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Predicted Fire Behavior in Selected Mountain Pine Beetle Infested Lodgepole Pine Stands within the Intermountain Region

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Abstract

Using custom fuel models we predicted and compared fire behavior in lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.) stands with endemic, current epidemic, and post-epidemic 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, due to increases in the amounts of fine surface fuels. In the post-epidemic stands, rates of fire spread, fireline intensity, and total heat release were higher due to decreased vegetative sheltering and heavy accumulations of large diameter fuels. Crown fires were more likely to initiate in the post-epidemic stands due to greater fireline intensities and lower crown base heights. However, active crown fires were less likely to develop in the post-epidemic stands due to decreased aerial fuel continuity. We suggest here that crown fire initiation in the current epidemic stands was also greater due to an abundance of dead aerial fuels; although, this relationship is unclear. None of the currently available standard fuel models predicted surface fire behavior adequately for both rate of spread and fireline intensity.

Keywords: custom fuel models, fire management

Introduction

The mountain pine beetle (MPB) (*Dendroctonus ponderosae* Hopkins (Coleoptera: Scolytidae)) is a common forest insect that infests a variety of pine tree species throughout western North America. Extensive epidemics of the MPB can develop in lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.) stands killing over 80% of suitable host trees and resulting 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 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 during current and post-epidemic MPB beetle populations and provide detailed information about these changes to fire, fuels, and forest health professionals.

The role of fire in lodgepole pine forests has been extensively studied (Lotan et al. 1985, Romme 1980, Romme 1982). Due to the seral nature of most forests the function of disturbance, especially fire, is known to be of significant importance (Pfister and Daubenmire 1975). In these seral stands a hypothesis of fuel buildup, caused by the MPB and other mortality agents, and subsequent high-intensity fires, which allow the serotinous cones to open, is frequently mentioned to describe the fire and fuel relationships (Brown 1975, Lotan 1975, Gara et al. 1985). Thus, accumulations of large

down woody fuels caused by the various mortality agents appears to be an important factor determining the intensity and severity of fires in lodgepole pine forests.

Currently, there are no specific studies available that have quantified either potential or observed fire behavior in MPB infested forests. While there are many studies which have indicated that mortality caused by the MPB increases fire potential, none have 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 due to large amounts of fine dead fuels (Romme et al. 1986). However, after this period of time, fire potential or the risk of 'destructive fire' may be lower (Romme et al. 1986) or substantially higher (Lotan et al. 1985, Schmid and Amman 1992) depending upon the specific study referenced. In addition to this disagreement in the literature, many studies refer to different variables such as destructive fire, fire potential, or fire hazard. Thus, clarification of these relationships is needed to help land managers understand the potential effects of MPB activity on fire behavior.

To capture the potential fire hazard in MPB infested lodgepole pine stands three study areas were chosen: 1) a 20 year old post-epidemic on the Ashley National Forest near Vernal, UT, 2) an active epidemic on the Sawtooth National Recreation Area near Stanley, ID, and 3) a developing epidemic on the Wasatch-Cache National Forest near Kamas, UT. The specific objectives of this study were to predict and compare fire behavior outputs including rate of spread, fireline intensity, and flame length for each stand type within each study area, to discuss the implications of these differences, and to compare the results of our fire behavior predictions with those from currently available

standard fuel models. It is hoped that these data will provide fire and fuels professionals more information on potential fire behavior in these forests.

Methods

Study Sites

General study areas were chosen by utilizing aerial detection surveys and site specific knowledge from USDA Forest Service personnel. Specific sites were selected by identifying locations of past and current MPB infestations and sites unaffected by the MPB. Current epidemics were identified as those stands with increasing MPB populations and significant recent mortality while endemic conditions were identified as those stands with low current beetle activity. Post-epidemic stands were identified as those stands with greater than 80% mortality occurring more than five years ago with no current beetle activity. Once possible locations were identified, aerial photographs and ground reconnaissance were used to verify beetle populations and make final site selections. Three sites were chosen; two sites with current epidemics, northern Utah and central Idaho, and one with a previous epidemic, northeastern Utah (Figure 1).

Using aerial photographs, four total stands were delineated within each study site; two stands were the treatment (current or post-epidemic) and two stands were the control (endemic). The delineated stands represented continuously forested areas sharing similar species composition, age, habitat type, size, slope, and aspect. In each of the delineated stands the entire fuels complex was measured, including ground, surface, and aerial fuels using a systematic grid of variable radius plots and standard fuel inventory techniques (Brown et al. 1982). The fuels data used in this study were obtained from Page (2006).

Site 1

An extensive MPB epidemic occurred in this area during the 1980's (Binder 1995). Increment cores from surviving trees in the post-epidemic stands were taken and growth releases identified to determine years of significant mortality. Most increment cores recorded a growth release around 1985 but mortality is assumed to have occurred prior to and after this date. Elevations of both the post-epidemic and endemic stands ranged from 2800 to 2930 meters with gentle slopes and mainly southerly aspects. The post-epidemic 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 these stands averaged approximately 40 hectares.

Site 2

The current widespread epidemic in site 2 began in the 1990's with the majority of the mortality occurring since the year 2000 (Page 2006). Elevations of the selected stands were approximately 2100 meters 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 hectares.

Site 3

The current epidemic occurring in site 3 began within the past few years and is continuing to develop. Elevations of the selected stands ranged from approximately 2700 to 2900 meters 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 hectares.

Custom Fuel Model Development

Fire behavior predictions were made using custom fuel models, which are stylized descriptions of the fuels complex based on site specific fuels data (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 data presented by Page (2006). Fuel bed depth was calculated using the average of the fuel bed bulk depth, average shrub height, and average herbaceous height from the fuels data. Rather than using the average fuel loadings for each stand to compare fire behavior the average fuel loadings between the two similar stands in each study area were used. This was done to provide a more sensible fuel model that is less site specific and to incorporate broader scale fuel conditions. In total, six custom fuel models were developed, one for each condition per study site: (Site 1) a post-epidemic fuel model and an endemic fuel model, (Site 2) a current epidemic and endemic fuel model, and (Site 3) a current epidemic and endemic fuel model. Besides fuels data each custom fuel model also required additional inputs including live and dead fuel heat content, surface to area volume ratios, and moisture of extinction. The values for these inputs were obtained using the default values from the standard fuel model 10, timber with litter and understory (Anderson 1982).

Fire Behavior Prediction

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). The limitations and assumptions of the model include; 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 the burning of fuels greater than 3 inches in diameter (1000 hour), and it assumes the weather variables do not change during the time frame of the prediction (Rothermel 1972).

To predict crown fire potential BehavePlus was also used, which uses either fireline intensity or flame length of a surface fire to determine crown fire initiation, crown fire rate of spread, and fire type based on crown bulk density, crown base height, and foliar moisture content (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 critical crown fire rate of spread is the rate of spread necessary to sustain an active crown fire calculated using canopy bulk density and based on Rothermel's (1991) crown fire spread model. Three types of fire are recognized by BehavePlus including, surface, passive crown, or active crown (Van Wagner 1977).

Although BehavePlus does not incorporate the contribution of 1000 hour fuels to fire intensity, Rothermel (1991) recognized that the combustion of these fuels can have significant impacts on crown fire development. Since some of the stands were dominated by 1000 hour fuels, these fuels were incorporated into fireline intensity and flame length predictions using the program BURNUP included in the first order fire effects model, FOFEM version 5.21 (Albini 1976, Albini and Reinhardt 1995, Reinhardt et al. 1997).

Specifically, FOFEM uses the fuel loadings and moistures for all size classes of fuels 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 and flame length equations. The new fireline intensities were then used as the input into BehavePlus to predict crown fire potential. This method only incorporates those fuels consumed during flaming combustion and assumes that large fuels do not contribute to rate of spread of a surface fire.

Each fire behavior prediction is based on specific mid-flame wind speeds, slope steepness, and fuel moistures. In order to better understand the differences in fire behavior caused by the fuels characteristics the predictions were made using a 0% slope. 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 1 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 post-epidemic 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 post-epidemic stands (Byram and Jemison 1943), Rothermel's (1983) fine dead fuel moisture tables were used to aid in estimating the unshaded fuel moistures.

In order to determine mid-flame wind speeds the standard 6.1 meter level wind speed was reduced using various wind adjustment factors based on the effects of vegetative sheltering (Albini and Baughman 1979). For the post-epidemic stands where few overstory trees remain a wind adjustment factor of 0.5 was used. For the current

epidemic stands, where 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).

The surface fire predictions made in this study were based on the average fuel loadings for each type of stand within each study area. Using average fuel loadings to predict fire behavior is a common method for fire behavior prediction but it fails to capture a range of potential spread rates that are dependent upon the variability in fuels data. In order to evaluate a potential range in surface fire rate of spread the 95% confidence intervals of the fuels data from both current epidemic stands on the Sawtooth N.R.A. and Wasatch-Cache N.F. were used. Specifically, the average of the maximum and minimum confidence intervals were used to determine a likely range of potential spread rates.

Fire Behavior Comparisons

The fire behavior predictions made using our custom fuel models were compared to predictions made based on sets of standard fuel models (Anderson 1982, Scott and Burgan 2005). The standard fuel models were developed to provide site specific fire behavior predictions based on the assumption that the specific site has fuels represented by one of the fuel models (Anderson 1982). The standard fuel models represent fuel conditions found throughout North America ranging from grasslands to high elevation conifer forests. However, given the wide range of conditions found in North America these small sets of fuel models are inadequate for predicting fire behavior when the fuel conditions are unusual or not easily represented. In order to determine if any currently available standard fuel model is equivalent to our custom models the predictions were

compared. The comparisons were made based on a range of 6.1 meter wind speeds under normal fire season fuel moistures with wind adjustment factors and shading based on the specific characteristics of the fuel models.

Results

Ashley National Forest

The predicted surface fire behavior (Table 2) shows that for both a low 6.1 meter wind speed of 10 km per hour and a high of 50 km per hour that the post-epidemic stands had greater rates of fire spread and fireline intensities than the endemic stands with approximately 80% and 242% increases, respectively. The greatest differences occurred at high wind speeds and low fuel moistures with active crown fires potentially developing under drought and extreme drought fuel moistures.

Maximum heat release, fuel consumption, and duration of burning during flaming and smoldering combustion are shown in Table 3. Maximum heat release was 13% higher in the post-epidemic stands while total fuel consumption and total duration of burning were 27% and 59% higher, respectively.

The critical fireline intensities, critical crown fire rates of spread, and crown fuel characteristics of both the post-epidemic and endemic stands are reported in Table 4. Critical fireline intensities were 45% lower in the post-epidemic stands due to the lower observed crown base heights. Critical crown rates of spread were 47% higher in the post-epidemic stands due to lower crown bulk densities.

Sawtooth National Recreation Area

The results from Page (2006) reported that the only statistically significant differences between the fuels in the current epidemic and endemic stands were the litter

and 1 hour fuel loadings. The importance of the extra fine fuels in the current epidemic stands is apparent when examining Table 5. For both the low and high 6.1 meter wind speeds of 10 and 50 km per hour, respectively, the rates of surface fire spread averaged about 5.8 times faster in the current epidemic stands than in the endemic stands while fireline intensities averaged about 11 times higher than in the endemic stands. However, even with the increased fireline intensities there was no transitioning to crown fires, based on the live fuels data.

Using the 95% confidence intervals for the fuels data, the fire behavior predictions were rerun to show the minimum and maximum rates of spread (Figure 2). The current epidemic stands, especially at high wind speeds, had higher rates of spread than the endemic stands indicating that the predicted increases were not affected by the variability of the fuels data.

Wasatch-Cache National Forest

On the Wasatch-Cache N.F. the only statistically significant differences between the fuels in the current epidemic and endemic stands were the amounts of 1 hour and litter fuels (Page 2006). The increases in these fine fuels produced significant increases in rates of spread, fireline intensities, and flame lengths (Table 6). The largest increases occurred during the lowest fuel moistures and highest wind speeds with average rate of spread and fireline intensity increases of 2.8 and 4.6 times the endemic stands, respectively, for both the low and high 6.1 meter wind speeds. Additionally, potential for active crown fire development occurred under drought and extreme drought fuel moistures at high wind speeds.

Using the 95% confidence intervals for the fuels data, the fire behavior predictions were rerun to show the minimum and maximum rates of spread (Figure 3). The average rates of spread in the current epidemic stands were higher than the endemic stands under both the 10 and 50 kilometer per hour wind speeds. The lack of overlap suggests that the predicted increases in rate of surface fire spread are significant and not due to the variability of the fuels data.

Fire Behavior Comparisons

Comparisons of the results of our fire behavior analysis were made with the 13 standard fuel models (Anderson 1982) and the new set of fuel models from Scott and Burgan (2005). All of the standard fuel models were evaluated but only the most closely matched fuel models were reported in Figures 4, 5, and 6. For the post-epidemic stands, the results indicated that the standard fuel model TU5 (very high load, dry climate timber-shrub) was closely related to the post-epidemic stands for rates of spread. However, when predicting fireline intensities, the standard fuel model TL7 (large down logs) was the most appropriate. For the current epidemic stands on the Sawtooth N.R.A., Figure 5 indicates that both standard fuel model TL5 (high load conifer litter) and TU5 shared similar rates of spread with the current epidemic stands. However, for fireline intensities the standard fuel models did not correlate as well, with TL5 being the most closely related standard fuel model. For the current epidemic stands on the Wasatch-Cache N.F., Figure 6 indicated that for rates of spread none of the presented fuel models correspond closely to the current epidemic stands but that fuel model TL5 was perhaps more closely related than the others. For fireline intensity, the predicted fire behavior in

the current epidemic stands on the Wasatch-Cache N.F. indicated that the standard fuel model TL5 was the most closely related fuel model.

Discussion

The results of this study indicated that potential fire behavior was significantly altered in the selected lodgepole pine stands during current and previous epidemics of the MPB. During current MPB epidemics, rates of surface fire spread increased but the magnitude of the increase varied substantially with average increases, compared to the endemic stands, ranging from 2.8 times on the Wasatch-Cache N.F. to 5.8 times on the Sawtooth N.R.A. This variation in rate of spread was most dependent upon the net gain in litter and 1 hour fuels with higher loadings corresponding to higher rates of spread. These increases in rates of spread could contribute to greater chances for large fire development (Wood 1982).

Rates of fire spread and fireline intensities in the post-epidemic stands were also greater than the endemic stands but the increases were not due to differences in fuel loadings but to greater mid-flame wind speeds. The lack of dominant overstory trees in the post-epidemic 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 to the effect of the wind, with increases ranging from 0 meters per minute at low wind speeds to a maximum of 0.4 meters per minute at high wind speeds, under extreme drought fuel moistures.

The heavy amounts of large diameter fuels in the post-epidemic 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 to post-fire 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 post-epidemic stands with surface fires transitioning to involve crown fuels under drought and extreme drought fuel moistures. However, the potential for active crown fire spread was less in the post-epidemic stands due to a lack of aerial fuel continuity.

The predicted crown fire potential in the current epidemic stands revealed that crown fire initiation occurred only under drought and extreme drought fuel moistures on the Wasatch-Cache N.F. but not at all for the stands on the Sawtooth N.R.A. These results are deceiving because they are based only on live fuels and do not incorporate the effect of dead aerial fuels in the overstory, reported to make up as much as 30% of the total foliage in current epidemic stands (Page 2006). The crown fire model used, based on Van Wagner (1977), utilizes live foliar moisture content, greater than 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 to crown base height (Scott 1998). However, fuel

moistures for dead fuels are generally less than 30% of oven dry weight and may be much lower depending upon 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) was 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).

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. This was true especially at high wind speeds when observed differences were exaggerated. For example, compared to the post-epidemic fire behavior, the standard fuel model TL7 (large down logs) worked well for

approximating fireline intensity but at high wind speeds it under predicted rate of spread by about 1 meter per minute. 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 over predicted rate of spread and fireline intensity at high wind speeds. The difficulty in finding an equivalent standard fuel model is not surprising since the standard fuel models were developed to represent much broader scale fuel conditions that are found throughout North America. While no one standard fuel model approximated our results exactly it appears that there are reasonable substitutes available, especially when predicting fire behavior at low wind speeds.

Conclusion

The MPB and its effects on fuels in lodgepole pine forests can result in drastic changes to fire behavior. Increased rates of surface fire spread, fireline intensities, and crown fire potential were all detected in both the current and post-epidemic stands. However, potential for active crown fire spread, from tree to tree, was lower in the post-epidemic stands. These changes should have important ramifications to fire and fuels managers who have to deal with large scale MPB epidemics. Although the results presented here indicate that MPB mortality increases fire behavior 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, while 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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Table 1. 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
1000 Hour	13	11	9	8	8	7
Live	117	117	78	78	70	70

All numbers are in percent

Table 2. Rates of spread, fireline intensities, and flame lengths for the post-epidemic and endemic stands under normal, drought, and extreme drought fuel moistures on the Ashley National Forest.

Normal				
6.1 meter wind speed (km/hr)	**10 km/hr**		**50 km/hr**	
	PE[a]	**EN[b]**	**PE[a]**	**EN[b]**
Rate of Spread (m/min)	0.4	0.3	3.2	1.5
Fireline Intensity (kW/m)	139	55	1112	273
Flame Length (m)	0.8	0.5	2.0	1.0
Drought				
6.1 meter wind speed (km/hr)	**10 km/hr**		**50 km/hr**	
	PE[a]	**EN[b]**	**PE[a]**	**EN[b]**
Rate of Spread (m/min)	0.5	0.3	4.3	2.1
Fireline Intensity (kW/m)	179	57	1540	396
Flame Length (m)	0.8	0.5	2.3	1.2
Transition to Crown			Yes	
Crown Fire Rate of Spread (m/min)			45.2	
Extreme Drought				
6.1 meter wind speed (km/hr)	**10 km/hr**		**50 km/hr**	
	PE[a]	**EN[b]**	**PE[a]**	**EN[b]**
Rate of Spread (m/min)	0.6	0.4	4.9	2.3
Fireline Intensity (kW/m)	216	76	1766	437
Flame Length (m)	0.9	0.6	2.4	1.3
Transition to Crown			Yes	
Crown Fire Rate of Spread (m/min)			51.7	

[a]PE, post-epidemic; [b]EN, endemic

Table 3. Comparison of maximum heat release, fuel consumption, and burning duration during both flaming and smoldering combustion between the post-epidemic and endemic stands under normal fuel moisture conditions on the Ashley National Forest.

	Max. HR[c] (kW/m^2)	**Flaming**		**Smoldering**		**Total D[e] (min)**
		C[d] (tonne/ha)	**D[e] (min)**	**C[d] (tonne/ha)**	**D[e] (min)**	
PE[a]	220	11.2	3.3	64.8	108	111
EN[b]	195	5.9	1.0	54.0	69	70

[a]PE, post-epidemic; [b]EN, endemic; [c]Max.HR, maximum heat release; [d]C, Consumption; [e]D, Duration

Table 4. Crown fuel characteristics, critical crown rates of spread, and fireline intensities during normal, drought, and extreme drought fuel moisture conditions for the post-epidemic and endemic stands on the Ashley National Forest.

				Critical FI[f] (kW/m)			
	ACFL[c] (tonne/ha)	**CBD[d] (kg/m^3)**	**CBH[e] (m)**	**Normal**	**Drought**	**Extreme Drought**	**Critical ROS[g] (m/min)**
PE[a]	9.50	0.1282	3.7	1461	874	766	23.4
EN[b]	19.82	0.1882	5.5	2648	1584	1389	15.9

[a]PE, post-epidemic; [b]EN, endemic; [c]ACFL, available canopy fuel load; [d]CBD, crown bulk density; [e]CBH, crown base height; [f]Critical FI, critical fireline intensity; [g]Critical ROS, critical crown rate of spread

Table 5. Rates of spread, fireline intensities, and flame lengths for the current epidemic and endemic stands under normal, drought, and extreme drought fuel moisture conditions on the Sawtooth National Recreation Area.

Normal				
6.1 meter wind speed (km/hr)	**10 km/hr**		**50 km/hr**	
	EP[a]	**EN[b]**	**EP[a]**	**EN[b]**
Rate of Spread (m/min)	0.5	0.1	3.8	0.6
Fireline Intensity (kW/m)	163	17	1242	104
Flame Length (m)	0.8	0.3	2.1	0.7
Drought				
6.1 meter wind speed (km/hr)	**10 km/hr**		**50 km/hr**	
	EP[a]	**EN[b]**	**EP[a]**	**EN[b]**
Rate of Spread (m/min)	0.7	0.1	5.1	0.8
Fireline Intensity (kW/m)	240	17	1745	139
Flame Length (m)	1.0	0.3	2.4	0.8
Extreme Drought				
6.1 meter wind speed (km/hr)	**10 km/hr**		**50 km/hr**	
	EP[a]	**EN[b]**	**EP[a]**	**EN[b]**
Rate of Spread (m/min)	0.8	0.2	5.7	0.9
Fireline Intensity (kW/m)	282	37	2010	165
Flame Length (m)	1.0	0.4	2.6	0.8

[a]EP, current epidemic; [b]EN, endemic

Table 6. Rates of spread, fireline intensities, and flame lengths for the current epidemic and endemic stands under normal, drought, and extreme drought fuel moisture conditions on the Wasatch-Cache National Forest.

Normal				
6.1 meter wind speed (km/hr)	**10 km/hr**		**50 km/hr**	
	EP[a]	**EN[b]**	**EP[a]**	**EN[b]**
Rate of Spread (m/min)	0.3	0.1	2.2	0.8
Fireline Intensity (kW/m)	90	16	660	129
Flame Length (m)	0.6	0.3	1.5	0.7
Drought				
6.1 meter wind speed (km/hr)	**10 km/hr**		**50 km/hr**	
	EP[a]	**EN[b]**	**EP[a]**	**EN[b]**
Rate of Spread (m/min)	0.4	0.2	3.1	1.2
Fireline Intensity (kW/m)	133	39	1033	234
Flame Length (m)	0.7	0.4	1.9	1.0
Transition to Crown			Yes	
Crown Fire Rate of Spread (m/min)			42.5	
Extreme Drought				
6.1 meter wind speed (km/hr)	**10 km/hr**		**50 km/hr**	
	EP[a]	**EN[b]**	**EP[a]**	**EN[b]**
Rate of Spread (m/min)	0.5	0.2	3.5	1.3
Fireline Intensity (kW/m)	168	39	1176	255
Flame Length (m)	0.8	0.4	2.0	1.0
Transition to Crown			Yes	
Crown Fire Rate of Spread (m/min)			48.2	

[a]EP, current epidemic; [b]EN, endemic

Figure Captions

Figure 1. The approximate locations and the number and type of stands sampled for the three study areas.

Figure 2. Rates of spread for the current epidemic and endemic stands on the Sawtooth N.R.A. incorporating the 95% confidence intervals for the fuels data for the 6.1 meter wind speeds of 10 km per hour and 50 km per hour under normal fuel moisture conditions.

Figure 3. Rates of spread for the current epidemic and endemic stands on the Wasatch-Cache N.F. incorporating the 95% confidence intervals for the fuels data for the 6.1 meter wind speeds of 10 km per hour and 50 km per hour under normal fuel moisture conditions.

Figure 4. Comparison of rates of spread and fireline intensities between the post-epidemic stands (Ashley N.F.), fuel model 10, fuel model TL7, and fuel model TU5 across a variety of 6.1 meter wind speeds. Based on normal fire season fuel moistures and wind adjustment factors of 0.5 for the post-epidemic, 0.3 for fuel model 10, 0.3 for TL7, and 0.2 for TU5.

Figure 5. 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 meter 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 6. 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 meter 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.

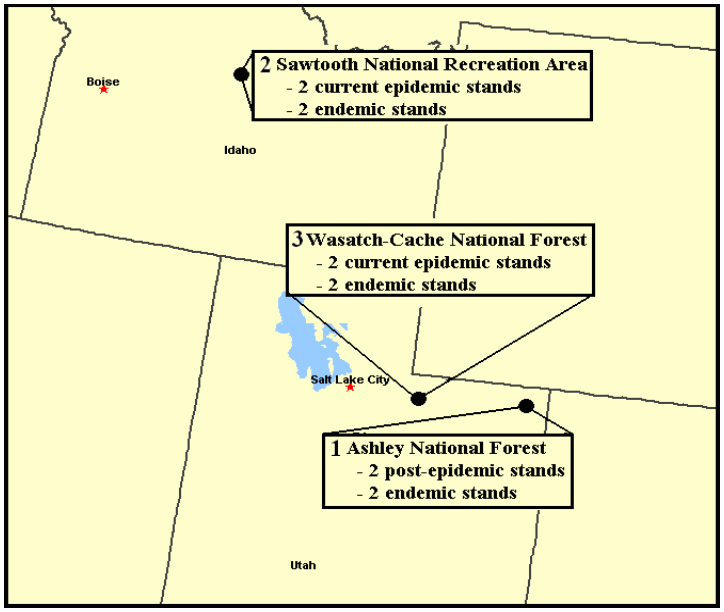

2 Sawtooth National Recreation Area
- 2 current epidemic stands
- 2 endemic stands
Boise
Idaho
3 Wasatch-Cache National Forest
- 2 current epidemic stands
- 2 endemic stands
Salt Lake City
1 Ashley National Forest
- 2 post-epidemic stands
- 2 endemic stands
Utah

Figure 1.

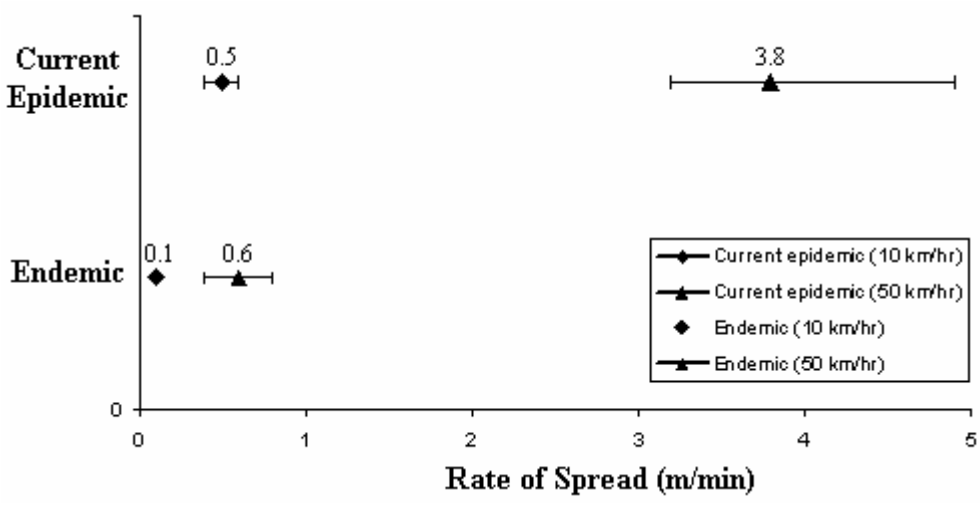

Current Epidemic
Endemic
0.5
3.8
0.1
0.6
Current epidemic (10 km/hr)
Current epidemic (50 km/hr)
Endemic (10 km/hr)
Endemic (50 km/hr)
0
0
1
2
3
4
5
Rate of Spread (m/min)

Figure 2.

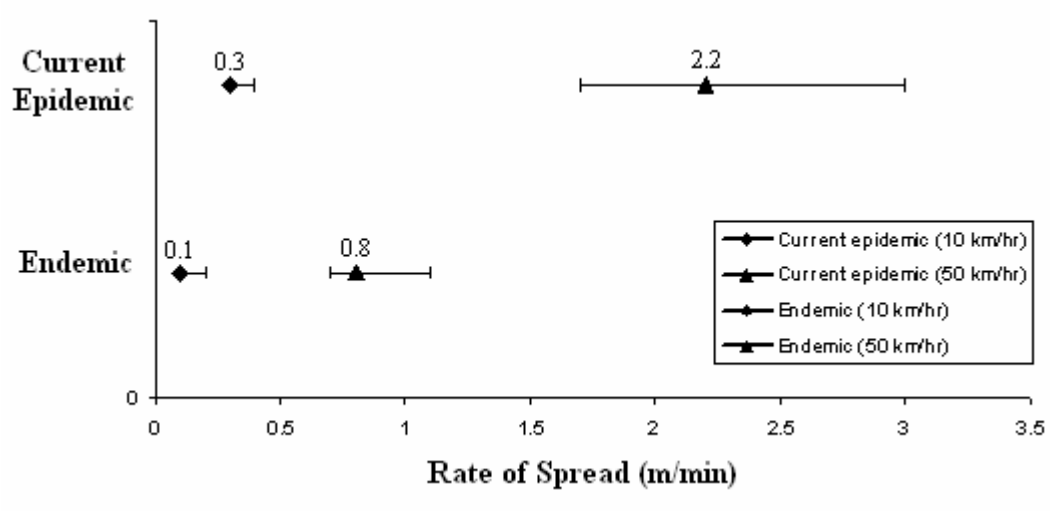
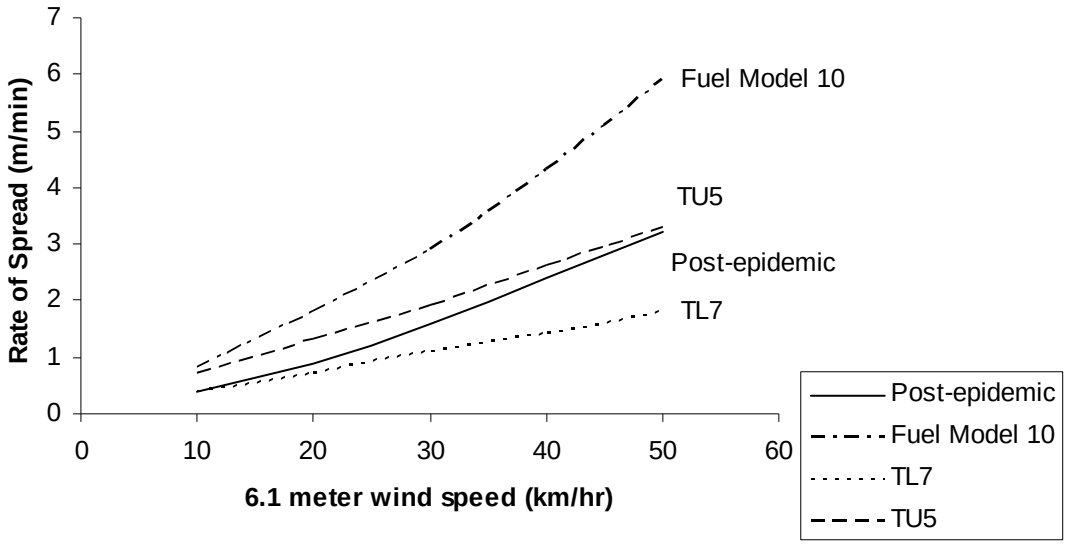

Current Epidemic
Endemic
0.3
2.2
0.1
0.8
Current epidemic (10 km/hr)
Current epidemic (50 km/hr)
Endemic (10 km/hr)
Endemic (50 km/hr)
0
0
0.5
1
1.5
2
2.5
3
3.5
Rate of Spread (m/min)

Figure 3.


Rate of Spread (m/min)
0
1
2
3
4
5
6
7
0
10
20
30
40
50
60
6.1 meter wind speed (km/hr)
Fuel Model 10
TU5
Post-epidemic
TL7
Post-epidemic
Fuel Model 10
TL7
TU5

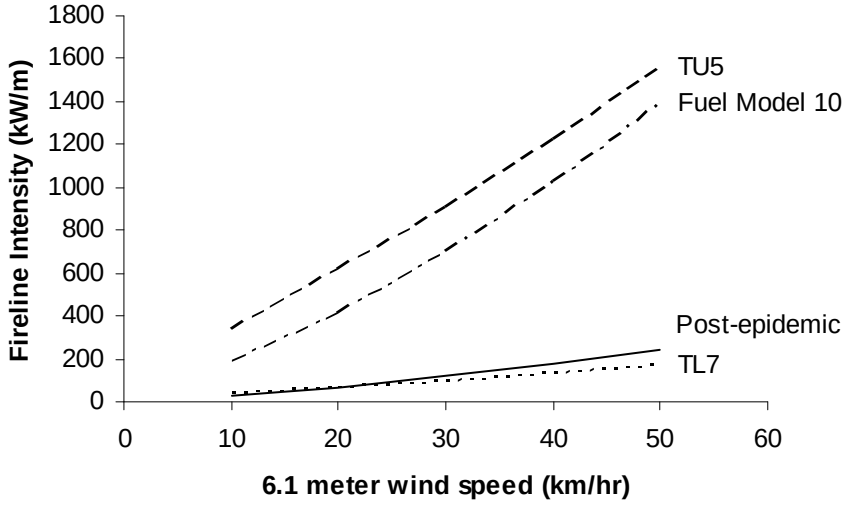

Fireline Intensity (kW/m)
0
200
400
600
800
1000
1200
1400
1600
1800
0
10
20
30
40
50
60
6.1 meter wind speed (km/hr)
TU5
Fuel Model 10
Post-epidemic
TL7

Figure 4.

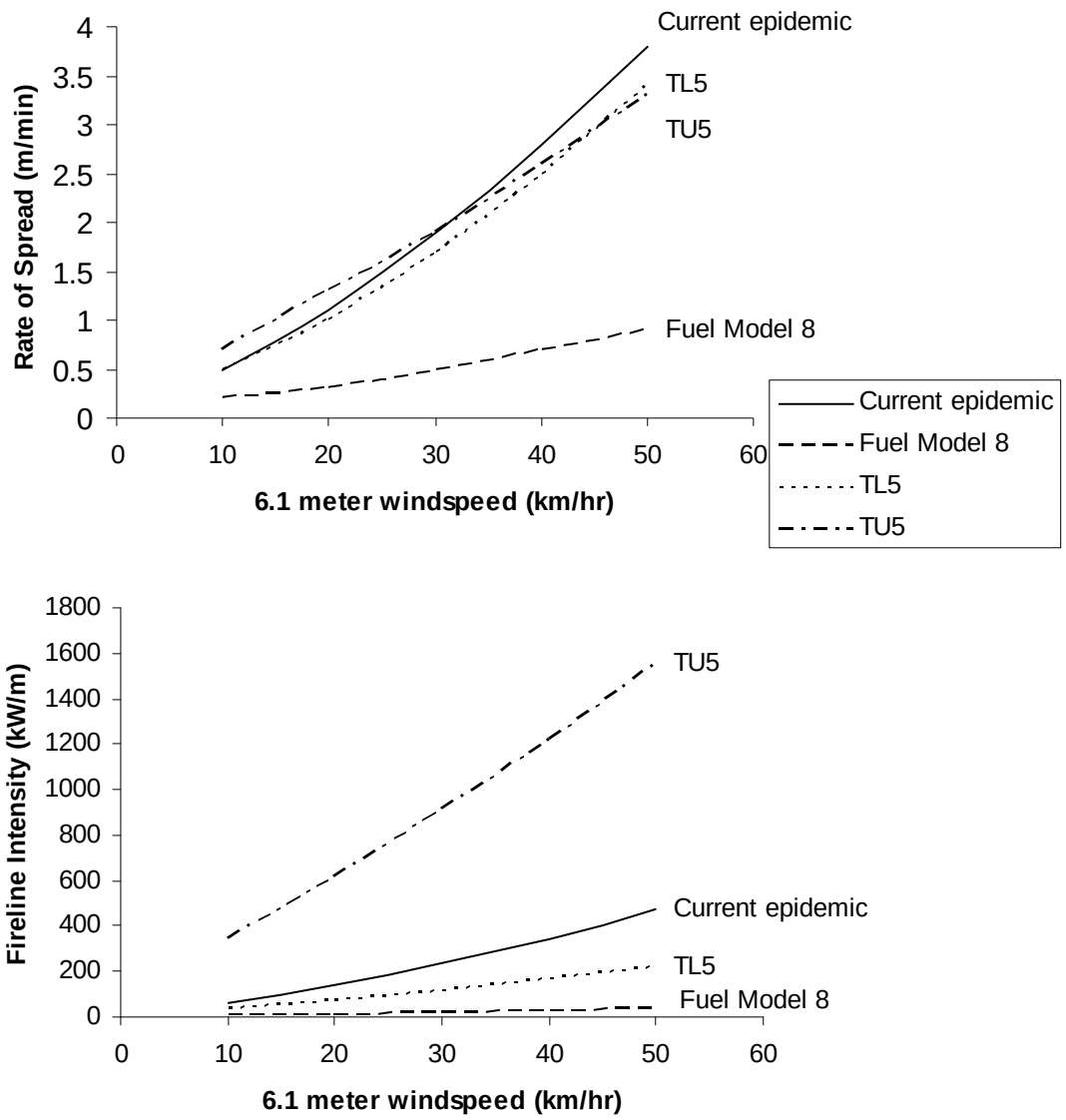
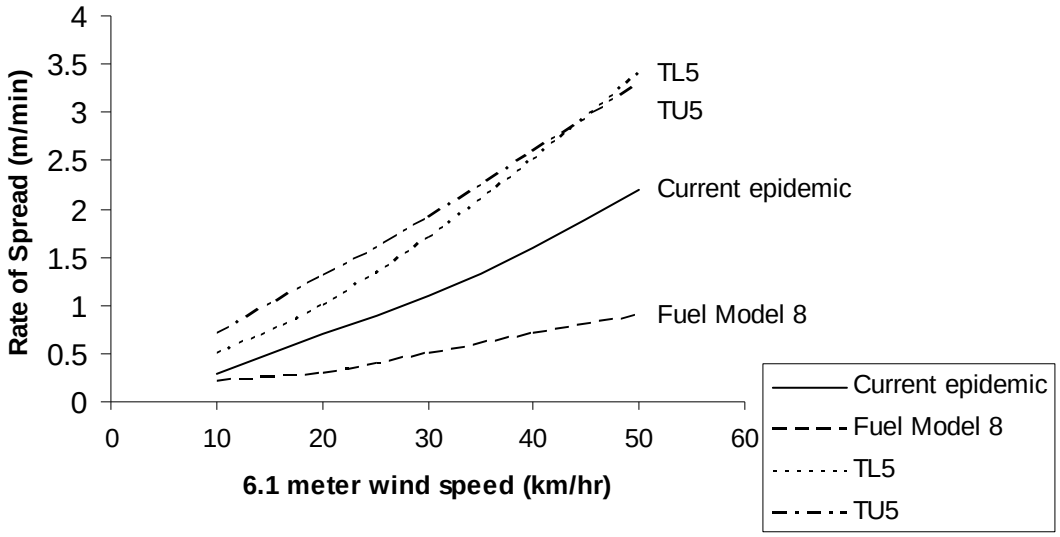

Rate of Spread (m/min)
4
3.5
3
2.5
2
1.5
1
0.5
0
0
10
20
30
40
50
60
6.1 meter windspeed (km/hr)
Current epidemic
TL5
TU5
Fuel Model 8
Current epidemic
Fuel Model 8
TL5
TU5
Fireline Intensity (kW/m)
1800
1600
1400
1200
1000
800
600
400
200
0
0
10
20
30
40
50
60
6.1 meter windspeed (km/hr)
TU5
Current epidemic
TL5
Fuel Model 8

Figure 5.


Rate of Spread (m/min)
4
3.5
3
2.5
2
1.5
1
0.5
0
0
10
20
30
40
50
60
6.1 meter wind speed (km/hr)
TL5
TU5
Current epidemic
Fuel Model 8
Current epidemic
Fuel Model 8
TL5
TU5

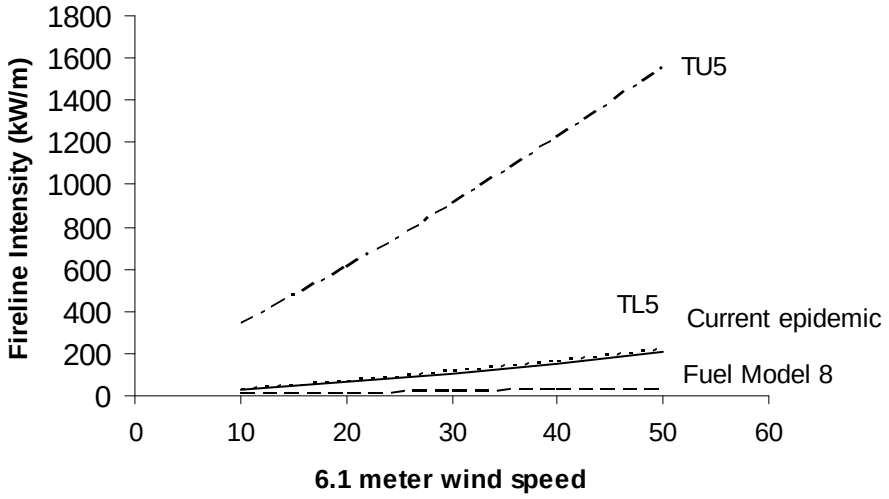

Fireline Intensity (kW/m)
1800
1600
1400
1200
1000
800
600
400
200
0
0
10
20
30
40
50
60
6.1 meter wind speed
TU5
TL5
Current epidemic
Fuel Model 8

Figure 6.