forest structure in mountain pine beetle-affected areas will modify the fire behavior on the forest floor by changing microclimate and herbaceous and shrub fuel loads. The canopy opening of infested plots due to tree mortality will potentially lower relative humidity and increase surface windspeeds (Brown 1975, Pollet and Omi 2002, Page and Jenkins

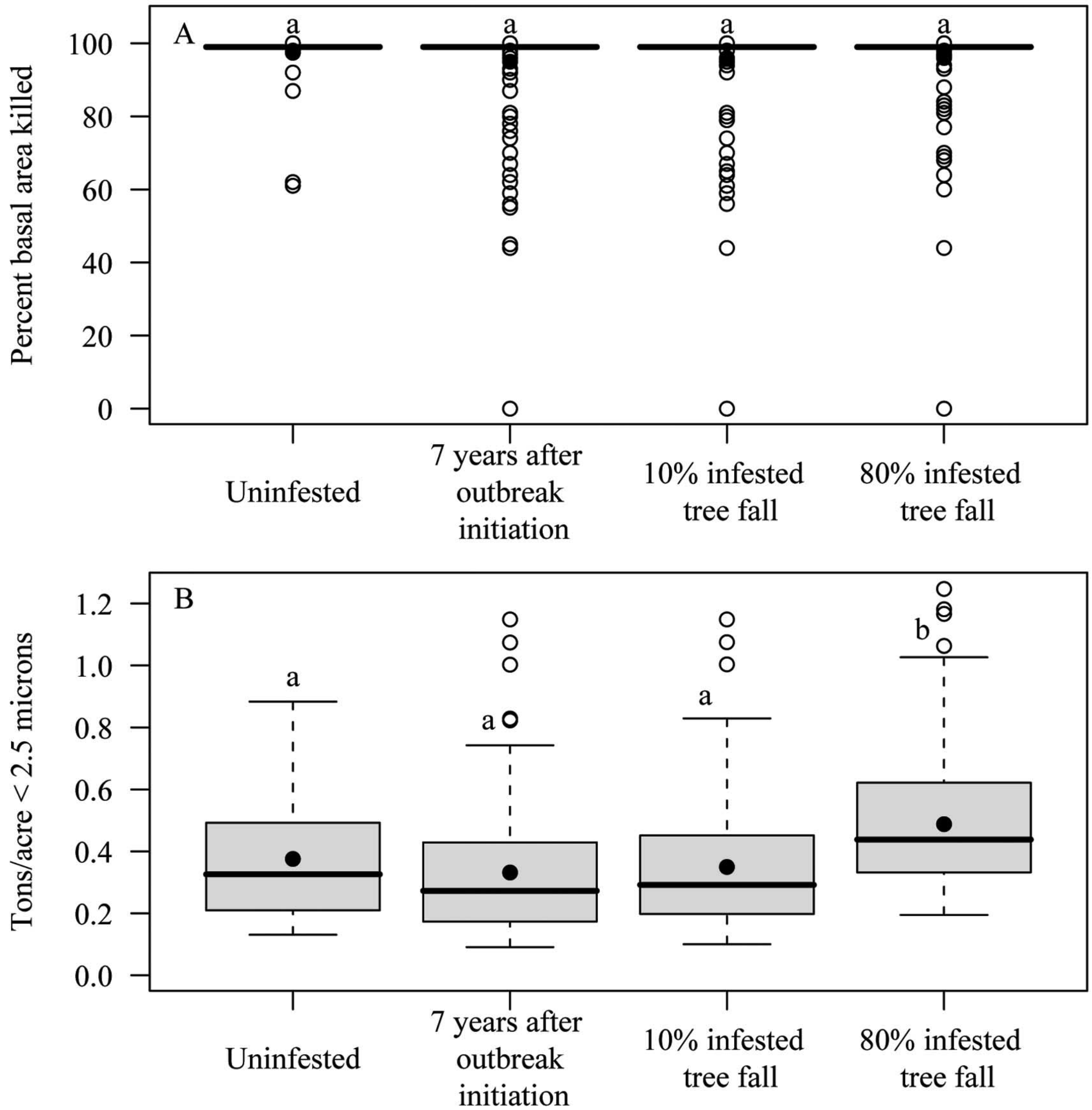

Figure 3. Potential probability of mortality from fire (A) and smoke production (B) under 90th percentile fire weather for uninfested plots, plots 7 years after mountain pine beetle outbreak initiation, and plots with 10 and 80% infested tree fall in lodgepole pine forests, Arapaho National Forest, Colorado, 2006–2007. In each box plot, the filled circle indicates the mean, the heavy line is the median, the box represents the 1st and 3rd quartiles, whiskers are Tukey's 1.5 interquartile range, and the open circles indicate outliers. Different letters denote significance at $P < 0.05$ from multiresponse permutation procedure analysis with Bonferroni adjustment.

2007b, Jenkins et al. 2008), affecting flame length. Klutsch et al. (2009) reported that the depth of litter and maximum height of grasses and herbs were significantly greater in plots 4–7 years after infestation by mountain pine beetle compared with recently infested plots and uninfested plots. In the short term, as needles accumulate on the forest floor from mountain pine beetle-killed trees and as understory vegetation responds to canopy opening, there will likely be changes in potential fire behavior. Our results support the hypothesis of an increase in flame height and surface rate of spread as potential changes in fire behavior due to the increase in surface fuel loads, fuel bed heights, and surface windspeeds from mountain pine beetle-caused mortality (Burgan 1987, Pollet and Omi 2002, Page and Jenkins 2007a, 2007b, Savadogo et al. 2007, Jenkins et al. 2008).

The response of understory vegetation and regeneration to bark beetle epidemics will influence future potential fire behavior during a wildfire. For example, there was an increase of the probability of a stand burning in the 1988 Yellowstone fire by 11% where a mountain pine beetle outbreak occurred in lodgepole pine 13–16 years before the fire due to understory vegetation responses (Lynch et al. 2006). In Engelmann spruce forests affected by a spruce beetle outbreak, active crown fire was modeled to occur in heavily affected areas because of tree regeneration several decades postinfestation (DeRose and Long 2009). Klutsch et al. (2009) and Collins et al. (2010) recorded the density of advanced regeneration in mountain pine beetle-affected lodgepole pine stands in northern Colorado to be about 800 trees/ac. Between 10 and 20 years after mountain pine beetle outbreak, when the majority of tree fall is expected to occur (Keen 1955, Mitchell and Preisler 1998), the stand density from advanced regeneration and tree recruitment is expected to be approximately 1,400–1,600 trees/ac based on modeling in FVS (Collins 2010). Potential fire behavior with high surface fuel loads, high density of released advanced regeneration, and tree recruitment after the mountain pine beetle outbreak would be expected to be a crown fire because of the high potential of torching from low canopy base heights. Our fire behavior modeling results from 80% infested tree fall may be conservative because of the exclusion of tree recruitment but was still expected to have a significant amount of crown fire with a torching index of zero. Furthermore, the very high mortality expected to be experienced during a fire with a high-density tree recruitment would also be similar to our modeled tree mortality, which has the potential to significantly affect stand development.

The fire type and amount of tree fall experienced will influence the risk experienced by fire fighters and the ability of fire containment. The speed at which the fire moves through uninfested and mountain pine beetle infested stands may be different, with surface and passive fires potentially moving more slowly than active crown fires (Rothermel 1991, Scott and Reinhardt 2001). However, high tree mortality from fire and stand replacement are consequences of both passive and active crown fires. Also, both passive and active crown fires can cause spotting by embers moving downwind starting new fires. Hazards from falling trees along with obstacles from downed logs will potentially affect fire containment. The greater smoke production predicted to occur because of the increased DWD loads will also interfere with visibility and negatively affect air quality. Because of the climate driven, high-severity fire regime of lodgepole pine, the occurrence of a fire during high fire weather could be a canopy fire or essentially stand-replacing regardless of levels of mountain pine beetle activity.

Conclusion

Mountain pine beetle-caused tree mortality after an outbreak in lodgepole pine-dominated forests will affect fire behavior through accumulations of surface fuels and changes in stand characteristics. Plots without mountain pine beetle-caused tree mortality with intact and continuous canopy fuel components are expected to have greater potential for crown fire than infested plots, although potential mortality from a fire was high for both uninfested and infested plots. Tree species composition is influential in fire type, with surface fires occurring only in the absence of nonhost conifer species. Infested plots, with and without tree fall, were modeled to have greater surface fire intensity and rate of spread. Although bark beetle-caused tree mortality changes fuel complexes and influences potential surface and crown fire behavior, the occurrence of a wildfire is still dependent on fire-conducive weather with a sustainable ignition event.

Literature Cited

Albini, F.A. 1976. *Estimating wildfire behavior and effects.* US For. Serv. Gen. Tech. Rep. INT-30. US For. Serv., Intermountain Res. Stn. 92 p.

Albini, F.A., and R.G. Baughman. 1979. *Estimating windspeeds for predicting wildland fire behavior.* US For. Serv. Res. Pap. INT-221. Ogden, UT. 12 p.

Anderson, H.E. 1982. *Aids to determining fuel models for estimating fire behavior.* US For. Serv. Gen. Tech. Rep. INT-122. US For. Serv., Intermountain Res. Stn. 22 p.

Arno, S.F. 1980. Forest fire history in the northern Rockies. *J. For.* 78:460–465.

Bradshaw, L., and E. McCormick. 2000. *Fire Family Plus user's guide*. Version 2.0. US For. Serv. Gen. Tech. Rep. RMRS-GTR-67WWW. US For. Serv., Rocky Mount. Res. Stn., Ogden UT.

Brown, J.K. 1975. Fire cycles and community dynamics in lodgepole pine forests. P. 429–456 in *Proc. of symp. on Management of lodgepole pine ecosystems*, Baumgartner, D.M. (ed.). Vol. 1 of 2. Washington State University Press, Pullman, WA.

Brown, J.K. 1978. *Weight and density of crowns of Rocky Mountain conifers.* US For. Serv. Res. Pap. INT-197. US For. Serv., Intermountain For. Range and Exp. Stn. 58 p.

Brown, J.K., R.D. Oberheu, and C.M. Johnston. 1982. *Handbook for inventorying surface fuels and biomass in the interior west.* GTR-INT-129. US For. Serv., Intermountain For. Range Exp. Stn. 22 p.

Brown, J.K., E.D. Reinhardt, and K.A. Kramer. 2003. *Coarse woody debris: Managing benefits and fire hazard in the recovering forest.* US For. Serv. Gen. Tech. Rep. RMRS-GTR-105. US For. Serv., Rocky Mount. Res. Stn. 20 p.

Burgan, R.E. 1987. *Concepts and interpreted examples in advancing fuel modeling.* US For. Serv. Gen. Tech. Rep. GTR- INT-238. US For. Serv., Intermountain Res. Stn. 40 p.

Certini, G. 2005. Effects of fire on properties of forest soils: A review. *Oecologia.* 143:1–10.

Collins, B.J. 2010. Initial and future stand development following mountain pine beetle in harvested and uncut lodgepole pine forests. MSc thesis, Colorado State Univ., Fort Collins, CO.

Collins, B.J., C.C. Rhoads, J. Underhill, and R.M. Hubbard. 2010. Post-harvest seedling recruitment following mountain pine beetle infestation of Colorado lodgepole pine stands: A comparison using historic survey records. *Can. J. For. Res.* 40:2452–2456.

Crosby, J.S., and C.C. Chandler. 2004. Get the most from your windspeed observations. *Fire Manag. Today.* 64(1):53–55.

Cruz, M.G., and M.E. Alexander. 2010. Assessing crown fire potential in coniferous forests of western North America: A critique of current approaches and recent simulation studies. *Int. J. Wildland Fire* 19:377–398.

Cruz, M.G., M.E. Alexander, and P.A.M. Fernandes. 2008. Development of a model system to predict wildfire behaviour in pine plantations. *Aust. For.* 71(2):113–121.

DeBano, L.F., D.G. Neary, and P.F. Ffolliott. 1998. *Fire's effects on ecosystems.* John Wiley and Sons, Inc., New York, NY. 333 p.

DeRose, R.J., and J.N. Long. 2009. Wildfire and spruce beetle outbreak: Simulation of interacting disturbances in the central Rocky Mountains. *Eoscience.* 16(1):28–38.

Edminster, B., H.T. Mowrer, R.L. Mathiasen, T.M. Schuler, W.K. Olson, and F.G. Hawksworth. 1991. *GENGYM: A variable density stand table projection system calibrated for mixed conifer and ponderosa pine stands in the Southwest.* US For. Serv. Res. Pap. RM-297. US For. Serv., Rocky Mount. For. Range Exp. Stn. 32 p.

Everett, R.L., B.J. Java-Sharpe, G.R. Scherer, F.M. Wilt, and R.D. Ottmar. 1995. Co-occurrence of hydrophobicity and allelopathy in sand pits under burned slash. *Soil Sci. Soc. Am. J.* 59:1176–1183.

Hartford, R.A., and W.H. Frandsen. 1992. When it's hot, it's hot … or maybe it's not! (Surface flaming may not portend extensive soil heating). *Int. J. Wildland Fire* 2(3):139–144.

Hungerford, R.D., M.G. Harrington, W.H. Frandsen, K.C. Ryan, and G.J. Neihoff. 1991. Influence of fire on factors that affect site productivity. P. 32–50 in *Proc. of the management and productivity of western-montane forest soils*, Harvey, A.E., and L.F. Neuenschwander (eds.), US For. Serv. Gen. Tech. Rep. INT-GTR-280. US For. Serv., Intermountain Res. Stn. Ogden, UT.

Jenkins, M.J., E. Hebertson, W. Page, and C.A. Jorgensen. 2008. Bark beetles, fuels, fires and implications for forest management in the Intermountain West. *For. Ecol. Manag.* 254:16–34.

Keen, F.P. 1955. The rate of natural falling of beetle-killed ponderosa pine snags. *J. For.* 53:720–723.

Keyes, C.R. 2006. Role of foliar moisture content in the silvicultural management of forest fuels. *West. J. Appl. For.* 21(4):228–231.

Kipfmueller, K.F., and W.L. Baker. 2000. A fire history of a subalpine forest in south-eastern Wyoming, USA. *J. Biogeogr.* 27:71–85.

Klutsch, J.G., J.F. Negron, S.L. Costello, C.C. Rhodes, D.R. West, J. Popp, and R. Caissie. 2009. Stand characteristics and downed woody debris accumulations associated with a mountain pine beetle (*Dendroctonus ponderosae* Hopkins) outbreak in Colorado. *For. Ecol. Manag.* 258:641–649.

Lynch, H.J., R.A. Renkin, R.L. Crabtree, and P.R. Moorcroft. 2006. The influence of previous mountain pine beetle (*Dendroctonus ponderosae*) activity on the 1988 Yellowstone fires. *Ecosystems* 9:1318–1327.

Mielke, P.W., Jr., and K.J. Berry. 2001. *Permutation methods: A distance function approach.* Springer Verlag, New York, NY. 352 p.

Miller, R.G., Jr. 1981. *Simultaneous statistical inference*, 2nd ed. Springer Verlag, New York, NY. 299 p.

Mitchell, R.G., and H.K. Preisler. 1998. Fall rate of lodgepole pine killed by the mountain pine beetle in central Oregon. *West. J. Appl. For.* 13:23–26.

Page, W., and M.J. Jenkins. 2007a. Mountain pine beetle-induced changes to selected lodgepole pine fuel complexes within the Intermountain Region. *For. Sci.* 53:507–518.

Page, W., and M.J. Jenkins. 2007b. Predicted fire behavior in selected mountain pine beetle-infested lodgepole pine. *For. Sci.* 53:662–674.

Pearson, J.A., T.J. Fahey, and D.H. Knight. 1984. Biomass and leaf area in contrasting lodgepole pine forests. *Can. J. For. Res.* 14:259–265.

Pollet, J., and P.N. Omi. 2002. Effect of thinning and prescribed burning on crown fire severity in ponderosa pine forests. *Int. J. Wildland Fire* 11:1–10.

Rebain, S.A., comp. 2010. *The Fire and Fuels Extension to the Forest Vegetation Simulator: Updated model documentation.* Internal Rep. US For. Serv., For. Manag. Serv. Ctr. Fort Collins, CO, 361 p.

Reinhardt, E.D., and N.L. Crookston (tech. eds.). 2003. *The Fire and Fuels Extension to the Forest Vegetation Simulator.* US For. Serv. Gen. Tech. Rep. RMRS-GTR-116. US For. Serv., Rocky Mount. Res. Stn. 209 p.

Reinhardt, E.D., and N.L. Crookston (tech. eds.). 2007. *The Fire and Fuels Extension to the Forest Vegetation Simulator—2007 Addendum.* US For. Serv. Gen. Tech. Rep. RMRS-GTR-116. US For. Serv., Rocky Mount. Res. Stn. 208 p.

Rothermel, R.C. 1972. *A mathematical model for predicting fire spread in wildland fuels.* US For. Serv. Res. Pap. INT-115. US For. Serv., Intermountain For. Range Exp. Stn, Ogden, UT. 40 p.

Rothermel, R.C. 1991. *Predicting the behavior and size of crown fires in the northern Rocky Mountains.* US For. Serv. Res. Pap. INT-RP-438. US For. Serv., Intermountain For. Range Exp. Stn., Ogden, UT. 46 p.

SAS Institute. 1999. *SAS/STAT user's guide, version 8.* SAS Institute Inc., Cary, NC.

Savadogo, P., D. Zida, L. Sawadogo, D. Tiveau, M. Tigabu, and P.C. Oden. 2007. Fuel and fire characteristics in savanna-woodland of West Africa in relation to grazing and dominant grass type. *Int. J. Wildland Fire* 16:531–539.

Scott, J., and E.D. Reinhardt. 2001. *Assessing crown fire potential by linking models of surface and crown fire behavior.* US For. Serv. Res. Pap. RMRS-RP-29. US For. Serv., Rocky Mount. Res. Stn. Fort Collins, CO. 59 p.

US Forest Service. *Region 2.* Available online at www.fs.fed.us/r2/resources/fhm/aerialsurvey/download; last accessed Dec. 2, 2010.

Van Wagner, C.E. 1977. Conditions for the start and spread of crown fire. *Can. J. For. Res.* 7:23–34.

Wells, C.G., R.E. Campbell, L.F. DeBano, C.E. Lewis, R.L. Fredriksen, R.C. Froelich, and P.H. Dunn. 1979. *Effects of fire on soil: A state-of-knowledge review.* US For. Serv. Gen. Tech. Rep. WO-7.