

## INTRODUCTION

Landscape-scale bark beetle outbreaks have occurred throughout the Western United States during recent years in response to dense forest conditions, climatic conditions, and wildfire (Fettig and others 2007, Bentz and others 2010). Previous studies, mostly conducted in moist forest types (such as lodgepole pine [*Pinus contorta*]) suggest that bark beetle outbreaks alter stand structural attributes and fuel profiles, and thus affect potential fire hazard (Jenkins and others 2008), where hazard is defined as the ease of ignition and resistance to control (Hardy 2005). A number of factors influence postoutbreak fire hazard, including the time since mortality and the proportion of trees killed (Hicke and others 2012, Hoffman and others 2013). In the first few years following tree mortality, canopy fuels are expected to decrease as needles fall to the ground. Lower canopy fuels are assumed to decrease the potential for crown fire spread but allow for greater wind penetration into the stand. Surface fuel accumulation, first from needles and eventually from larger woody fuels, can increase the probability of surface fires transitioning to crowns. There is also a concern that accumulation of heavy woody fuels as dead trees fall to the ground can lead to accumulations above recommended amounts for both fireline construction and for sustaining ecosystem services such as soil protection and wildlife habitat (Brown and others 2003). In some forest types, postoutbreak logging (salvage)

of dead trees has been used to recuperate the value of the trees and to potentially reduce fire hazard and enhance forest recovery (Collins and others 2011, Fettig and others 2007). Yet, how postoutbreak logging alters fuel complexes, tree regeneration, and subsequent fire behavior is largely understudied, especially for drier forest types such as those dominated by ponderosa pine (*P. ponderosa*) or Douglas-fir (*Pseudotsuga menziesii*).

Forest Health Monitoring aerial detection surveys (ADS) documented more than 150,000 acres of ponderosa pine forest impacted by mountain pine beetle (*Dendroctonus ponderosae*) in the Black Hills National Forest between 2002 and 2008. Douglas-fir beetle (*D. pseudotsugae*) outbreaks have been detected by ADS in both the Shoshone National Forest (120,000 acres) and Bighorn National Forest (10,000 acres) during the same period. The objectives of this project were to (1) quantify fuels in forest stands with (a) high levels of bark beetle-caused ponderosa pine or Douglas-fir mortality, (b) high tree mortality followed by logging that removed dead trees, and (c) no tree mortality; and (2) model fire behavior in these stands under severe weather scenarios. To accomplish these objectives, we established 60 plots in ponderosa pine stands in the Black Hills National Forest in 2007 and an additional 75 plots in Douglas-fir stands in 2010: 30 in the Bighorn National Forest and 45 in the Shoshone National Forest. We have sampled all 135 plots since either 2009 or 2010 to quantify changes in the fuel

## CHAPTER 12.

### Bark Beetle Outbreaks in Ponderosa Pine Forests: Implications for Fuels, Fire, and Management (Project INT-F-09-01)

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complexes through time. This chapter presents data collected in the Black Hills National Forest 2 years after tree mortality following a mountain pine beetle outbreak, and it contrasts fuel complexes in ponderosa pine stands with and without mortality and in logged mortality stands. Our aim here is to characterize canopy fuel loadings relative to preoutbreak levels, tally surface woody fuel loadings, and simulate two fire behavior metrics in these stand types. This baseline information is critical to addressing our ultimate question about how fuel complexes in these forest types change through time with and without postmortality logging.

## METHODS

The data presented here were collected on 60 plots we established in 2007 on the Black Hills National Forest and sampled in 2009. At the time we established the plots, infested trees were green. We established 15 0.05-acre plots in each of four treatments in ponderosa pine stands. The four treatments included (1) bark beetle-caused mortality, (2) bark beetle-caused mortality with logging leaving moderate postlogging basal area (24 to 72 square feet per acre), (3) bark beetle-caused mortality with logging leaving low basal area (3 to 24 square feet per acre), and (4) no bark beetle-caused mortality controls. In mortality/logged plots, trees killed by bark beetles were removed by whole-tree harvesting in the winter of 2007–08, and nonmerchantable portions of harvested trees were removed offsite.

We quantified stand structure attributes by measuring the diameter at breast height (d.b.h.; measured at 4.5 feet height) for trees greater than 2 inches d.b.h., height, and lowest live branch of each tree, and recorded whether it was alive or dead. We measured stump diameters for recently cut trees in mortality/ logged treatments. We calculated basal area and tree density and estimated canopy base height as the average of the lowest live branch heights for each plot. We reconstructed preoutbreak basal area and tree density by including trees killed by the bark beetles into totals. For logged stands, we converted stump diameters into d.b.h. based on locally derived algorithms from 130 trees we measured on the study site. Using stand level average basal area, tree density, and tree height, we estimated canopy fuel loading and canopy bulk density for each treatment and for preoutbreak conditions using equations from Cruz and others (2003).

We tallied surface fuels along two 50-foot transects per plot by time-lag size diameter classes following Brown's (1974) protocols. Size diameter classes included 1-hour (< 0.25 inches), 10-hour (0.25 to 1.00 inches), 100-hour (1.10 to 3.00 inches), and 1,000-hour (> 3 inches) fuels. We tallied 1- and 10-hour fuel classes along 12 feet of each transect (0 to 6 and 44 to 50 feet), 100-hour fuels along 24 feet per transect (0 to 12 and 38 to 50 feet), and 1,000-hour fuels along the entire length of each transect. In addition, we classified 1,000-hour fuels as either sound or rotten. Woody

fuel loading by size classes on each plot was calculated using Brown's (1974) algorithms. Total coarse woody debris (CWD) was calculated as the sum of sound and rotten 1,000-hour fuels, and total woody fuel load was the sum of loadings in all size classes.

We used NEXUS (Scott 1999) to simulate two fire behavior metrics for each treatment: torching index, or the wind speed at which a surface fire is expected to transition into the canopy, and crowning index, or the wind speed at which active crowning is possible (Scott and Reinhardt 2001). Given that total surface fuel loadings averaged less than 10 tons per acre on all treatments, we represented the surface fuels as a fuel model 9 (Anderson 1982) for all simulations. Dead fuel moisture contents were set at 3, 4, and 5 percent respectively for 1-, 10- and 100-hour fuel time lag size classes. Given that considerable differences existed in posttreatment tree densities, we altered the wind reduction factor across treatments to account for greater wind penetration into stands with fewer trees. We used a wind reduction factor of 0.1, which reduces the 20-foot wind speed by 90 percent for no-mortality stands, and factors of 0.2, 0.3, and 0.4 (or wind reductions of 80, 70, and 60 percent, respectively) for the mortality only, mortality/logged moderate basal area, and mortality/logged low basal area treatments, respectively.

## RESULTS

Ponderosa pine stands in the Black Hills National Forest averaged between 164 and 325 trees per acre, with basal areas between 129 and 174 square feet per acre before the mountain pine beetle outbreak. Stands were 100 percent dominated by ponderosa pine trees, which averaged 11 to 12 inches d.b.h. and 48 to 65 feet tall. Comparing postmortality stand structure with reconstructed preoutbreak levels, basal area was reduced 71 percent and tree density 41 percent in bark beetle mortality plots without logging. Mountain pine beetle-caused mortality and postoutbreak logging reduced the basal area 74 percent (to 37.7 square feet per acre) in moderate residual basal area plots and 89 percent (to 14.6 square feet per acre) in low residual basal area plots. Snag density was highly variable among the treatments and mostly the result of recent bark beetle-induced tree mortality. Snag density averaged 28 snags per acre on no-mortality plots compared with 191 per acre on mortality plots without logging. Logged plots had very low snag densities, averaging less than 6 snags per acre across all plots.

Canopy base height averaged 27.9 feet in no-mortality plots. After the bark beetle-caused mortality occurred, canopy base height averaged 23.67 feet in unlogged plots and averaged 24.40 and 20.95 feet in moderate and low residual basal area logged plots, respectively. Compared

with preoutbreak levels, average canopy fuel loading was reduced 66.8 percent in mortality plots without logging, 71.6 percent in mortality/logged moderate residual basal area plots, and 86.0 percent in mortality/logged low-residual basal area plots.

Total woody surface fuel loadings averaged between 5.1 and 9.3 tons per acre on the four treatments (fig. 12.1A). CWD, or woody material greater than 3 inches in diameter, ranged from an average of 2.6 tons per acre on no-mortality plots to 5.1 tons per acre on moderate residual basal area logged plots (fig. 12.1B), and in all plot types was dominated by rotten material.

Fire behavior simulations predicted that crowning index increased with decreasing stand density (fig. 12.2A). That is, the simulations indicated that crowning would occur in no-mortality stands under lower wind speeds compared with stands with bark beetle mortality and that even higher wind speeds were required for crowning to occur in mortality/logged stands. Torching indices showed the opposite trend (fig. 12.2B), where higher wind speeds were required for torching to occur in no-mortality stands, and lower wind speeds in the more open mortality and mortality/logged stands.

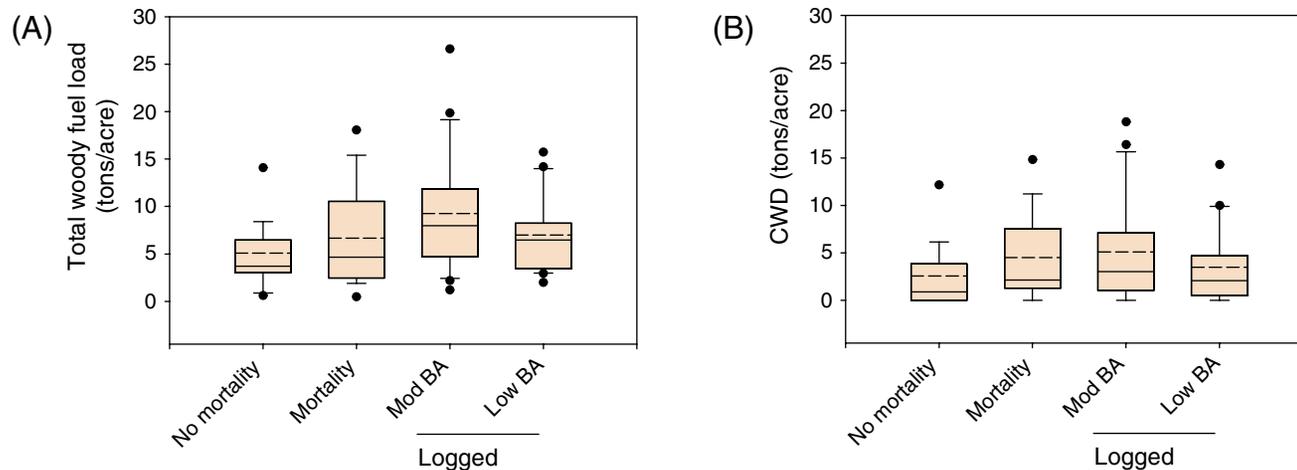


Figure 12.1—Total woody surface fuel loading (A) and coarse woody debris (B) for no-mortality stands, unlogged mortality stands, mortality/logged stands with moderate postlogging residual basal areas, and mortality/logged stands with low residual basal areas. Boxes indicate 25<sup>th</sup> and 75<sup>th</sup> percentiles with medians (solid line), whiskers above and below boxes show 90<sup>th</sup> and 10<sup>th</sup> percentiles, and dots indicate outliers.

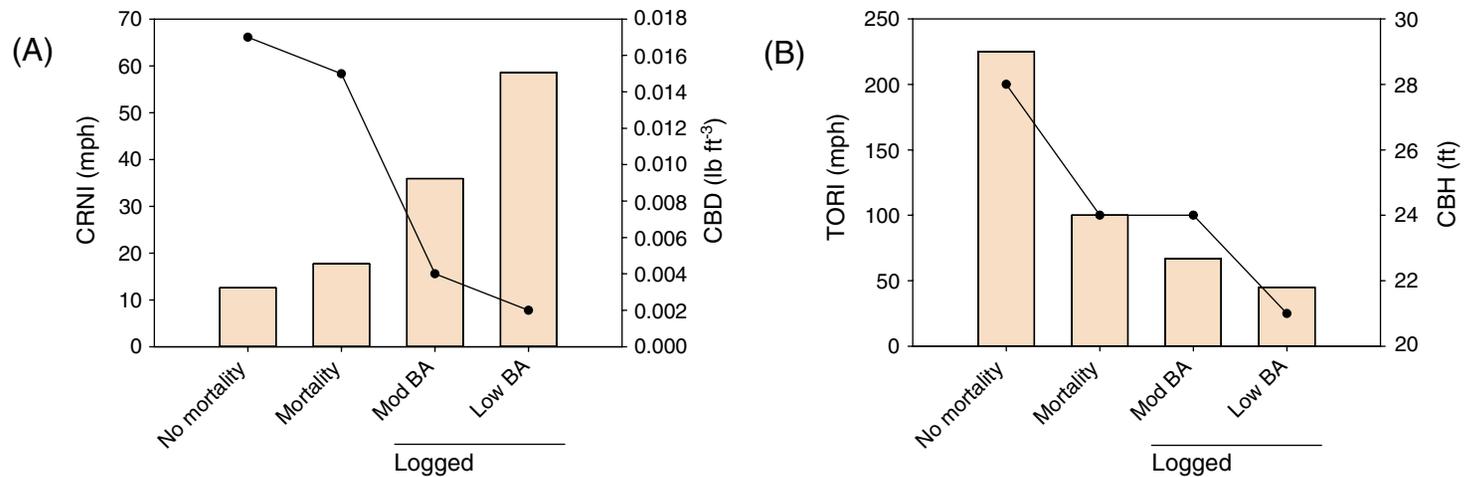


Figure 12.2—(A) Crowning index (bars; CRNI; left axis) and canopy bulk density (dots; CBD; right axis), and (B) torching index (bars; TORI; left axis) and canopy base height (dots; CBH; right axis) for no-mortality stands, unlogged mortality stands, mortality/logged stands with moderate postlogging residual basal areas, and mortality/ logged stands with low residual basal areas stands. Fuel models were held constant (model 9) and wind reduction factor was 0.1, 0.2, 0.3, 0.4, respectively, for the four treatments.

## DISCUSSION

Bark beetles alone and in combination with postoutbreak logging greatly reduced overly dense stands of ponderosa pine in the Black Hills National Forest. Preoutbreak basal areas in many plots were above 120 square feet per acre, thus making them highly favorable for mountain pine beetle infestations (Schmid and others 1994). High levels of tree mortality resulted in stands with lower canopy fuel loading, similar to trends following bark beetle tree mortality in ponderosa pine forests in the Southwest (Hoffman and others 2012) and lodgepole pine forests in Yellowstone National Park (Simard and others 2011). Another consequence of the

tree mortality was a trend of lower canopy base height in mortality plots compared with no-mortality plots, which we attributed to higher mortality of larger trees, leaving smaller trees with crowns closer to the ground.

Total surface woody fuel loadings were relatively similar among stand types. The generally low input of woody material on logged plots was a reflection of the harvesting technique used. Trees were whole-tree harvested when the needles were still green and limbed at landings adjacent to the plots. It is also interesting to note that only 5 (out of 60) plots across all treatments had CWD loadings within recommended ranges (10 to 20 tons per acre) for

dry coniferous forests (Brown and others 2003). The remainder, or nearly 90 percent of the plots, had CWD loadings below recommended ranges. As remaining snags fall to the ground in the future in unlogged mortality plots, target levels of CWD will likely be reached, and perhaps exceeded. In a previous study in the Southwest, 20 percent of ponderosa pine stands killed by both *Ips* and *Dendroctonus* beetles had CWD loadings above recommended levels 5 years after outbreak (Hoffman and others 2012). In our unlogged stands, the large number of dead trees will likely fall within 7 to 10 years, as Schmid and others (1985) found in Colorado. Additional contributions of large woody fuels as well as inputs of smaller twigs and needles will likely raise concerns about increasing surface fuels in the future.

Fire simulations based on fuel complexes 2 years after bark beetle-caused tree mortality suggest that changes in canopy fuels and canopy base heights led to altered fire behavior attributes. Dense no-mortality stands with high canopy fuel loading were predicted to require less wind for crowning to occur, followed by mortality stands and then logged stands. In contrast, due to lower wind penetration and slightly higher canopy base heights, greater wind speeds were predicted to be needed for torching to occur in no-mortality stands. The gradient of increasing wind penetration and decreasing canopy base heights across mortality, mortality/ logged moderate basal area, and mortality/

logged low basal area plots corresponded to torching predicted to occur at decreasing wind speeds along this gradient.

In summary, 2 years after mountain pine beetle-caused mortality in ponderosa pine stands in the Black Hills National Forest, the major impact on the fuel complex was the loss of at least two-thirds of the basal area and canopy bulk density compared with preoutbreak levels. Removal of the dead trees by logging reduced the basal area and canopy bulk density by an additional 3 to 20 percent. Woody surface fuel loadings in the majority of plots, regardless of treatment, were below recommended ranges for these dry coniferous forests. Fire behavior simulations suggest that stands without bark beetle-caused mortality would require less wind to carry crown fires, whereas the more open stands with mortality, and especially following logging, were less vulnerable to crown fire. Surface fires were predicted to transition into the canopies under lower wind speeds in more open stands after bark beetle mortality, however, due to lower canopy base heights. By continuing to monitor these plots through time, we will be able to test how fuel accumulation patterns through time align with various conceptual models such as Hicke and others (2012). As remaining snags fall in unlogged stands, and seedlings and other vegetation establish in all mortality plots, concerns about fuel continuity and increased potential for fire spread will likely be heightened.

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