Predicted Fire Behavior in Selected Mountain Pine Beetle–Infested Lodgepole Pine

Wesley Page and Michael J. Jenkins

Abstract: Using custom fuel models developed for use with Rothermel's surface fire spread model, we predicted and compared fire behavior in lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.) stands with endemic, current epidemic, and postepidemic mountain pine beetle (*Dendroctonus ponderosae* Hopkins) populations using standardized sets of wind speeds and fuel moistures. We also compared our fire behavior results with those from standard fuel models. Results indicated that for surface fires both rates of fire spread and fireline intensities were higher in the current epidemic stands than in the endemic stands owing to increases in the amounts of fine surface fuels. In the postepidemic stands, rates of surface fire spread and fireline intensities were higher than in the endemic stands owing to decreased vegetative sheltering and its effect on mid-flame wind speed. Total heat release of surface fires, including postfrontal combustion, was also higher in the postepidemic stands owing to heavy accumulations of large diameter fuels. Crown fires were more likely to initiate in the postepidemic stands owing to greater fireline intensities and lower crown base heights. However, the critical rate of spread needed to sustain an active crown fire was higher in the postepidemic stands owing to decreased aerial fuel continuity. We suggest here that crown fire initiation in the current epidemic stands was also greater because of an abundance of dead aerial fuels; although this relationship is unclear. FOR. SCI. 53(6):662–674.

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THE MOUNTAIN PINE BEETLE (MPB) (*Dendroctonus ponderosae* Hopkins [Coleoptera: Scolytidae]) is a native forest insect that infests a variety of pine tree species throughout western North America. Populations of the MPB usually remain at endemic levels within lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.) forests until suitable conditions such as drought and large areas of mature-sized trees exist to cause widespread epidemics. When epidemics do occur, they can kill more than 80% of suitable host trees, which can result in changes to stand composition, structure, and fuel loading (Amman et al. 1989, Safranyik 1989, Page 2006). Of particular concern to land managers is the potential impact of MPB epidemics on fire hazard and behavior in infested stands. Previous work has suggested that the fuel accumulations caused by the MPB can lead to increases in fire hazard; however, little quantitative evidence exists to support these claims (Amman 1991, Schmid and Amman 1992). The purpose of this research was to quantify changes in fire behavior in lodgepole pine stands infested by the MPB by comparing predicted fire behavior in the infested stands to predicted fire behavior in uninfested endemic stands.

The role of fire in lodgepole pine forests has been extensively studied (Lotan et al. 1985, Romme 1980, Romme 1982). Because of the seral nature of most forests, the function of disturbance, especially fire, is known to be significant (Pfister and Daubenmire 1975). In these seral forests a hypothesis of fuel buildup, caused by the MPB and other mortality agents, and subsequent high-intensity fires is frequently mentioned to describe the fire and fuel relationships (Brown 1975, Lotan 1975, Gara et al. 1985). The hypothesis is that once a fire occurs, the site is reseeded to lodgepole pine, from serotinous cones, forming another even-aged lodgepole pine stand that will support a future MPB epidemic, creating high fuel loadings, which will lead to another high-intensity fire (Brown 1975). This hypothesis of disturbance interactions in lodgepole pine forests supports the assumption that accumulations of large down woody fuels caused by mortality agents is an important factor determining the intensity and severity of fires.

Currently, no specific studies that have quantified either potential or observed fire behavior in MPB-infested forests are available. Although there are many studies indicating that mortality caused by the MPB increases fire hazard, none has provided detailed reasoning for these findings (Lotan et al. 1985, Amman 1991, Schmid and Amman 1992). Generally, fire hazard is thought to be at its highest during the first few years after the epidemic owing to large amounts of fine dead fuels (Romme et al. 1986). However, after this period, the risk of "destructive fire" may be lower (Romme et al. 1986) or substantially higher (Lotan et al. 1985, Schmid and Amman 1992), depending on the specific study referenced. Although the literature is unclear as to how fire hazard is altered by the MPB, we will attempt to demonstrate potential changes in terms of quantitative measures of fire behavior such as rate of spread and fireline intensity.

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Fire behavior prediction involves the "art" of using constantly changing, over time and space, weather, fuels, and topographic information to calculate expected behavior of a fire (Rothermel 1983). Behavior of fires burning in wildland fuels usually is referred to in terms of the rate of spread and intensity (heat release per unit time per unit of flame front length) of the flaming portion of combustion. The most widely used method of predicting surface fire behavior involves the use of a semiempirical model developed by Rothermel (1972), which applies information about the physical properties and characteristics of a fuel bed as well as fuel moisture, wind speed, and slope to calculate rate of spread at the flaming portion of a surface fire. To aid managers in applying the model to field applications a set of fuel models were developed by Rothermel (1972), Albini (1976a), Anderson (1982), and Scott and Burgan (2005) to supply the fuel properties and characteristics for different fuel situations to solve Rothermel's (1972) equation. Altering the fuel properties and characteristic inputs into Rothermel's (1972) equation is known as building a custom fuel model (Burgan and Rothermel 1984), which is used to predict fire behavior in fuel situations not present in the standard fuel models. In this study we present a set of custom fuel models developed from fuel inventory data to predict and compare fire behavior in MPB-infested lodgepole pine stands. Although using fuel inventory data is not a common method of predicting fire behavior, it has been used in similar situations (Hummel and Agee 2003) in which fire behavior prediction is needed for unusual fuel situations. In our case, we have altered the fuel load and depth data of a standard horizontally oriented fuel model (fuel model 10) to reflect changes in the abundance of different size fuels and their compactness, in which the effects are similar to those reported by Burgan (1987). However, the results presented in this study may be limited in their application in the field not only because of the limitations of the fuels data but also because of the lack of testing and refinement to real-world conditions. As suggested by Burgan and Rothermel (1984) custom fuel models developed from fuel inventories need tuning and adjustment to real fires using the procedures referenced in Rothermel and Reinhardt (1983); however, testing these models in these potentially hazardous fuel complexes is and will be limited. It is hoped that fire and fuels professionals will be able to take the models presented here and adjust them further based on actual fire behavior encountered during wildfires and prescribed fires.

To capture the potential fire behavior in MPB-infested lodgepole pine stands and for ease of sampling, three study areas were chosen: a 20-year-old postepidemic on the Ashley National Forest (N.F.) near Vernal, UT; an active current epidemic on the Sawtooth National Recreation Area (N.R.A.) near Stanley, ID; and a current epidemic on the Wasatch-Cache National Forest (N.F.) near Kamas, UT, that is continuing to develop. Within the postepidemic and current epidemic study areas lodgepole pine forest types were selected and stratified into postepidemic or current epidemic stands, respectively, using aerial detection surveys. Similar endemic stands were then selected within each of the study areas and paired with the postepidemic or current epidemic stands. Within each of these stands extensive fuel inventories were conducted on both surface and aerial fuels, which were used to construct custom fuel models (Burgan and Rothermel 1984). These custom fuel models were then used to predict and compare fire behavior outputs including rate of spread and fireline intensity for surface fires in each stand type within each study area. Crown fire potential was also reported for the stands on the Ashley N.F. but not on the stands measured on the Sawtooth N.R.A. and Wasatch-Cache N.F. owing to the limitations of the crown fire model in dealing with dead aerial fuels.

Methods

Study Site Selection and Study Design

Study sites were selected using a combination of US Forest Service aerial detection surveys and expertise from local US Forest Service personnel. Once sites were identified, aerial photographs and ground reconnaissance were used to verify beetle populations and make the final site selections. Three sites were chosen; two sites, Sawtooth N.R.A. and Wasatch-Cache N.F., had current epidemics and one site, Ashley N.F., had a previous epidemic. Each site represented a separate study area in which only one treatment (current epidemic or postepidemic) was selected.

Within each study site aerial photographs were used to delineate a total of four stands: two treatment stands of either current epidemic or postepidemic conditions and two control stands (endemic), which were homogeneous in density and species composition. Current epidemics were identified as those stands with increasing MPB populations and significant mortality within the past 5 years, whereas endemic conditions were identified as those stands with low current beetle activity. Postepidemic stands were identified as stands with >80% mortality occurring more than 5 years ago with no current beetle activity. The lodgepole pine stands were selected so that they shared similar aspects, slope steepness, stand age, density, and habitat type to minimize potential confounding factors.

Site 1—Ashley National Forest

An extensive MPB epidemic occurred in this area during the 1980s (Binder 1995). Increment cores from surviving trees in the postepidemic stands were taken and growth releases were identified to determine years of significant mortality. Most increment cores recorded a growth release around 1985, but mortality is assumed to have occurred before and after this date. Table 1 shows the average stand characteristics for the stands sampled at this study site. Mortality averaged 80% of the suitable host trees with fewer than 200 live lodgepole remaining per ha in the postepidemic stands. Elevations of both the postepidemic and endemic stands ranged from 2,800 to 2,930 m above sea level with gentle slopes and mainly southerly aspects. The postepidemic stands were dominated by subalpine fir (*Abies lasiocarpa* Nutt.) with only remnant patches of lodgepole pine. The endemic stands were dominated by lodgepole pine with understories of subalpine fir and Engelmann spruce (*Picea engelmannii* Parry ex Engel.). The sizes of

Table 1. The average stand characteristics for all four sampled stands on the Ashley National Forest

			Trees (/ha)		Average dbh (cm)			
	N	CC (%)	Live PICO	PA	Live ABLA	Live PICO	PA	Mortality (%)
PE #1	25	16	157	156	537	21.0	27.9	71
PE #2	24	12	163	529	588	20.6	25.2	89
EN #1	24	39	1,675	37	0	22.9	26.1	4
EN #1	24	41	1,548	29	0	22.8	32.5	11

N, number of plots; CC; canopy cover; PICO, lodgepole pine; PA, past successfully attacked lodgepole (before 2000); ABLA, subalpine fir.; PE, postepidemic; EN, endemic.

Table 2. The average stand characteristics for all four sampled stands on the Sawtooth National Recreation Area

			Trees (/ha)		Average dbh (cm)		
	N	CC (%)	Live PICO	PA	Live ABLA	RA	Mortality (%)
PE #1	15	54	1,577	398	17.1	24.5	48
PE #2	22	41	1,293	305	16.5	25.8	46
EN #1	16	28	1,018	29	19.3	29.1	8
EN #1	22	37	1,132	26	21.5	36.5	8

N, number of plots; CC; canopy cover; PICO, lodgepole pine; PA, past successfully attacked lodgepole (before 2000); ABLA, subalpine fir.; PE, postepidemic; EN, endemic.

Table 3. The average stand characteristics for all four sampled stands on the Wasatch-Cache National Forest

			Trees (/ha)		Average dbh (cm)		
	N	CC (%)	Live PICO	PA	Live ABLA	RA	Mortality (%)
PE #1	23	46	1,214	288	18.8	24.8	40
PE #2	14	33	530	195	19.2	23.7	42
EN #1	24	33	601	25	21.7	29.1	6
EN #1	22	33	662	18	22.1	24.9	3

N, number of plots; CC; canopy cover; PICO, lodgepole pine; PA, past successfully attacked lodgepole (before 2000); ABLA, subalpine fir.; PE, postepidemic; EN, endemic.

these stands averaged approximately 40 ha. Both the postepidemic and endemic stands currently have little mortality from non-MPB insects and diseases.

Site 2—Sawtooth National Recreation Area

The current widespread epidemic in site 2 began in the 1990s with the majority of the mortality occurring since the year 2000 (Page 2006). Table 2 shows the average stand characteristics for all of the sampled stands. Mortality since the year 2000 averaged 47%. Elevations of the selected stands were approximately 2,100 m above sea level with gentle slopes and a variety of aspects. The sampled stands were dominated by lodgepole pine with an extensive cover of elk sedge (*Carex geyeri* Boott) in the understory. The sizes of the delineated stands averaged approximately 40 ha. Attack by the MPB was the cause for the vast majority of mortality in both the current epidemic and endemic stands sampled.

Site 3—Wasatch-Cache National Forest

The current epidemic occurring in site 3 began within the past few years and is continuing to develop. Table 3 shows the average stand characteristics for all the sampled stands. Mortality since the year 2000 averaged 41%. Elevations of the selected stands ranged from approximately 2,700 to 2,900 m above sea level with flat to steep slopes occupying eastern to northwestern aspects. The stands were dominated by seral lodgepole pine with a developing understory of subalpine fir and Engelmann spruce. The sizes of the selected stands averaged approximately 30 ha. The overwhelming majority of the mortality in the current epidemic and endemic stands was caused by the MPB.

Sampling Procedures

A systematic North-South or East-West grid of variable radius plots was laid out within the delineated stands on U.S, Geological Survey 7.5 minute topographic maps. The overall objective was to have at least 20 plots per stand (Avery and Burkhart 1994), but this number varied between 14 and 25 plots per stand.

At each plot center. a general plot description including percent canopy cover, elevation, aspect, percent slope, and habitat type was determined. Ground and surface fuels were measured using the methods developed by Brown et al. (1982). Specifically, using Brown's (1971) planar intersect method, between three and seven 19.8-m-long transects were laid out from each plot center. The total number of transects installed was based on an accumulation standard of at least 100 down woody debris pieces in the total sample. The diameters of down woody debris were measured based on size classes that correspond to the theoretical amount of time needed for the particle to respond to changes in atmospheric moisture, a concept known as timelag (Fosberg 1970). On the basis of the suggestions of Brown et al.

Table 4. Custom fuel model values for the postepidemic stands on the Ashley National Forest

	N	Average	Range	95% CI
1 hour (tonne/ha)	149	4.87	2.62–9.46	±0.61
10 hour (tonne/ha)	149	4.47*	0.92–12.08	±0.90
100 hour (tonne/ha)	149	8.75*	1.46–23.18	±1.86
1,000 hour sound (tonne/ha)	149	83.65*	5.54–181.49	±15.89
1.000 hour rotten (tonne/ha)	149	18.18	0.94–55.86	±4.41
Live herbaceous (tonne/ha)	298	0.47	0.16–0.94	±0.07
Live woody (tonne/ha)	298	1.24*	0.40–3.30	±0.20
1 hour surface SAV (m^2/m^3)		6,562		
Live herbaceous SAV (m^2/m^3)		4,921		
Live woody SAV (m^2/m^3)		4,921		
Fuel bed depth (m)	149	0.1*	0.04–0.24	±0.02
Dead fuel moisture of extinction (%)		25		
Dead fuel heat content (kJ/kg)		18,622		
Live fuel heat content (kJ/kg)		18,622		

N, number of fuel transects or the number of microplots for the shrub/herbaceous data; CI, confidence interval; SAV, surface-to-air volume.
* Significantly different from the associated endemic stands at the $\alpha = 0.05$ level (Page 2006).

Table 5. Custom fuel model values for the endemic stands on the Ashley National Forest

	N	Average	Range	95% CI
1 hour (tonne/ha)	197	4.49	2.11–8.05	±0.52
10 hour (tonne/ha)	197	1.81	0.34–4.80	±0.38
100 hour (tonne/ha)	197	4.13	0–10.31	±0.96
1,000 hour sound (tonne/ha)	197	10.74	0–44.72	±3.84
1.000 hour rotten (tonne/ha)	197	43.33	7.67–132.40	±9.48
Live herbaceous (tonne/ha)	394	0.63	0.09–1.84	±0.11
Live woody (tonne/ha)	394	0.58	0–1.43	±0.13
1 hour surface SAV (m^2/m^3)		6,562		
Live herbaceous SAV (m^2/m^3)		4,921		
Live woody SAV (m^2/m^3)		4,921		
Fuel bed depth (m)	197	0.09	0.02–0.14	±0.01
Dead fuel moisture of extinction (%)		25		
Dead fuel heat content (kJ/kg)		18,622		
Live fuel heat content (kJ/kg)		18,622		

N, number of fuel transects or the number of microplots for the shrub/herbaceous data; CI, confidence interval; SAV, surface-to-air volume.

Table 6. Custom fuel model values for the current epidemic stands on the Sawtooth National Recreation Area.

	N	Average	Range	95% CI
1 hour (tonne/ha)	125	7.98*	3.52–11.57	±0.43
10 hour (tonne/ha)	125	2.22	0.18–6.75	±0.52
100 hour (tonne/ha)	125	3.73	0–9.57	±0.90
1,000 hour sound (tonne/ha)	125	11.80	0–54.23	±4.63
1.000 hour rotten (tonne/ha)	125	23.93	2.53–63.69	±7.12
Live herbaceous (tonne/ha)	250	1.14	0.20–2.00	±0.16
Live woody (tonne/ha)	250	0.51	0–2.58	±0.29
1 hour surface SAV (m^2/m^3)		6,562		
Live herbaceous SAV (m^2/m^3)		4,921		
Live woody SAV (m^2/m^3)		4,921		
Fuel bed depth (m)	125	0.1	0.06–0.16	±0.01
Dead fuel moisture of extinction (%)		25		
Dead fuel heat content (kJ/kg)		18,622		
Live fuel heat content (kJ/kg)		18,622		

N, number of fuel transects or the number of microplots for the shrub/herbaceous data; CI, confidence interval; SAV, surface-to-air volume.
* Significantly different from the associated endemic stands at the $\alpha = 0.05$ level (Page 2006)

(1982) for sampling plane distances, each 19.8-m transect had the number of 0–0.64 cm (1 hour timelag) and 0.64–2.54 cm (10 hour timelag) diameter fuels tallied from 1.5 to 3.6 m, the number of 2.54–7.62 cm (100 hour timelag) diameter fuels tallied from 1.5 to 6.1 m, and those fuels >7.62 cm (1,000 hour timelag) in diameter tallied from 1.5 to 19.8 m. In addition, 1,000 hour fuels had their respective diameters measured and a decay class assigned.

At the 10.7- and 19.8-m points along each transect, duff and litter depth, the high particle intercept depth, and shrub/herbaceous information were recorded. The average high particle intercept depth was used to calculate the fuel bed bulk depth by taking 63.8% of the average high particle intercept depth (Albini and Brown 1978). The shrub and herbaceous data were collected at the 10.7- and 19.8-m points on each transect using fixed 1.8-m diameter microplots, from

Table 7. Custom fuel model values for the endemic stands on the Sawtooth National Recreation Area

	N	Average	Range	95% CI
1 hour (tonne/ha)	137	3.91	1.84–6.10	±0.20
10 hour (tonne/ha)	137	2.45	0.22–4.33	±0.52
100 hour (tonne/ha)	137	6.76	0.31–27.57	±2.42
1,000 hour sound (tonne/ha)	137	11.16	0–35.82	±4.49
1.000 hour rotten (tonne/ha)	137	17.90	0–111.82	±11.68
Live herbaceous (tonne/ha)	274	1.40	0.72–2.26	±0.16
Live woody (tonne/ha)	274	0.15	0–1.03	±0.07
1 hour surface SAV (m^2/m^3)		6,562		
Live herbaceous SAV (m^2/m^3)		4,921		
Live woody SAV (m^2/m^3)		4,921		
Fuel bed depth (m)	137	0.07	0.05–0.14	±0.01
Dead fuel moisture of extinction (%)		25		
Dead fuel heat content (kJ/kg)		18,622		
Live fuel heat content (kJ/kg)		18,622		

N, number of fuel transects or the number of microplots for the shrub/herbaceous data; CI, confidence interval; SAV, surface-to-air volume.

Table 8. Custom fuel model values for the current epidemic stands on the Wasatch-Cache National Forest

	N	Average	Range	95% CI
1 hour (tonne/ha)	171	6.28*	3.63–13.16	±0.98
10 hour (tonne/ha)	171	2.89	0.72–9.39	±0.86
100 hour (tonne/ha)	171	2.90	0–9.39	±1.14
1,000 hour sound (tonne/ha)	171	11.63	0–43.35	±4.62
1.000 hour rotten (tonne/ha)	171	17.74	0–85.45	±8.99
Live herbaceous (tonne/ha)	342	0.70	0.31–1.64	±0.11
Live woody (tonne/ha)	342	1.37	0.20–6.86	±0.41
1 hour surface SAV (m^2/m^3)		6,562		
Live herbaceous SAV (m^2/m^3)		4,921		
Live woody SAV (m^2/m^3)		4,921		
Fuel bed depth (m)	171	0.08	0.04–0.16	±0.01
Dead fuel moisture of extinction (%)		25		
Dead fuel heat content (kJ/kg)		18,622		
Live fuel heat content (kJ/kg)		18,622		

N, number of fuel transects or the number of microplots for the shrub/herbaceous data; CI, confidence interval; SAV, surface-to-air volume.
* Significantly different from the associated endemic stands at the $\alpha = 0.05$ level (Page 2006)

Table 9. Custom fuel model values for the endemic stands on the Wasatch-Cache National Forest

	N	Average	Range	95% CI
1 hour (tonne/ha)	201	3.42	1.55–6.10	±0.38
10 hour (tonne/ha)	201	3.06	0.69–7.87	±0.30
100 hour (tonne/ha)	201	3.91	0–8.77	±0.42
1,000 hour sound (tonne/ha)	201	5.60	0–25.53	±2.24
1.000 hour rotten (tonne/ha)	201	25.77	0.12–96.21	±7.13
Live herbaceous (tonne/ha)	402	0.71	0.25–4.04	±0.20
Live woody (tonne/ha)	402	1.07	0–5.09	±0.29
1 hour surface SAV (m^2/m^3)		6,562		
Live herbaceous SAV (m^2/m^3)		4,921		
Live woody SAV (m^2/m^3)		4,921		
Fuel bed depth (m)	201	0.08	0.03–0.15	±0.01
Dead fuel moisture of extinction (%)		25		
Dead fuel heat content (kJ/kg)		18,622		
Live fuel heat content (kJ/kg)		18,622		

N, number of fuel transects or the number of microplots for the shrub/herbaceous data; CI, confidence interval; SAV, surface-to-air volume.

which percent cover of live and dead shrubs, percent cover of live and dead herbaceous vegetation, and average height of both shrubs and herbaceous vegetation were collected. All cover estimates were by 10% categories.

At each plot center aerial fuels and mortality were quantified using a 20 basal area factor measuring device (prism). The dbh of each "in" tree was measured along with condition and crown dominance. Tree condition was classified as healthy, unhealthy, recently killed, or older mortality. Unhealthy trees were those currently being affected by a mortality agent that were assumed would survive. Recently killed trees were those that were successfully killed by the MPB, not including strip attacks, since the year 2000, whereas older mortality trees were killed by any mortality agent. If the older mortality trees had evidence of MPB attack, it was noted and the year of attack was assumed to be 4 or more years ago, before 2000.

All of the sampled stands on the Ashley N.F., the endemic stands on the Sawtooth N.R.A., and the endemic stands on the Wasatch-Cache N.F. had additional aerial fuel characteristics measured that are important to understanding the structure of the aerial component of the fuels complex. At each plot a randomly selected live "in" tree had its total height and crown base height measured. Crown base heights were determined visually following the descriptions by Scott and Reinhardt (2001) for which the crown bases corresponded to the point where there is enough canopy fuel to carry fire vertically through the crown. Total crown length was then determined, which with available canopy fuel load was used to calculate crown bulk density (Keane et al. 1998). For the current epidemic stands on the Sawtooth N.R.A. and the Wasatch-Cache N.F., crown bulk densities were determined using equations developed by Cruz et al. (2003) based on average stand basal area and the number of trees per hectare. To estimate crown base heights for the current epidemic stands the average crown base heights from the adjacent endemic stands were used.

Available live canopy fuel load was calculated using Brown's (1978) allometric equations for live crown weight based on tree species, crown dominance, and dbh. Available canopy fuel load was based not only on live foliage weight but also on a proportion of the amount of 1 hour fuels within the crown. Call and Albini (1997) determined that 65% of 1 hour fuels in a tree crown would be consumed at 100% moisture content during a crown fire. Therefore, based on Brown's (1978) allometric equations, 65% of the proportion of 1 hour fuels in each live tree crown was added to the live crown weight to determine the available canopy fuel load.

Data Analysis

The data collected were analyzed using the software program SAS version 9.1. Student's two tailed *t*-tests were used to compare the sample means for the treatments (current or postepidemic stands) to the controls (endemic stands) for each fuel category within each study site using an α of 0.05 to determine significance.

Custom Fuel Model Development

Fire behavior predictions were made using custom fuel models, which are stylized descriptions of a surface fuel bed's physical properties and characteristics (Burgan and Rothermel 1984). The custom fuel models were constructed using the average litter, 1 hour, 10 hour, 100 hour, live shrub, and live herbaceous fuel loadings, by MPB population level, from the fuels inventory conducted for this study. Tables 4–9 show the custom fuel models developed for this study along with the number of observations, ranges, and 95% confidence intervals. In total, six custom fuel models were developed, one for each condition per study site: site 1, a postepidemic fuel model (Table 4) and an endemic fuel model (Table 5), site 2, a current epidemic (Table 6) and endemic fuel model (Table 7), and site 3, a current epidemic (Table 8) and endemic fuel model (Table 9). In addition to the inventoried fuels data the custom fuel models include fuel properties that are needed to solve Rothermel's (1972) surface fire spread equation, such as, live and dead fuel heat content, surface area to volume ratios, and moisture of extinction. Because of the similarity of the fuels complexes sampled with fuel types commonly represented by the standard fuel models we used the fuel properties given in standard fuel model 10, which is often used to predict fire behavior in bark beetle-affected areas.

Fire Behavior Prediction

Surface Fire Spread

The surface fire module in BehavePlus (version 3.0.1) was used to determine the rates of spread, fireline intensities, and flame lengths for the flaming front of surface fires under a variety of wind and fuel moisture conditions (Andrews et al. 2003). BehavePlus is a software program that combines many fire-related models into one graphical interface. All of the models contained within BehavePlus have their own assumptions and limitations; for surface fire spread the assumptions are based on those stated by Rothermel (1972) whose model is the basis for surface fire spread. The limitations and assumptions of the model include the following: it only predicts surface fire spread; it assumes that there is a continuous layer of uniform fuels in contact with the ground; it does not incorporate spotting into spread rates; it does not incorporate the burning of fuels >3 inches in diameter (1,000 hour); and it assumes that the weather variables do not change during the time frame of the prediction (Rothermel 1972).

Each fire behavior prediction is based on specific midflame wind speeds, slope steepness, and fuel moistures. To better understand the differences in fire behavior caused by the fuels characteristics the predictions were made using a 0% slope. Additionally, all of the predictions presented in this article are the predicted maximums under the set of environmental conditions given, i.e., the fire behavior at the head of the surface fire moving with the wind. The 6.1-m

Table 10. Normal summer, drought summer, and extreme drought summer fuel moisture contents for shaded and unshaded conditions used to make fire behavior predictions

	Normal		Drought		Extreme drought	
	Shaded	Unshaded	Shaded	Unshaded	Shaded	Unshaded
	(%)					
1 hour	6	4	4	3	3	2
10 hour	8	6	5	4	4	3
100 hour	10	8	7	6	6	5
1,000 hour	13	11	9	8	8	7
Live	117	117	78	78	70	70

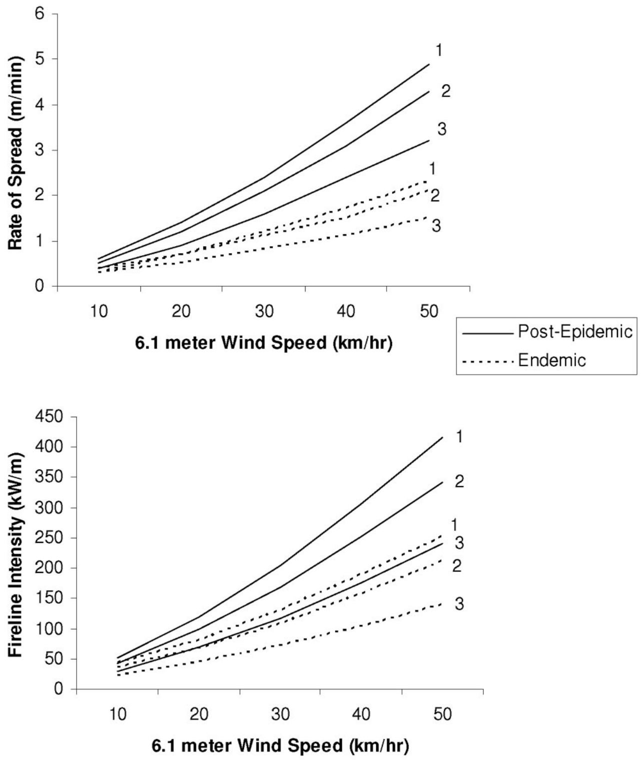

Figure 1. Rates of surface fire spread and fireline intensities for the postepidemic and endemic stands on the Ashley N.F. under extreme drought (1), drought (2), and normal (3) fire season fuel moistures. Wind adjustment factor used was 0.5 for the postepidemic stands and 0.2 for the endemic stands.

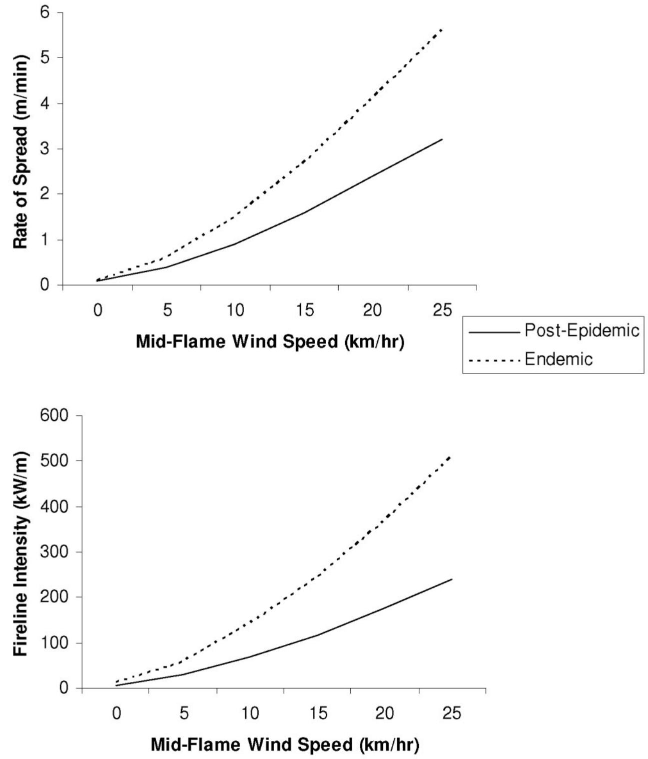

Figure 2. Rates of surface fire spread and fireline intensities for the postepidemic and endemic stands on the Ashley N.F. under normal fire season fuel moistures with a variety of mid-flame wind speeds.

wind speeds used in this study were all between 10 and 50 km/hr. To capture a range of fuel moisture conditions three sets of fuel moistures were used: normal summer, drought summer, and late summer severe drought (Rothermel 1991). Table 10 lists the specific fuel moistures used for each fuel size for both shaded and unshaded conditions. All fire behavior predictions in this study, except those for the postepidemic stands, were based on shaded conditions. To incorporate the effect of increased drying on the surface fuels caused by the removal of the overstory in the postepidemic stands (Byram and Jemison 1943), Rothermel's (1983) fine dead fuel moisture tables were used to aid in estimating the unshaded fuel moistures.

To determine mid-flame wind speeds the standard 6.1-m level wind speed was reduced using various wind adjustment factors based on the effects of vegetative sheltering (Albini and Baughman 1979). For the postepidemic stands in which few overstory trees remain, a wind adjustment factor of 0.5 was used. For the current epidemic stands, in which the overstory was still largely intact, a wind adjustment factor of 0.3 was used. For the endemic stands a wind adjustment factor of 0.2 was used because there was a continuous open pine canopy with little defoliation (Rothermel 1983).

Crown Fire Potential

To predict crown fire potential the crown module in BehavePlus was used, which applies either fireline intensity or flame length of a surface fire along with crown base height, crown bulk density, and foliar moisture content to determine crown fire initiation, crown fire rate of spread, and fire type (Van Wagner 1977). Critical fireline intensity is the surface fireline intensity required for a surface fire to transition to a crown fire and is based on foliar moisture content and canopy base height. The foliar moisture contents used in the crown fire analysis were 100% for all of the predictions. The critical crown fire rate of spread is the rate of spread necessary to sustain an active crown fire calculated using canopy bulk density (Van Wagner 1977). Three types of fire are recognized including surface, passive crown, or active crown (Van Wagner 1977).

Although the surface fire behavior prediction does not incorporate the contribution of 1,000 hour fuels to fire intensity, Rothermel (1991) recognized that the combustion of these fuels can have significant impacts on crown fire development. Since the postepidemic stands were dominated by 1,000 hour fuels, these fuels were incorporated into fireline intensity calculations for the crown fire potential predictions using the program BURNUP included in the first order fire effects model, FOFEM version 5.21 (Albini 1976b, Albini and Reinhardt 1995, Reinhardt et al. 1997). Specifically, the fuel loadings and moistures for all size classes of fuels were used to provide estimates of total fuel consumption by size class during flaming and smoldering combustion. To calculate the new fireline intensities and flame lengths, the total fuel consumed during flaming combustion was input into Byram's (1959) fire intensity equations. The new fireline intensities were then used as the input to predict crown fire potential. This method only

Table 11. Comparison of total heat release, total fuel consumption, and duration during flaming and smoldering combustion between the postepidemic and endemic stands on the Ashley National Forest under normal fire season fuel moistures

	Total heat release (kW/m^2)	Flaming		Smoldering		Total duration (sec)
		Consumption (tonne/ha)	Duration (sec)	Consumption (tonne/ha)	Duration (sec)	
PE	9252	11.2	195	64.8	6600	6795
EN	4646	5.9	60	54.0	4110	4170

PE, postepidemic; EN, endemic.

Table 12. Crown fuel characteristics, critical crown rates of spread, and fireline intensities during normal, drought, and extreme drought fuel moisture conditions for the postepidemic and endemic stands on the Ashley National Forest

	ACFL (tonne/ha)	CBD (kg/m^3)	CBH (m)	Critical FLI (kW/m)	Critical ROS (m/min)
PE	9.50*	0.1282	3.7	1193	23.4
EN	19.82	0.1882	5.5	2162	15.9

ACFL, available canopy fuel load; CBD, crown bulk density; CBH, crown base height; FLI, critical fireline intensity; Critical ROS, critical crown rate of spread; PE, postepidemic; EN, endemic.
* Significantly different from the endemic stands at the $\alpha = 0.05$ level (Page 2006).

incorporates those fuels consumed during flaming combustion and assumes that large fuels do not contribute to rate of spread of a surface fire.

Fire Behavior Comparisons

The fire behavior predictions made using our custom fuel models were compared with predictions made using the standard fuel models (Anderson 1982, Scott and Burgan 2005). The purpose of the comparisons was to determine whether any currently available standard fuel model is equivalent to our custom models and to better understand the range of fire behavior predicted by our models. These comparisons are the first step in the extensive testing that is required for new fuel models (Burgan and Rothermel 1984). The comparisons were made on the basis of a range of 6.1-m wind speeds under normal fire season fuel moistures with wind adjustment factors and shading based on the specific characteristics of the fuel models. The contribution of 1,000 hour fuels used in our crown fire predictions were not incorporated in these comparisons.

Results

Ashley National Forest

Surface Fire Spread

The maximum predicted surface fire behavior, not including the contribution of 1,000 hour fuels, indicates that the postepidemic stands had greater rates of fire spread and fireline intensities than the endemic stands under all three fuel moisture conditions and wind speeds (Figure 1). The greatest differences occurred at high wind speeds and low fuel moistures with a 113% increase in rate of spread and a 64% increase in fireline intensity under extreme drought fuel moistures and a 6.1-meter wind speed of 50 km/hr. Figure 2 shows the surface fire predictions using only the mid-flame wind speeds, without using a 6.1-meter wind speed and adjustment factor. In this case the endemic stands had faster rates of spread and fireline intensities than the endemic stands under normal fire season fuel moisture conditions. Likewise, under the drought and extreme drought fuel moistures, the endemic stands had faster rates of spread and higher fireline intensities than the postepidemic stands when just the mid-flame wind speed was used.

Total heat release, fuel consumption, and duration of burning during flaming and smoldering combustion are shown in Table 11. The heat release reported incorporates heat from both frontal and postfrontal combustion. Total heat release from surface fires was 99% higher in the postepidemic stands, whereas total duration of burning was 63% longer than in the endemic stands under normal fire season fuel moistures.

Crown Fire Potential

The critical fireline intensities, critical crown fire rates of spread, and crown fuel characteristics of both the postepidemic and endemic stands are reported in Table 12. Critical fireline intensities were 81% lower and the critical crown rates of spread were 47% higher in the postepidemic stands than in the associated endemic stands. Predicted fireline intensities, including the heat contribution from 1,000 hour fuels and associated fire types are displayed in Table 13 under normal, drought, and extreme drought fuel moistures. The critical fireline intensities needed to initiate crowning were never reached in the endemic stands within the range of 6.1-m wind speeds reported. In the postepidemic stands, the predicted fireline intensities achieved the critical threshold above a 6.1-m wind speed of 50 km/hr under drought fire season fuel moistures and above 40 km/hr under extreme drought fuel moistures. In all cases in which the critical fireline intensities were reached, the crown fire rate of spread was fast enough to cause an active crown fire.

Sawtooth National Recreation Area

Surface Fire Spread

The predicted rate of surface fire spread and fireline intensities at the head of a surface fire under a range of 6.1-meter wind speeds is shown in Figure 3. The fireline intensities reported in Figure 3 do not incorporate the contribution of 1,000 hour fuels. For all three fuel moisture scenarios the current epidemic stands had faster rates of spread and fireline intensities than the endemic stands. The differences between the reported fire behaviors were large with a >533% increase in rate of spread and a 1,420%

Table 13. **Fireline intensities and fire type for the postepidemic and endemic stands on the Ashley National Forest under normal, drought, and extreme drought fuel moistures**

	6.1-m wind speed (km/hr)									
	10		20		30		40		50	
	FLI	Fire type	FLI	Fire type	FLI	Fire type	FLI	Fire type	FLI	Fire type
Normal										
PE	139	S	312	S	555	S	833	S	1,112	S
EN	55	S	91	S	146	S	200	S	273	S
Drought										
PE	179	S	430	S	752	S	1,111	S	1,540	AC
EN	57	S	132	S	207	S	283	S	396	S
Extreme drought										
PE	216	S	504	S	865	S	1,297	AC	1,766	AC
EN	76	S	133	S	228	S	323	S	437	S

The fireline intensities include the contribution of 1000 hour fuels for both stand types. FLI, fireline intensity (kW/m); PE, postepidemic; EN, endemic. Fire type: S, surface fire; AC, active crown fire.

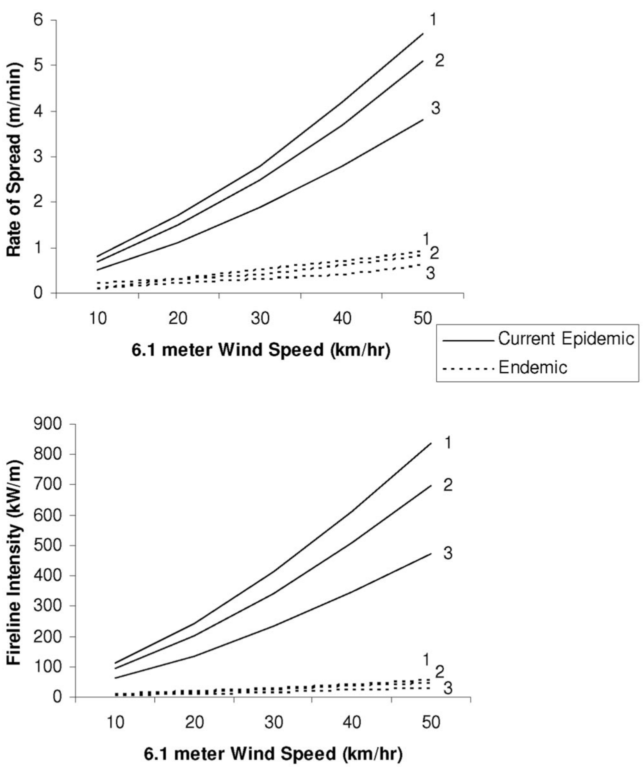

Figure 3. Rates of surface fire spread and fireline intensities for the current epidemic and endemic stands on the Sawtooth N.R.A. under extreme drought (1), drought (2), and normal (3) fire season fuel moistures. Wind adjustment factor used was 0.3 for the current epidemic stands and 0.2 for the endemic stands.

increase in fireline intensity under the extreme drought fuel moistures and a 6.1-m wind speed of 50 km/hr.

Crown Fire Potential

Crown fire potential is not directly reported in this section because of the characteristics of the aerial fuel component in the current epidemic stands and the current limitations in crown fire modeling. In these current epidemic stands >30% of the total foliage fuel load is currently dead (Table 14). These dead aerial fuels with their lower fuel moistures and the significant increase in predicted fireline intensities should have a significant impact on the initiation of crown fire activity in the current epidemic stands.

Table 14. **Average tree foliage characteristics for the current epidemic and endemic stands on the Sawtooth National Recreation Area and the Wasatch-Cache National Forest**

	LFL (tonne/ha)	DFL (tonne/ha)	Canopy foliage dead (%)	CBH (m)
Sawtooth N.R.A.				
EP	6.38	2.79	30%	8.0
EN	8.74	0.09	1%	8.0
Wasatch-Cache N.F.				
EP	9.93	2.04	17%	3.9
EN	10.66	0.23	2%	3.9

LFL, live aerial foliage load; DFL, dead aerial foliage load; CBH, crown base height; EP, current epidemic; EN; endemic.

Wasatch-Cache National Forest

Surface Fire Spread

Figure 4 illustrates the surface fire rates of spread and fireline intensities at the head of the fire for the current epidemic and endemic stands under a range of 6.1-m wind speeds. These predictions do not include the contribution of 1,000 hour fuels. Across all three fuel moisture conditions, the current epidemic stands had faster rates of spread and higher fireline intensities than the endemic stands. As with the current epidemic stands on the Sawtooth N.R.A., the predicted increases were large when compared with those for the endemic stands. The rate of spread was approximately 169% faster and the fireline intensities were approximately 232% higher than the predictions for the endemic stands under extreme drought fuel moistures and a 6.1-m wind speed of 50 km/hr.

Crown Fire Potential

As with the current epidemic stands on the Sawtooth N.R.A. crown fire potential is not directly reported here. However, Table 14 shows the aerial foliage characteristics for both stand types. The current epidemic stands averaged >17% of the total foliage load as dead. These dead aerial

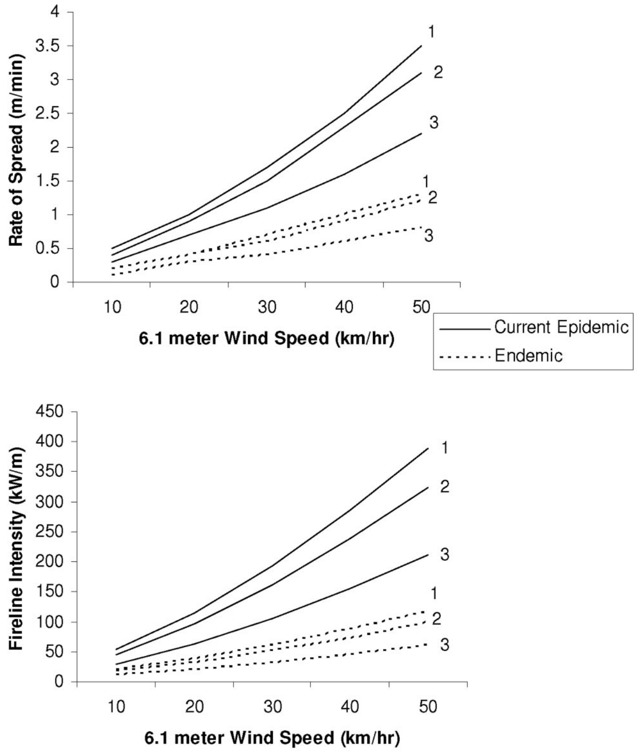

Figure 4. Rates of surface fire spread and fireline intensities for the current epidemic and endemic stands on the Wasatch-Cache N.F. under extreme drought (1), drought (2), and normal (3) fire season fuel moistures. Wind adjustment factor used was 0.3 for the current epidemic stands and 0.2 for the endemic stands.

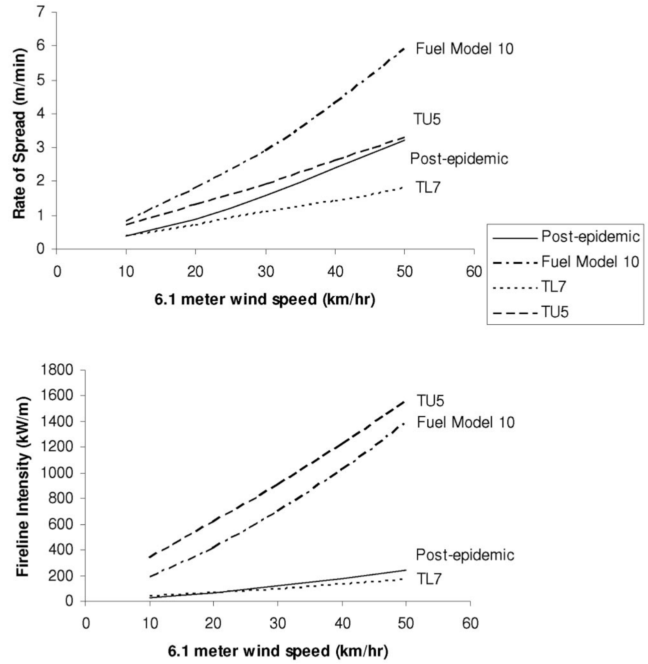

Figure 5. Comparison of rates of spread and fireline intensities between the postepidemic stands (Ashley N.F.), fuel model 10, fuel model TL7, and fuel model TU5 across a variety of 6.1-m wind speeds. based on normal fire season fuel moistures and wind adjustment factors of 0.5 for the postepidemic, 0.3 for fuel model 10, 0.3 for TL7, and 0.2 for TU5.

fuels with low fuel moistures as well as the predicted increase in surface fire intensity should have important implications for crown fire initiation in the current epidemic stands.

Fire Behavior Comparisons

Figures 5, 6, and 7 show the comparisons made between our custom fuel models for the postepidemic and current epidemic stands with a selected set of standard fuel models. Figure 5 shows the comparisons between the postepidemic, fuel model 10 (timber with litter and understory), TL7 (large down logs), and TU5 (very high load timber-shrub). Figure 6 shows comparisons between the current epidemic (Sawtooth N.R.A.), fuel model 8 (closed timber litter), TL5 (high load conifer litter), and TU5. Figure 7 shows the comparisons between the current epidemic (Wasatch-Cache N.F.), fuel model 8, TL5, and TU5. Most of the comparisons revealed that the custom fuel models differed from most standard fuel models when both rate of spread and fireline intensity were considered. Many of the predictions had similar outputs in terms of either rate of spread or fireline intensity, but none were close for both.

Discussion

Ashley National Forest

The results of this study indicated that potential fire behavior was significantly altered in the selected lodgepole pine stands during previous epidemics of the MPB. Rates of fire spread and fireline intensities in the postepidemic stands were greater than those for the endemic stands, but the increases were not due to differences in fuel loadings but to greater mid-flame wind speeds. When mid-flame wind speed was held constant, the endemic stands had faster rates of spread and higher fireline intensities than the endemic stands. The lack of dominant overstory trees in the postepidemic stands decreased the sheltering effect of vegetation, which allowed more wind to reach the forest floor. The greater surface wind speeds increased the fire's ability to transfer heat through convection and radiation heat transfer methods, thereby increasing rate of fire spread and the rate of heat release at the flaming front. The drier surface fuels, caused by a lack of a dominant overstory, also produced increases in rate of fire spread. However, the increase caused by the drier fuels was negligible compared with the effect of the wind, as Figure 2 shows that the endemic stands had greater fire behavior than the postepidemic stands even with the incorporated drop in fuel moisture.

The heavy amounts of large diameter fuels in the postepidemic stands also produced increased durations of flaming and smoldering combustion along with higher total heat release per unit area. These increased durations of flaming and smoldering combustion should have important implications for postfire effects, causing severe damage to living vegetation and higher mortality rates (Whelan 1995).

The predicted increases in fireline intensity, in conjunction with low crown base heights, also contributed to greater potential for crown fire initiation in the postepidemic stands with surface fires transitioning to involve crown fuels under drought and extreme drought fuel moistures. The removal of most of the mature lodgepole pine in the overstory and

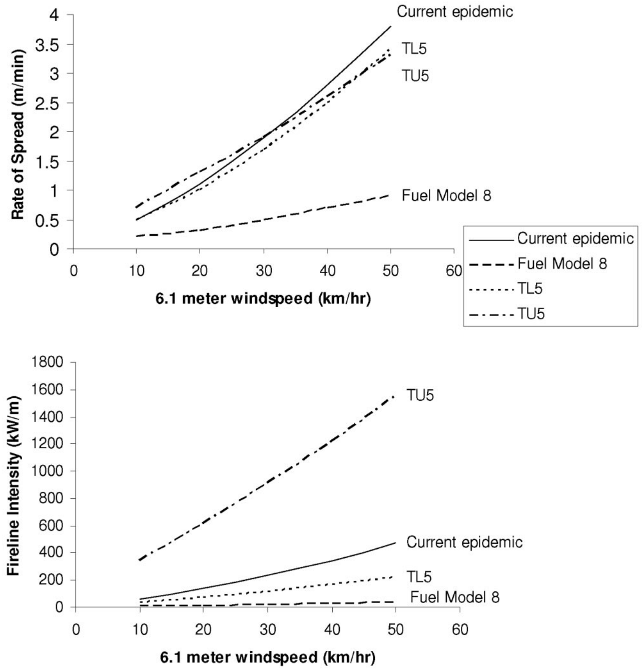

Figure 6. Comparison of rates of spread and fireline intensities between the current epidemic stands (Sawtooth N.R.A.), fuel model 8, fuel model TL5, and fuel model TU5 across a variety of 6.1-m wind speeds, based on normal fire season fuel moistures and wind adjustment factors of 0.3 for the current epidemic, 0.2 for fuel model 8, 0.3 for TL5, and 0.2 for TU5.

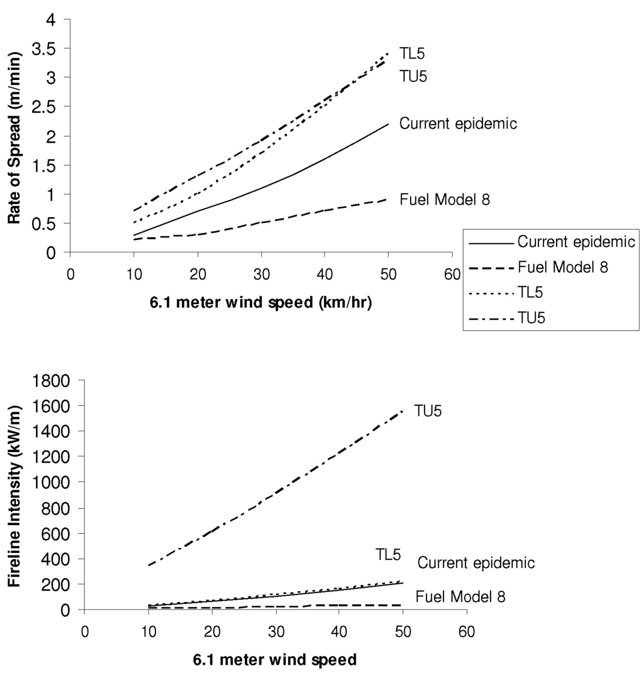

Figure 7. Comparison of rates of spread and fireline intensities between the current epidemic stands (Wasatch-Cache N.F.), fuel model 8, fuel model TL5, and fuel model TU5 across a variety of 6.1-m wind speeds, based on normal fire season fuel moistures and wind adjustment factors of 0.3 for the current epidemic, 0.2 for fuel model 8, 0.3 for TL5, and 0.2 for TU5.

the subsequent increase in the density of more shade-tolerant subalpine fir led to a decrease in the average crown base height of the stand. However, the potential for active crown fire spread was less in the postepidemic stands because of a lack of aerial fuel continuity. The large gaps in the overstory reduced the amount of available fuel in the canopy, which reduced the overall crown bulk density of the stand.

Sawtooth National Recreation Area and Wasatch-Cache National Forest

During the current MPB epidemics we sampled, rates of surface fire spread and fireline intensities increased, but the magnitude of the increase varied substantially. This variation in fire behavior was dependent on the net gain in litter and 1 hour fuels as well as a deeper fuel bed, with higher loadings and greater fuel bed depths corresponding to higher rates of spread and intensities. Burgan (1987) showed that increasing the amount of these smallest fuels in Rothermel's (1972) spread model would produce increased spread rates until the increase in fuel loading causes the optimum packing ratio of the fuel bed to be surpassed. Likewise, increasing the depth of the fuel bed would allow more air to penetrate the fuel bed and increase the rate of fuel consumption.

Crown fire potential in the current epidemic stands on both the Sawtooth N.R.A. and the Wasatch-Cache N.F. is currently unclear. The crown fire model used, based on Van Wagner (1977), uses live foliar moisture content, >70% of oven-dry weight, and crown base height to model crown fire initiation, in which the effect of foliar moisture content is minor compared with crown base height (Scott 1998). However, fuel moistures for dead fuels are generally <30% of oven-dry weight and may be much lower depending on specific environmental conditions. Thus, the Van Wagner (1977) model is inadequate to predict crown fire potential in the current epidemic stands in this study. Nevertheless, enough evidence is available to suggest that the large amounts of dead foliage in the current epidemic stands will increase the probably of crown fire initiation. Stockstad (1975) determined that dead ponderosa pine (*Pinus ponderosa* Laws) needles with moisture contents as low as 7.7% of oven-dry weight had minimum ignition temperatures of 280°C, using piloted ignitions. Compare that result to a minimum ignition temperature of 400°C for live foliage based on air temperature (Xanthopoulos and Wakimoto 1993). Although the data from Stockstad (1975) were based on ponderosa pine needles and used pilot ignition rather than air temperature, the difference illustrates that dead fuels will ignite under lower temperatures than live fuels. Thus, with a significant proportion of dead aerial fuels in the current epidemic stands, we can state that surface fires will transition to involve crown fuels in these stands with greater ease than in the endemic stands, with a given surface fire intensity. With regard to crown fire spread, the effect of dead foliage is also unknown but may be significant, given the differences in chemical composition, such as volatile oils and flammability of live versus dead foliage (Van Wagner 1974).

Fire Behavior Comparisons

The fire behavior comparisons between our results and those from the standard fuel models revealed that a few of the standard fuel models approximated our results closely, but no one fuel model fit our data exactly, especially at high wind speeds when observed differences were exaggerated. For example, compared with the postepidemic fire behavior, the standard fuel model TL7 (large down logs) worked well for approximating fireline intensity, but at high wind speeds it underpredicted rate of spread by about 1 m/min. Additionally, for the current epidemic stands the standard fuel model TL5 (high load conifer litter) was the most closely related fuel model, but it either under- or overpredicted rate of spread and fireline intensity at high wind speeds. The difficulty in finding an equivalent standard fuel model is not surprising because the standard fuel models were developed to represent much broader scale fuel conditions. Although no one standard fuel model approximated our results exactly, it appears that there are reasonable substitutes available, especially when one is predicting fire behavior at low wind speeds.

Conclusion

The MPB and its effects on fuels in our selected lodgepole pine stands resulted in drastic changes in fire behavior. Increased rates of surface fire spread, fireline intensities, and crown fire potential were all detected in both the current and postepidemic stands. However, potential for active crown fire spread, from tree to tree, was lower in the postepidemic stands. Changes in these aerial fuels in the postepidemic stands and their effect on wind sheltering were also important to surface fire predictions, indicating that the predicted increases in surface fire behavior were due to greater mid-flame wind speed and not to the differences in surface fuel loading. Although the results presented here indicate that MPB mortality increases surface fire behavior directly from increases in fine fuel loading (current epidemics) and indirectly by changing the effect of vegetative sheltering (postepidemic), these increases need to be evaluated in the context of larger scale processes, including the spatial pattern of fuels across large landscapes and the role that these changes have in the development and maintenance of lodgepole pine forests (Lotan et al. 1985, Finney 2001). Thus, although fire behavior may be altered by the MPB, it is not necessarily out of its historical range and should not be considered unnatural (Schoennagel et al. 2004). In any case, fire and fuels managers should be able to use the information presented here to aid in both short-term and long-term planning for both wildland fire and prescribed fire operations.

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