Mountain Pine Beetle-Induced Changes to Selected Lodgepole Pine Fuel Complexes within the Intermountain Region

Wesley Green Page and Michael James Jenkins

Abstract: The mountain pine beetle (*Dendroctonus ponderosae* Hopkins) is a forest insect that infests lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.) forests in the Intermountain West. The often widespread mortality caused by the mountain pine beetle has been suggested to result in significant changes to stand structure, composition, and total fuel loading; however, little quantitative information that documents these changes is available. We examined mountain pine beetle–induced changes to ground, surface, and aerial fuels in lodgepole pine stands during current epidemics and 20 years after an epidemic. Results indicated that there were statistically significant increases in the amounts of fine surface fuels in recently infested stands, i.e., those stands ≤5 years past peak mortality. In the previously infested stands, there were large increases in the amounts of dead woody fuels in all but the smallest size classes, with a 7.8-fold increase in down woody fuels ≥7.62 cm in diameter. Live shrubs and the amount of subalpine fir (*Abies lasiocarpa* Nutt.) regeneration were also significantly greater in the postepidemic stands. The net result of epidemic mountain pine beetle activity was a substantial change in species composition and a highly altered fuels complex in which large dead woody fuels and live surface fuels dominate. FOR. SCI. 53(4):507–518.

Keywords: mountain pine beetle, lodgepole pine, disturbance ecology, fuels management

THE ECOLOGICAL ROLE of the mountain pine beetle (MPB) (*Dendroctonus ponderosae* Hopkins [Coleoptera: Scolytidae]) in lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.) forests in the Rocky Mountains has been well documented (Roe and Amman 1970, Amman 1977, Peterman 1978). During epidemic population levels, MPB activity has been shown to alter stand composition, structure, and successional patterns (Amman 1977, Gara et al. 1985, Shore et al. 2006). Additionally, past research has suggested that increases in the amounts of dead woody fuels caused by extensive MPB mortality have been significant, resulting in highly altered fuels complexes (Romme et al. 1986, Amman 1991, Schmid and Amman 1992, Hawkes et al. 2004). These potential alterations to affected fuels complexes have also been suggested to have substantial impacts on short- and long-term fire hazards (Knight 1987). However, few studies have attempted to quantify changes to the entire fuels complex with most work being limited to discussing relative changes to dead and down woody fuels in broad fuel categories, i.e., large or small dead fuels. With the recent emphasis on fuels management in land management agencies and a lack of quantitative information on fuels complexes in MPB-infested forests, more detailed information needs to be provided to fire and fuels professionals so that they can make more informed decisions.

Extensive epidemics of the MPB have occurred in lodgepole pine forests throughout western North America both recently and historically. Widespread epidemics tend to occur when conditions such as drought (Mattson and Haack 1987) or pathogens (Goheen and Hansen 1993) weaken enough host trees for populations to build and subsequently attack relatively healthy trees of suitable size (Berryman 1982). Generally, lodgepole pine stands with a large proportion of mature trees greater than 20 cm dbh are frequently considered the most susceptible to MPB epidemics (Safranyik 1989). When epidemics do occur, they can be locally intense, resulting in nearly complete mortality of trees greater than 10–13 cm dbh (Furniss and Carolin 1977, Safranyik and Carroll 2006).

In lodgepole pine forests the amount, arrangement, and continuity of fuels can vary widely by location and through time with fuel loadings being strongly influenced by various mortality agents, such as the dwarf mistletoe (*Arceuthobium americanum* Nutt. ex Engelm.) and the MPB (Brown 1975, Alexander and Hawksworth 1976, Brown and See 1981). During early stand development total fuel loadings can be relatively high, because of remaining unburned fuel and suppression mortality in overly dense stands (Muraro 1971, Brown 1975). As stands develop and fuels decompose, low fuel loadings can dominate, especially where low-intensity surface fires consume surface fuels (Muraro 1971). Over time, as stands continue to age and individual trees reach preferential sizes, high total fuel loadings can develop once again as the stands become susceptible to various mortality agents (Lotan et al. 1985).

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Changes in the amounts of total dead and down woody fuels have been previously quantified in lodgepole pine stands affected by the MPB by Armour (1982) and Romme et al. (1986) in Montana and Wyoming, respectively. Romme et al. (1986) observed increases of 36% in needle litter for 6 years after an epidemic, whereas Armour (1982) failed to find significant differences in loading of fuels 0–0.64 cm in diameter from 2–6 years after an epidemic. For larger size dead and down woody fuels both Romme et al. (1986) and Armour (1982) found substantial increases in the total amounts of fuel, but the rate and duration of the increase varied according to the different habitat types sampled. Habitat type and site productivity have also been shown to affect the fall rates of MPB-killed lodgepole pine in central Oregon, which could influence total down woody debris loading over time (Mitchell and Preisler 1998). Missing from these earlier studies was a more detailed evaluation of changes to the entire fuels complex, including aerial and live surface fuels. These aerial and live surface components often interact with the down woody element to influence potential fire spread and intensity either directly through flame contact or indirectly through changes in fuel moisture and wind relationships (Albini and Baughman 1979, Whitehead et al. 2006). Thus, understanding the entire fuels complex and the relationship of its individual components to each other are necessary to fully grasp changes to stand dynamics and future fire potential.

To provide a more detailed description of the fuels complex in MPB infested lodgepole pine forests we conducted an intensive fuels inventory measuring ground, surface, and aerial fuels. A total of three separate study sites were selected, two with large scale and severe current epidemics and one 20 years after a large-scale epidemic. Current epidemic and 20-year postepidemic MPB population levels were chosen to study because of their relative importance in fuels and fire management decisionmaking. Current epidemic stands contain large amounts of fine dead fuel that are highly flammable, whereas postepidemic stands, particularly those where the majority of the MPB-killed trees are on the ground and still solid, represent fuel conditions for which fire suppression efforts are more difficult. Additionally, management actions such as salvage logging are usually undertaken to prevent the postepidemic stand conditions often encountered. Within the postepidemic and current epidemic study sites lodgepole pine forest types were selected and stratified into postepidemic or current epidemic stands, respectively. Similar endemic stands were then selected within each of the study sites and paired with the postepidemic or current epidemic stands. Statistical comparisons between the various fuels components in the current epidemic or postepidemic stands were then made with the endemic stands to determine whether significant differences existed and the magnitude of the differences. Because of the dissimilarity between the history, habitat type, and other ecological attributes of the study sites, each of the selected sites represented a single evaluation of the MPB and its effects on lodgepole pine stands; i.e., the data were not compared between sites. Whereas the data provided should be considered specific to our selected sites, it is hoped that fire and fuels professionals will be able to apply our findings to other similar lodgepole pine stands within the Intermountain West by focusing on the general changes we observed. These professionals should then be able to make more informed decisions regarding MPB epidemics and their potential alterations to lodgepole pine fuel complexes.

Methods

Study Site Selection and Statistical 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, northern Utah and central Idaho, had current epidemics and one site, northeastern Utah, had a previous epidemic. Each site represented a separate study area in which only one treatment (current epidemic or postepidemic) was selected. Because of a combination of limited time, funding, and lack of adequate representation of each treatment in all three study sites, we were unable to design this study with each treatment occurring in each study area. Data from the current epidemic stands in central Idaho and northern Utah were not combined because of different stand histories and ecological characteristics.

Within each study site aerial photographs were used to delineate a total of four stands: two treatment stands of either current epidemic (northern Utah and central Idaho) or postepidemic stands (northeastern Utah) and two control stands (endemic) that 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 greater than 80% mortality occurring more than 5 years ago with no current beetle activity. Because of the exploratory nature of this study, the overall study design and site selection were based on procedures used to develop a chronosequence or space-for-time substitution (Pickett 1989). 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. This procedure was aided, given the fact that the selected stands were essentially even-aged and showed little evidence of recent disturbance by fire or other non-MPB insects and diseases. A stratified sampling design was implemented to subdivide the population of interest into experimental units (stands). Stands were selected on the basis of previously mentioned standards. Plots within stands were sampled by using a systematic design with a simple random start to measure the response variables of interest. This stratified sampling design allowed flexibility in determining proper sampling locations and made the extensive field sampling required more manageable. However, this design limits the applicability of the results to areas outside of our selected sites.

Study Sites

The site in northeastern Utah was located on the Ashley National Forest (Ashley NF) in the eastern Uinta Mountains. The sampling of all four stands was completed during the summer of 2005. An extensive MPB epidemic occurred in this area beginning in the early 1980s and lasted through the decade (Binder 1995). Within the postepidemic stands that were delineated, increment cores from surviving trees were taken and growth releases were identified to verify the years of significant mortality. Because aerial detection surveys from the Forest Service were available that date back to the epidemic, the growth releases were used only to verify the aerial detection maps. Therefore, the identification of growth releases was done roughly in the field by searching for a point in the rings where the change ingrowth rate was abrupt, continuous, and greater than the previous year's average widths (Veblen et al. 1991). Most increment cores recorded a growth release around 1985, but mortality is assumed to have also occurred before and after this date. The long-term history of the MPB at this site is unknown, but the stands showed little evidence of extensive disturbance by non-MPB insects, diseases, or surface fire activity. Elevations of both the postepidemic and endemic stands ranged from 2,800 to 2,930 m above sea level with slopes of less than 10% and mainly southerly aspects. The postepidemic stands were dominated by mature and immature subalpine fir (*Abies lasiocarpa* Nutt.) with only remnant patches of lodgepole pine. The endemic stands were dominated by mature lodgepole pine with understories of subalpine fir and Engelmann spruce (*Picea engelmannii* Parry ex Engel.). A prominent cover of grouse whortleberry (*Vaccinium scoparium* Leib. ex Coville) was present in all stands, indicating that the habitat type was *A. lasiocarpa*/*V. scoparium* (Mauk and Henderson 1984). The distance between the postepidemic and endemic stands was about 9.5 km, whereas the distance between similar stands was about 1.5 km. All of the stands sampled averaged approximately 40 ha in size.

The site in central Idaho was located on the Sawtooth National Recreation Area (Sawtooth NRA) near Stanley, Idaho. The sampling of the two current epidemic stands was completed during the summer of 2004, and the two endemic stands were sampled during 2005. A widespread epidemic that began in the 1990s is currently occurring in the area (Jorgensen and Mocettini 2005). Widespread and severe MPB epidemics have occurred in the Sawtooth Valley at least twice within the past 150 years, once in the early 1900s and again in the 1920s (US Forest Service 2003). Within the sampled stands a large amount of rotten fuels greater than 7.62 cm in diameter was present, indicating this past mortality. Elevations of the selected stands were approximately 2,100 m above sea level with slopes of generally less than 10% and a variety of aspects. The sampled stands were dominated by mature lodgepole pine with an extensive cover of elk sedge (*Carex geyeri* Boott) and an understory dominated by lodgepole pine regeneration. The habitat type selected for these stands was *P. contorta*/*C. geyeri*; however, the two endemic stands did have significant subalpine fir regeneration indicating an *A. lasiocarpa* habitat type (Steele et al. 1981). Both current epidemic stands were located within approximately 4.5 km of each other, but because of the widespread nature of the epidemic, suitable endemic stands were not located until a distance of about 8 km from the epidemic stands. The sizes of the delineated stands averaged approximately 40 ha.

The site in northern Utah was located on the Wasatch-Cache National Forest (Wasatch-Cache NF) in the western Uinta Mountains. The two current epidemic stands were sampled during the summer of 2004, and the two endemic stands were sampled during 2005. The long-term history of the MPB in these stands is unknown, but aerial detection surveys dating from the 1980s do not indicate a widespread epidemic occurring within the sampled stands. The stands also showed little evidence of recent surface fire activity, non-MPB insects, or diseases. Elevations of the selected stands ranged from approximately 2,700 to 2,900 m above sea level with slopes ranging from 10 to 52% occupying eastern to northwestern aspects. The stands were dominated by seral lodgepole pine with a developing understory of subalpine fir and Engelmann spruce and a cover of grouse whortleberry, which was classified as the *A. lasiocarpa*/*V. scoparium* habitat type (Mauk and Henderson 1984). All four sampled stands were located within a maximum distance between stands of about 3 km. The sizes of the selected stands averaged approximately 30 ha.

Quantifying the Fuels Complex

A systematic North–South or East–West grid of variable radius plots was laid out within the delineated stands on US Geological Survey 7.5-min topographic maps. Where possible, 100.6-m spacing between transects and 160.9-m spacing between plots along the transects were used. The spacing of the plots varied to accommodate varying stand shapes, sizes, and other logistical considerations. 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 based on Mauk and Henderson's (1994) and Steele et al.'s (1981) keys to identifying habitat types was determined. Ground and surface fuels were measured using the methods developed by Brown et al. (1982) and Anderson (1974). Specifically, using Brown's (1971) planar intersect method, between three and seven 19.8-m-long transects were laid out from each plot center (Figure 1). 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 on the basis of 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, Brown et al. 1982). On the basis of the suggestions by Brown et al. (1982) for sampling plane distances, each 19.8-m transect had the number of 0- to 0.64-cm (1-h timelag) and 0.64- to 2.54-cm (10-h timelag) diameter fuels tallied from 1.5 to 3.6 m, the number of 2.54- to 7.62-cm (100-h timelag) diameter fuels tallied from

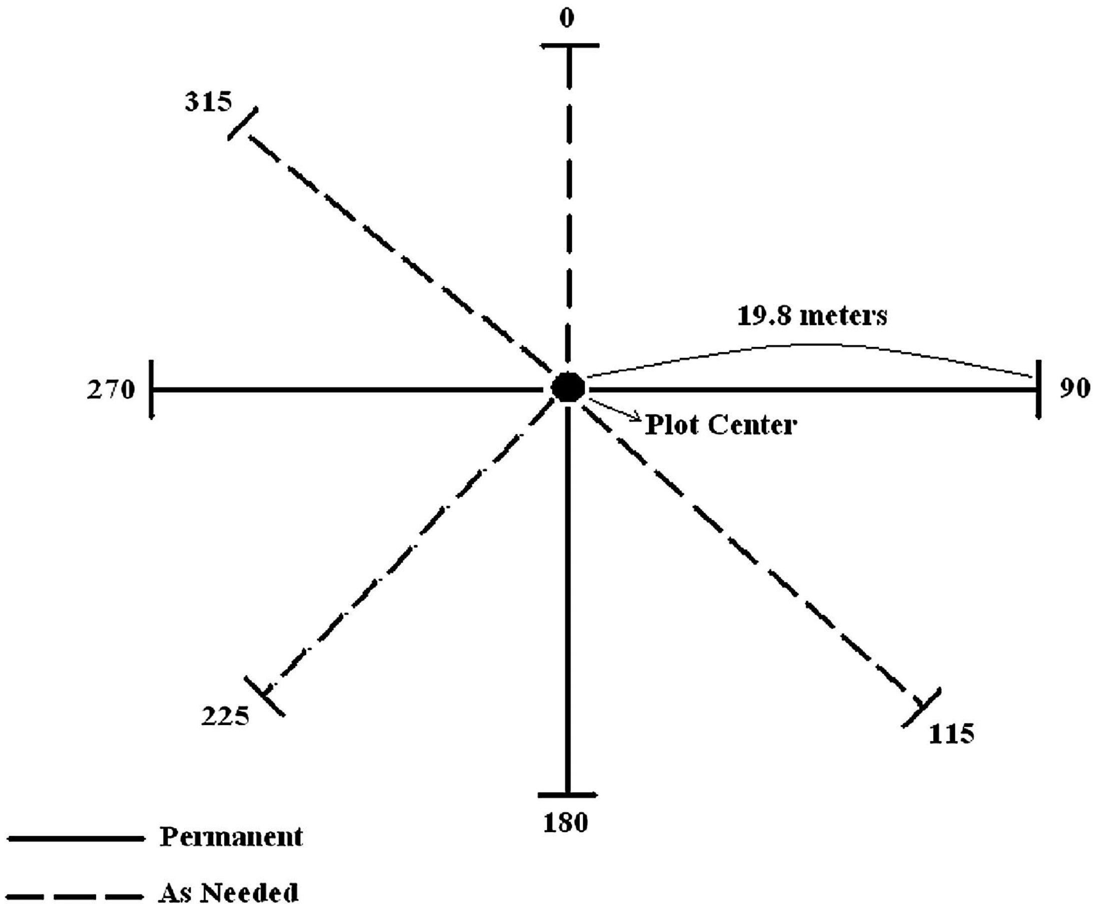

Figure 1. View of the transect layout for each plot. The first three transects were laid out along 90°, 180°, and 270° azimuths with additional transects installed at 0°, 115°, 225°, and 315° until intersections ≥100 pieces.

1.5 to 6.1 m, and those fuels greater than 7.62 cm (1,000-h timelag) in diameter tallied from 1.5 to 19.8 m. In addition, 1,000-h fuels had their respective diameters measured, and a decay class was assigned. Decay classes were broken into five categories that ranged from 1 for recently fallen with bark and needles intact to 5 for completely rotten. Fuel measurements were not made from the beginning of the transect to 1.5 m because of possible trampling of fuels during initial plot setup.

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. To measure the high particle intercept depth an imaginary plane perpendicular to the main transect of 0.3 m in length was used and the height of the highest dead fuel particle less than 7.62 cm in diameter that crossed the plane was measured from the bottom of the litter layer to the top of the fuel particle. The average high particle intercept depth was then 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 marks on each transect using fixed 1.8-m diameter microplots, from 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. Also, within each microplot the numbers of shrub stems by diameter class were tallied by species through measuring the basal stem diameter of each shrub. The diameter classes used for the shrub stem count corresponded to Brown's (1976) basal stem diameter classes 0–0.49, 0.5–1.0, 1.0–1.49, 1.5–1.99, 2–2.99, 3–4.99, and 5–6 cm.

At each plot center aerial fuels and mortality were quantified using a 20 basal area factor measuring device (prism). Each "in" tree's dbh was measured along with condition and crown dominance. There was no minimum diameter limit for in trees in the variable radius plots, but the approximate minimum diameters measured were 5 cm dbh. Tree condition was classified as healthy, unhealthy, recently killed, or older mortality. Unhealthy trees were currently being affected by a mortality agent and were assumed would survive. Recently killed trees were those that were successfully killed by the MPB, not including strip attacks, within the past 4 years, since 2000, and 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. In addition, for each recently killed tree, a year of attack ranging from 0, for current attacks, to 4 was determined along with an estimation of the proportion of the crown remaining on the tree, to the nearest 10%. These crown measurements applied only to the dead needles on the successfully attacked trees to aid in estimating the remaining aerial fuel load in these trees.

Those stands sampled during the summer of 2005 had additional aerial fuel characteristics measured that are important to understanding of the structure of the aerial component of the fuels complex. These additional aerial fuel measurements were only measured on those stands sampled during 2005 and not for the stands sampled during 2004. At each plot a randomly selected live in tree had its total height and crown base height measured. Crown base heights were determined following the descriptions by Scott and Reinhardt (2001), where the crown bases corresponded to the point at which there is enough canopy fuel to carry fire vertically through the crown. Trees were randomly selected by breaking the total number of in trees into equal proportions of time and using a second hand of a watch to determine which tree to measure. Total crown length was then determined, which with available canopy fuel load was used to calculate crown bulk density (Keane et al. 1998). For those stands sampled during the summer of 2004 crown bulk density was determined using equations developed by Cruz et al. (2003) based on average stand basal area and the number of trees per hectare. The equations from Cruz et al. (2003) only incorporate foliage as the available canopy fuel and thus crown bulk density comparisons between the 2004 and 2005 stands were not performed. To estimate crown base height for the current epidemic stands sampled during 2004, the average crown base height from the adjacent endemic stands sampled during 2005 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-h fuels within the crown. Call and Albini (1997) determined that 65% of 1-h fuels in a tree crown would be consumed at 100% moisture content during a crown fire. Therefore, on the basis of Brown's (1978) allometric equations, 65% of the proportion of 1-h fuels in each live tree crown was added to the live crown weight to determine the available canopy fuel load.

The amount of MPB-caused mortality in the current epidemic stands was determined for the Wasatch-Cache NF and Sawtooth NRA by taking the sum of the number of recently attacked trees (since 2000) and older attacked trees (before 2000) divided by the total number of lodgepole pine that were greater than 15.2 cm dbh. The amount of MPB-caused mortality in the postepidemic stands on the Ashley NF was calculated using 8.03-m diameter fixed area plots installed at each plot center. Within each plot, the number of lodgepole pine that survived the epidemic, the number of dead standing, and the number of dead on-the-ground lodgepole pine were tallied for all lodgepole pine that had diameters greater than 15.2 cm and evidence of MPB attack. An on the ground lodgepole pine was tallied if its entire base was within the fixed area plot and the bole had evidence of MPB attack.

The quantity of tree regeneration by species and height class was measured in a 2.1-m diameter fixed area plot from each plot center for trees less than 3.1 m in height, by 0.04-m size classes (Brown et al. 1982). Stand age was determined from the most dominant live in lodgepole pine cored at stump height with the total number of annual rings estimated in the field. The average of all lodgepole pine ages within each stand was used to determine the age of the stand.

To obtain the oven-dry weights of the dead and down woody fuels, duff, litter, and live surface vegetation, the fire effects monitoring and inventory protocol FIREMON, version 2.1.1 (Lutes et al. 2006) was used. FIREMON converted the number of dead fuel particle intersections into oven-dry weights based on the composite values for specific gravity, quadratic mean diameters, and nonhorizontal correction factors from Brown (1974). Shrub and herbaceous weights were determined based on summarized bulk densities from a variety of applicable publications (Duncan Lutes, pers. comm., US Forest Service, Nov. 6, 2006). The total oven-dry weight of aboveground biomass was calculated for tree regeneration, including foliage and all branchwood, using Brown et al.'s (1982) table based on species and height, expanded to a per hectare basis.

Data Analysis

The data collected were analyzed using the software program SAS, version 9.1 (SAS Institute, Inc. 2005). 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 because of the exploratory nature of the study. As reported by others, fuel loading data usually have rightly skewed distributions (Brown and See 1981, Brown and Bevins 1986). Therefore, transformations were applied to the data to meet the assumptions of a normal distribution and equal variances for the t test. Square root and log transformations were used on most of the variables, but the dead fuel loadings for the shrubs and herbaceous fuels across all study sites still had unequal variances. In these cases the Satterthwaite method was used (Zar 1999). The averages, standard deviations, and 95% confidence intervals (CI) were also reported for each fuel category by study area.

Results

Ashley NF

The results of the statistical comparisons between the postepidemic and endemic stands revealed that MPB activity had significantly altered the fuels complex (Figure 2). These changes was due in part to an average of 80% lodgepole pine mortality, with 33% of the MPB-killed trees still standing after 20 years and 67% lying on the ground as of the year 2005 (Table 1). The high level of mortality in overstory lodgepole pine has resulted, over a period of 20 years, in densities of live trees greater than 3.1 m in height of 161 and 1,611 lodgepole pine per hectare ($t = 22.79$, $P = 0.002$) and 563 and 0 subalpine fir per hectare ($t = 22.27$, $P = 0.002$) for the postepidemic and endemic stands, respectively. The high level of mortality has also resulted in

Figure 2. Postepidemic versus endemic stand conditions on the Ashley NF.

Table 1. The average stand structure characteristics for all four sampled stands on the Ashley NF

	n	Average age ± 95% CI (yr)	Average dbh Live PICO	Average dbh PA	Mortality (%)	ACFL (ton/ha)	CBH (m)	CBD (kg/m^3)
			.........(cm)					
PE #1	25	85 ± 14	21.0	27.9	71	10.02*	3.1†	0.1378‡
PE #2	24	106 ± 14	20.6	25.2	89	8.97*	4.2†	0.1185‡
EN #1	24	128 ± 18	22.9	26.1	4	17.57*	6.2†	0.1794‡
EN #2	24	143 ± 23	22.8	32.5	11	22.06*	4.8†	0.1970‡

PE, postepidemic; EN, endemic; PICO, lodgepole pine; PA, past attack (before 2000); ACFL, available canopy fuel load; CBH, crown base height; CBD, crown bulk density. *t*- and *P*-values are used to show significant differences.
* *t*-test: *t*-value = 5.13, $P = 0.04$.
† *t*-test: *t*-value = 4.95, $P = 0.04$.
‡ *t*-test: *t*-value = 4.60, $P = 0.04$.

significantly lower crown base heights, less available canopy fuels, and lower crown bulk densities in the postepidemic stands than in the endemic stands (Table 1).

Detailed analysis of the surface fuels revealed significant differences between dead and down woody fuels and live surface vegetation. Table 2 shows statistically significant increases in the postepidemic stands for dead fuels in the 10-, 100-, and 1,000-h sound sizes classes as well as for fuel bed depth. The average increases were 2.5 times (147%), 2.1 times (112%), and 7.8 times (679%) the loading of the endemic stands for the 10-, 100-, and 1,000-h sound fuels, respectively. There were also statistically significant increases in live shrub loading and average shrub height in the postepidemic stands compared with the endemic stands (Table 3).

Differences in tree regeneration biomass also existed between the postepidemic and endemic stands on the Ashley NF (Table 4). The loading of subalpine fir was significantly more in the postepidemic stands than in the endemic stands, averaging 2.30 metric tons per hectare. Subalpine fir loading made up approximately 95% of the total loading in the postepidemic stands compared with just 11% in the endemic stands. However, total loading, the number for lodgepole pine, and the number for all species were not significantly different at the 0.05 level.

Sawtooth NRA

The results of the statistical comparisons between the current epidemic and endemic stands sampled on the Sawtooth NRA have shown that MPB activity has altered only a portion of the fuels complex. The number of live and healthy lodgepole pine greater than 3.1 m in height was comparable ($t = 2.36$, $P = 0.14$) with an average of 1,435 and 1,075 live lodgepole pine per hectare occurring in the current epidemic and endemic stands, respectively. Mortality of the susceptible lodgepole pine in the current epidemic stands averaged 59% compared with 11% in the endemic stands with approximately 47% of the mortality in the current epidemic stands occurring since 2000 (Table 5). This high level of recent mortality in the current epidemic stands has produced significant amounts of dead foliage in the overstory as of 2004, which was quantified for both the current epidemic and endemic stands (Figure 3). Approximately 30% of the total foliage in the current epidemic stands is dead compared with 1% in the endemic stands.

Surface fuels data from the Sawtooth NRA revealed few statistically significant differences between the current epidemic and endemic stands (Table 6). Fine fuel loadings of the litter and 1-h fuels were the only fuel components that were significantly greater in the current epidemic stands

Table 2. The characteristics of down woody debris for the sampled size classes on the Ashley NF

	Average	SD ± 95% CI	df	*t*-value	$P > t$
1 h					
PE	1.19	0.37 ± 0.15	2	3.00	0.10
EN	0.72	0.24 ± 0.10			
10 h					
PE	4.47	2.26 ± 0.90	2	6.09	0.03*
EN	1.81	0.97 ± 0.39			
100 h					
PE	8.75	4.70 ± 1.87	2	4.58	0.05*
EN	4.13	2.41 ± 0.97			
1,000-h sound					
PE	83.65	40.18 ± 15.89	2	12.36	0.01*
EN	10.74	9.59 ± 3.84			
1,000-h rotten					
PE	18.18	11.14 ± 4.41	2	3.66	0.07
EN	43.33	23.72 ± 9.48			
Duff					
PE	28.25	10.45 ± 4.14	2	0.62	0.60
EN	30.77	9.18 ± 3.67			
Litter					
PE	3.68	1.14 ± 0.45	2	0.28	0.80
EN	3.77	1.09 ± 0.44			
Fuel bed depth (cm)†					
PE	12.16	8.35 ± 3.30	2	21.60	0.002*
EN	3.49	2.66 ± 1.06			

PE, postepidemic; EN, endemic. All numbers except fuel bed depth are reported as metric tons per hectare.
* Significant at the 0.05 level.
† Fuel bed depth indicates only the depth of the dead and down woody fuels.

Table 3. The live/dead shrub and herbaceous characteristics for the stands sampled on the Ashley NF

	Shrubs				Herbaceous			
	Live				Live			
	Cover (%)	Height (m)	Oven-dry weight (ton/ha)	Dead: oven-dry weight (ton/ha)	Cover (%)	Height (m)	Cover (%)	Dead: oven-dry weight (ton/ha)
PE	18	0.10	1.24	0.09	7	0.09	0.47	0.14
EN	9	0.07	0.58	0.01	13	0.09	0.63	0.14
t-test*	2/3.54/0.07	2/4.55/0.05†	2/28.72/0.001†	1.04/0.57/0.67‡	2/2.79/0.11	2/0.02/0.98	2/2.92/0.10	2/0.05/0.97

PE, postepidemic; EN, endemic.
* *t*-tests are of the form: degrees of freedom/*t*-value/$P > t$.
† Significant at the 0.05 level.
‡ The Satterthwaite method was used because of unequal variances.

Table 4. The live tree regeneration characteristics for the postepidemic and endemic stands on the Ashley NF

							$P > t$		
	Species	Stems/ha	Average height (m)	Oven-dry weight*	df	*t*-value stems	Oven-dry weight	Stems	Oven-dry weight
PE	ABLA	7,129	0.66	2.30					
EN		334	0.62	0.07	2	2.52	100.05	0.13	<0.001†
PE	PICO	854	0.61	0.11					
EN		597	1.26	0.33	2	0.30	0.85	0.79	0.49
PE	Total‡	8,309	0.65	2.41					
EN		1,122	1.03	0.63	2	2.66	3.19	0.12	0.09

PE, postepidemic; EN, endemic; ABLA, subalpine fir; PICO, lodgepole pine.
* Oven-dry weight, loading in metric tons per hectare.
† Significant at the 0.05 level.
‡ Total, total live regeneration for all species.

than in the endemic stands. The largest increase observed was for the loading of litter with an average of 6.82 metric tons per hectare in the current epidemic stands, which was about 2.2 times or 123% greater than the loading in the endemic stands. The loading of 1-h fuels in the current epidemic stands was about 1.4 times or 36% greater than the

Table 5. The average stand structure characteristics for all four stands sampled on the Sawtooth NRA

	n	Average age ± 95% CI (yr)	Average dbh Live PICO	RA	PA	Mortality RA	PA	ACFL (ton/ha)	CBH (m)	CBD (kg/m^3)
			...............(cm)...............			......(%)......				
EP #1	15	110 ± 16	17.1	24.5	23.4	48	7	9.42	8.0*	0.2090†
EP #2	22	129 ± 18	16.5	25.8	36.1	46	17	8.77	8.0*	0.1898†
EN #1	16	110 ± 15	19.3	29.1	26.3	8	5	10.94	6.9	0.1073
EN #2	22	95 ± 7	21.5	36.5	24.9	8	1	13.9	9.1	0.1442

EP, current epidemic; EN, endemic. PICO, lodgepole pine; RA, recent attack (2000–2004); PA, past attack (before 2000); ACFL, available canopy fuel load (live fuel); CBH, crown base height; CBD, canopy bulk density (live fuel). Crown data are only for live fuels.
* Average from the two endemic stands.
† These data were calculated from Cruz et al. (2003)

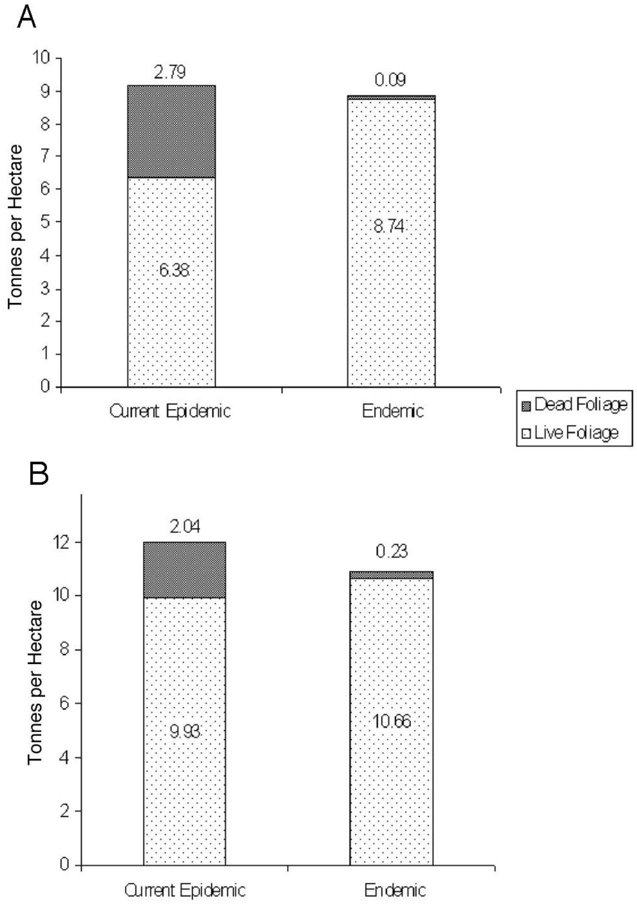

Figure 3. Average amount of live versus dead foliage, in metric tons per hectare, for the current epidemic and endemic stands in the Sawtooth NRA (a) and Wasatch-Cache NF (b).

Table 6. The characteristics of down woody debris for the sampled size classes on the Sawtooth NRA

	Average	SD ± 95% CI	df	t-value	$P > t$
1 h					
EP	1.16	0.27 ± 0.12	2	7.90	0.02*
EN	0.85	0.27 ± 0.13			
10 h					
EP	2.22	1.14 ± 0.51	2	1.19	0.36
EN	2.45	1.13 ± 0.51			
100 h					
EP	3.73	1.94 ± 0.91	2	1.47	0.28
EN	6.76	5.44 ± 2.41			
1,000-h sound					
EP	11.80	10.17 ± 4.63	2	0.58	0.62
EN	11.16	9.97 ± 4.49			
1,000-h rotten					
EP	23.93	15.62 ± 7.12	2	1.70	0.23
EN	17.90	25.17 ± 11.68			
Duff					
EP	31.22	13.23 ± 6.04	2	0.63	0.59
EN	28.24	12.16 ± 5.44			
Litter					
EP	6.82	1.61 ± 0.73	2	7.11	0.02*
EN	3.06	0.61 ± 0.28			
Fuel bed depth (cm)†					
EP	3.26	2.08 ± 1.00	2	0.90	0.46
EN	3.47	1.85 ± 0.84			

EP, current epidemic; EN, endemic. All numbers except fuel bed depth are reported as metric tons per hectare.
* Significant at the 0.05 level.
† Fuel bed depth is only the depth of dead and down woody fuels.

loading in the endemic stands. There were no other statistically significant differences in any other fuels including vegetation and regeneration between the current epidemic and endemic stands.

Wasatch-Cache NF

The results of the statistical comparisons between the current epidemic and endemic stands showed that MPB activity has not significantly altered stand structure, live tree densities, or live canopy fuel characteristics (Table 7). Live tree densities greater than 3.1 m in height averaged 872 and 631 live lodgepole pine per hectare ($t = 0.70$, $P = 0.56$) in the current epidemic and endemic stands, respectively. The level of mortality was significantly different, with the current epidemic stands averaging 52% and the endemic stands averaging only 7% (Table 7). This increase in mortality is also reflected in the amount of dead foliage as of 2004 in the overstory, making up approximately 17% of the total foliage in the current epidemic stands and 2% in the endemic stands (Figure 3).

Dead and down woody fuels for the current epidemic stands are reported in Table 8. The only statistically significant differences that occurred were for the fine fuel loadings, litter and 1 h, with nearly significant differences for the loading of 100-h fuels. The largest increase was from the 1-h fuels with an average of 1.10 metric tons per hectare in the current epidemic stands, which was approximately 2.1 times or 112% greater than the loading in the endemic stands. The litter loading in the current epidemic stands increased by an average of 1.8 times or 79% greater than the

Table 7. The average stand structure characteristics for all four stands sampled on the Wasatch-Cache NF

	n	Average age ± 95% CI (yr)	Average dbh			Mortality		ACFL (ton/ha)	CBH (m)	CBD (kg/m^3)
			Live PICO	RA	PA	RA	PA			
			...............(cm)..............			......(%)......				
EP #1	23	92 ± 8	18.8	24.8	17.2	40	8	14.44	3.9*	0.2206†
EP #2	14	80 ± 8	19.2	23.7	22.0	42	13	13.05	3.9*	0.1528†
EN #1	24	106 ± 19	21.7	29.1	18.0	6	3	15.47	3.6	0.1426
EN #2	22	90 ± 9	22.1	24.9	33.8	3	2	14.37	4.2	0.1410

EP, current epidemic; EN, endemic; PICO, lodgepole pine; RA, recent attack (2000–2004); PA, past attack (before 2000); ACFL, available canopy fuel load (live fuel); CBH, crown base height; CBD, crown bulk density (live fuel). Crown data are only for live fuels
* Average from the two endemic stands.
† These data were calculated from Cruz et al. (2003).

Table 8. The characteristics of down woody debris for the sampled size classes on the Wasatch-Cache NF

	Average	SD 95% CI	df	*t*-value	$P > t$
1 h					
EP	1.10	0.41 ± 0.39	2	7.00	0.02*
EN	0.52	0.27 ± 0.11			
10 h					
EP	2.89	1.81 ± 0.86	2	0.82	0.50
EN	3.06	1.65 ± 0.67			
100 hour					
EP	2.90	2.45 ± 1.14	2	3.77	0.06
EN	3.91	2.32 ± 0.95			
1,000 h sound					
EP	11.63	10.27 ± 4.62	2	2.01	0.18
EN	5.60	5.50 ± 2.24			
1,000-h Rotten					
EP	17.74	19.36 ± 8.99	2	0.91	0.46
EN	25.77	17.58 ± 7.13			
Duff					
EP	32.20	15.77 ± 7.41	2	0.62	0.60
EN	28.08	12.03 ± 4.90			
Litter					
EP	5.18	1.54 ± 0.69	2	6.71	0.02*
EN	2.90	0.69 ± 0.28			
Fuel bed depth (cm)†					
EP	1.48	1.42 ± 0.64	2	1.99	0.19
EN	2.25	1.40 ± 0.57			

EP, current epidemic; EN, endemic. All numbers except fuel bed depth are reported as metric tons per hectare.
* Significant at the 0.05 level.
† Fuel bed depth is only the depth of the dead and down woody fuels.

loading in the endemic stands. All other fuel categories, including vegetation and regeneration, failed to show any statistically significant differences.

Discussion

MPB activity in the selected postepidemic and current epidemic lodgepole pine stands has resulted in significant alterations to the fuels complexes. In the postepidemic stands, the high levels of mortality produced dramatic increases in dead and down woody fuels in all but the smallest size classes, with the largest increase occurring in the 1,000-h sound size class. These results are consistent with other studies, which have shown similar increases in the amounts of large woody fuels after MPB epidemics (Armour 1982, Romme et al. 1986). These heavy accumulations of large-diameter fuels are important because they can promote long-term smoldering and slow-spreading surface fires, allowing fires to sustain themselves until conditions are more favorable for active burning, and they can increase potential severity by raising total heat release and increasing duration of burning (Davis et al. 1980, Smith and Fischer 1997). Additionally, large-diameter fuels can provide a vector for fire movement when fuel moisture conditions prohibit the spread by fine fuels (Agee 1993). Live shrubs and total live understory fuels in the postepidemic stands were also significantly greater in the 20-year postepidemic MPB stands. This agrees with previous work by Stone and Wolfe (1996), who also found increases in total understory biomass in postepidemic MPB stands. Although the specific reasons for this increase in live shrub biomass is unknown, other research suggests that the loss of the overstory results in moister duff and mineral soil layers (Hélie et al. 2005). This, in combination with increased light levels, could explain the increased growth of shrubs observed in the postepidemic stands.

In the current epidemic stands, the surface fuels remained relatively unchanged. The only significant differences observed were for the loadings of the litter and 1-h fuels. These increases can be linked to the contribution of the dead needles and small branches from the recently killed lodgepole pine trees. Over time, these small fuels break apart from the main tree because of deterioration and breakage from wind, and accumulate on the forest floor. Accumulations of these small fuels have important implications on surface fire behavior because of their high surface area to volume ratios and ability to increase surface fire rates of spread and fire line intensities (Burgan 1987). However, results from the postepidemic stands indicate that over time these small fuels decay sufficiently so that the differences return to background levels at least after 20 years, which may result in a decreasing surface fire rate of spread.

Regeneration was also another fuel component that showed statistically significant differences. The increase in the total amount of regeneration in the postepidemic stands can lower the effective crown base height of the stand, thereby influencing crown fire initiation (Van Wagner 1977). There was also a significant increase in the amount of subalpine fir loading in the postepidemic stands compared with lodgepole pine regeneration. This high level of subalpine fir regeneration in conjunction with the removal of the majority of the overstory lodgepole pine component reinforces the concept of successional advancement caused by the MPB (Amman 1977). The habitat type classified for these stands was *A. lasiocarpa/V. scoparium*; thus, the postepidemic stands appear to be moving toward their predicted climax of subalpine fir and will continue to advance until the next stand-replacing disturbance (Mauk and Henderson 1984, Bradley et al. 1992). The timing of the increase in subalpine fir regeneration is unknown as regeneration ages were not sampled.

The amount and composition of aerial fuels in both the postepidemic and current epidemic stands were significantly different from those for their associated endemic stands. In the postepidemic stands, the high mortality and discontinuous overstory resulted in significantly lower available canopy fuels, crown base heights, and crown bulk densities. The decrease in crown base heights can be attributed in part to a shift in species composition to subalpine fir and the previously mentioned increase in regeneration. Subalpine fir branches and foliage tend to remain on the trees for longer periods of time and remain closer to the forest floor than pine species because of the ability of the foliage to tolerate lower light levels (Alexander 1987). The decreases in available canopy fuel and associated crown bulk density indicate that the mortality in the dominant overstory lodgepole pine has removed significant amounts of fuel from the canopies of these stands. These decreases in aerial fuel continuity can increase the amount of solar radiation on surface fuels and alter the wind profile within stands, which in turn can alter surface fuel moistures and the relative speed of the wind reaching the forest floor (Albini and Baughman 1979, Knight 1987, Whitehead et al. 2006). Although regeneration is increasing in the postepidemic stands, the increase in surface wind and solar radiation should occur until the regeneration matures and reaches crown closure, which may take decades, depending on species and site quality.

In the current epidemic stands, the high mortality also resulted in large amounts of dead foliage in the overstories of the sampled stands. These dead needles slowly fall off the trees over a period of about 4 years after the tree was successfully attacked. The high amounts of dead needles should be present in the current epidemic stands for approximately 5 years past the peak mortality year, but because the epidemics tend to span several years there may be an extended window in which dead foliage is present in the stands. Although the dead fuels remain in the majority of tree crowns, they should have important implications for crown fire initiation because of lower fuel moistures and decreased times to ignition (Van Wagner 1977).

Conclusion

In this study we attempted to quantify and compare fuels complexes of lodgepole pine stands affected by the MPB during current epidemics and 20 years after an epidemic. Three separate study sites were evaluated, with each site representing separate assessments of the effects of the MPB. We found that during the course of a MPB epidemic the fuels complexes of lodgepole pine stands undergo significant and in some cases drastic changes. Initially in stands with significant recent mortality, buildup of the fine fuels occurs. Over time, woody surface fuel loadings continue to increase with time since the MPB mortality, with the large size classes of woody fuels increasing until they dominate the fuels complex. During the period when dead and down woody fuels increase, live shrubs respond to the changes in the stands, eventually becoming significant components in the postepidemic stands. Along with these biological changes important physical changes take place within affected stands that can alter the amount of solar radiation on surface fuels and the relative amount of wind reaching the forest floor. These changes to the fuels complex will have important implications for potential fire hazards. Although the results presented here reaffirm long-held beliefs of MPB mortality and fuel buildup, it should be recognized that these changes probably occur naturally within lodgepole pine forests at the stand scale. Large-scale and intense MPB epidemics have been documented in lodgepole pine forests before extensive manipulation of these forests by man (Hopkins 1909); thus, the resulting buildup of dead fuels from these epidemics has also occurred for an equally long period of time. However, recent research suggests that in British Columbia, Canada, the current spatial extent of mature lodgepole pine across landscapes is higher than what occurred before influence by man, which may result in higher than historic fuel loads where MPB epidemics occur, at the landscape scale (Taylor and Carroll 2003, Taylor et al. 2006). The results of this study are a first attempt to quantify natural fuels of the entire fuels complex in MPB-affected lodgepole pine stands. We have demonstrated several useful relationships between the MPB and total fuel loading; however, because of the variable nature of fuels accumulation and the site-specific variation encountered, the comparability of our results with other areas is limited. The general relationships we detected should prove to be useful to fire and fuels professionals dealing with similar stand conditions.

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