CHAPTER 12.

Forest Fuels and Predicted Fire Behavior in the First 5 Years after a Bark Beetle Outbreak With and Without Timber Harvest

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INTRODUCTION

Unprecedented levels of tree mortality from native bark beetle species have occurred in a variety of forest types in Western United States and Canada in recent decades in response to beetle-favorable forest and climatic conditions (Bentz 2009, Meddens and others 2012). Previous studies suggest that bark beetle outbreaks alter stand structural attributes and fuel profiles, and thus affect the fire environment and potential fire hazard (Jenkins and others 2008, 2014). A number of factors influence post-outbreak fire hazard, including the time since mortality, the proportion of trees killed, and the spatial pattern of dead trees (Hicke and others 2012; Hoffman and others 2012a, 2015; Linn and others 2013; Simard and others 2011). There is also a concern that accumulation of heavy woody fuels as dead trees fall to the ground can lead to large surface fuel loads that are higher than the recommended amounts for fireline construction, fire intensity, and sustaining ecosystem services such as soil protection and wildlife habitat (Brown and others 2003). In some forest types, post-outbreak 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, 2012). Recent studies have explored post-outbreak stand structure, surface fuels, snag retention rates, and predicted fire behavior in ponderosa pine *(Pinus ponderosa)* forests (Chambers and Mast 2014, Hansen and others 2015, Hoffman and others 2012b), but the effects of post-outbreak timber harvest are largely unstudied in this drier forest type.

Forest Health Protection (FHP) national Insect and Disease Detection Survey (IDS) documented 416,000 acres of ponderosa pine forest impacted by mountain pine beetle (*Dendroctonus ponderosae*) in the Black Hills National Forest (NF) between 1996 and 2012 (Harris 2013). The objectives of this project were to quantify changes in stand structure, fuel loading, and predicted fire behavior during the first 5 years following high levels of bark beetle-caused mortality in stands with and without post-mortality timber harvest that removed the dead trees.

METHODS

We established 47 plots in 2007 in beetle-infested ponderosa pine stands on the Black Hills NF and sampled them in 2009 and 2012. Fifteen 0.05-acre plots were left untreated (“mortality-only”) and 32 plots were timber-harvested (“mortality/TH”). In mortality/TH plots, trees killed by bark beetles were removed by whole-tree harvesting in the winter 2007/2008, and nonmerchantable portions of harvested trees were removed offsite. At the time the plots were established, infested trees still had green foliage.

We quantified stand structure attributes by measuring the diameter at breast height (d.b.h., measured at 4.5 feet height) for trees > 2 inches d.b.h. and the height of the lowest live branch of each tree, and recorded whether the tree was alive or dead. We measured stump diameters for recently cut trees in mortality/TH treatments. We calculated basal area and tree density and estimated canopy base height (CBH) as the average of the lowest live branch heights for each plot. We reconstructed pre-outbreak 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. measures based on locally derived algorithms from 130 trees we measured on the study site.

We tallied surface fuels along two 50-foot planar transects centered on each plot center by time-lag size diameter classes following Brown's (1974) protocols. Size diameter classes included: 1-hour (< 0.25 inches), 10-hour (0.25–1 inch), 100-hour (1.1–3 inches) and 1000-hour (> 3 inches). We tallied 1- and 10-hour fuel classes along the distal 6 feet of each transect end, 100-hour fuels along the distal 12 feet per transect end, and 1000-hour fuels along the entire length of each transect. We classified 1000-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; material > 3 inches diameter) was the sum of sound and rotten 1000-hour fuels; total woody fuel load was the sum of loadings in all size classes.

We analyzed changes in overstory and surface fuels response variables through time using generalized linear mixed models (PROC GLIMMIX; SAS Institute 2014) with log-link functions and unstructured covariance specifications for the residuals, with plot as the random effect, repeated measure subject. We used dead tree density as a covariate to control for differing levels of tree mortality and compared means using Tukey's multiple range tests (Holm 1979).

We used the Crown Fire Initiation and Spread (CFIS) model (Cruz and others 2004) to predict the probability of crown fire initiation across a range of wind speeds. CFIS predicts crown fire probability (both passive and active) based on 10-m open wind speed, CBH, fine dead fuel moisture content, and surface fuel consumption. In addition to probability of crown fire initiation, CFIS also classifies fires as either "surface" or "crown fire" and differentiates crown fires as either "passive," which burn the crowns of individual trees or small groups of trees (also called "torching"), or "active," which burn continuously through the fuels complex (Scott and Reinhardt 2001). We estimated canopy bulk density (CBD) using equations from Cruz and Alexander (2003); CBD affects the estimation of fire type in CFIS. Dead fuel moisture contents were set at 6 percent for all simulations.

RESULTS AND DISCUSSION

Pre-outbreak, stands were 100 percent ponderosa pine, averaged 9.8–11.6 inches d.b.h., and were 55 feet tall with an average CBH of 30 feet. Mortality-only stands had higher basal areas ($p < 0.001$; fig. 12.1A) and tree densities ($p < 0.001$) before the outbreak than mortality/TH stands. The decline in tree density and basal area by 2 years post-outbreak was significant ($p < 0.001$) in both stand types. By 5 years post-outbreak, tree density was reduced a total of 70–79 percent and basal area was 78–85 percent lower than pre-outbreak levels due to bark beetle-induced tree mortality. In addition to reducing tree density and basal area, by 5 years post-outbreak, mortality of mostly larger trees resulted in stands of significantly ($p < 0.01$) smaller diameter trees (7.8–9 inches d.b.h.) in both stand types and significantly ($p < 0.001$) lower CBH in mortality/TH stands.

The bark beetle outbreak also resulted in large numbers of snags, especially on mortality-only stands. By 5 years post-outbreak, mortality-only stands averaged 240 snags per acre and mortality/TH stands averaged 31 snags per acre. The loss of much of the overstory from the bark beetle outbreak also stimulated prolific tree regeneration. By 5 years post-outbreak, seedling densities averaged 1,636 seedlings per acre on mortality-only stands and 1819 seedlings per acre on mortality/TH plots. The majority of the seedlings established post-outbreak.

Bark beetle-caused tree mortality resulted in little change in woody surface fuels by 2 years post-outbreak, but a dramatic increase by 5 years post-outbreak. Two years post-outbreak, total woody surface fuel loading did not differ significantly ($p = 0.42$) between mortality-only (6.7 tons per acre) and mortality/TH stands (8.1 tons per acre) (fig. 12.1B), and CWD averaged 4.5 tons per acre on mortality-only stands and 4.3 tons per acre on mortality/TH stands ($p = 0.88$). Five years post-outbreak, however, total woody surface fuel load was higher ($p < 0.001$) on mortality-only stands (30.7 tons per acre) than on mortality/TH stands (8.1 tons per acre). The same pattern was observed for CWD fuel loading, as mortality-only stands had more ($p < 0.001$) fuels in this class (24.5 tons per acre) than mortality/TH stands (5.5 tons per acre).

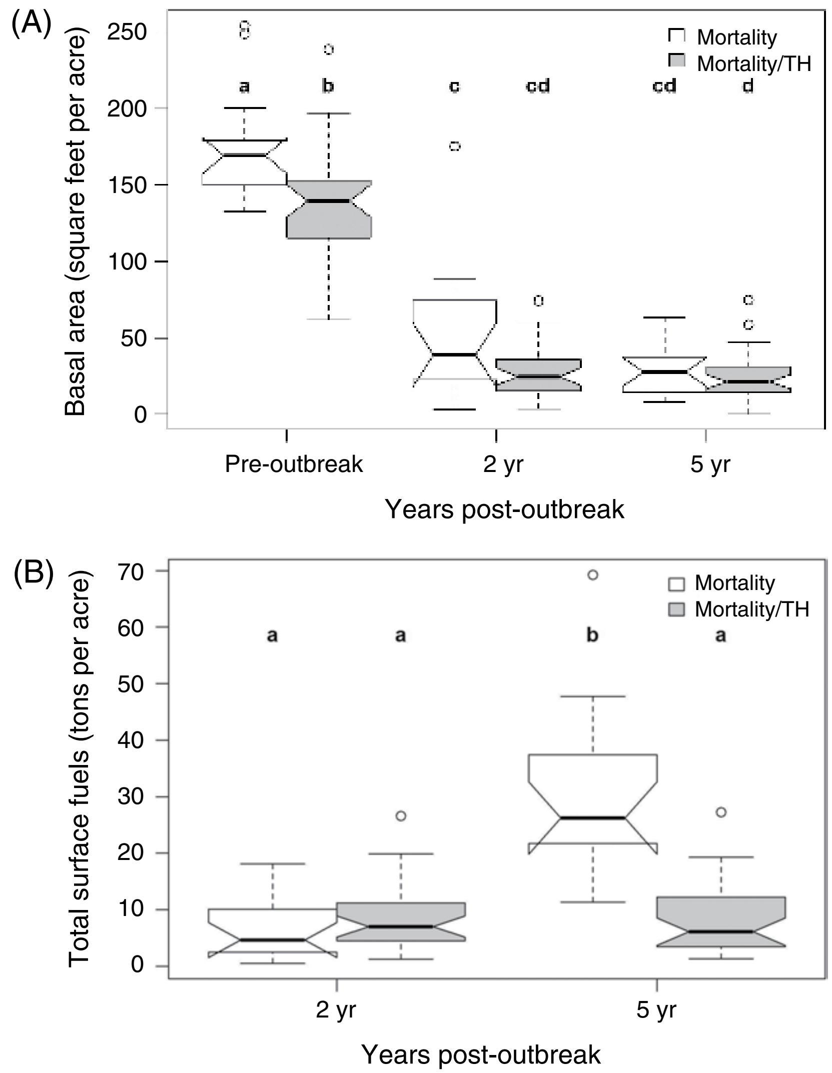

Figure 12.1— (A) Average basal area pre-outbreak and 2 and 5 years post-outbreak, and (B) average total surface load 2 and 5 years post-outbreak on mortality-only and mortality/timber-harvested. Significantly different (α =0.05) means are indicated with different letters. Note: TH = timber-harvested.

Stand structural changes and surface fuel accumulations resulting from the bark beetle-induced tree mortality led to changes in predicted crown fire potential through time. At wind speeds < 10 miles per hour, surface fires were predicted for pre-outbreak stands; above 10 miles per hour, active crown fires were predicted (table 12.1). At 2 years post-outbreak, the pattern of surface fires switching to active crown fires at wind speeds above 10 miles per hour was maintained in mortality-only stands due to higher tree densities and CBD. In contrast, in mortality/TH stands, crown fires occurring above 10-mile-per-hour winds were predicted to be passive. Due to the lower CBH in mortality/TH stands, however, the probability of crown fire occurrence was predicted to be higher at 2 years post-outbreak than in mortality-only stands (fig. 12.2). At 5 years post-outbreak, due to higher surface fuel accumulation in mortality-only stands, surface fires were predicted to transition to passive crown fires at lower wind speeds and become active crown fires at wind speeds above 17 miles per hour (table 12.1),

Table 12.1—Major fire type by wind speed for pre-outbreak and 2 and 5 years post-outbreak, on mortality-only and mortality/timber-harvested (TH) stands

	Wind speed			
	< 5	6–9	10–17	> 17
	miles per hour			
Pre-outbreak	S	S	A	A
2 year mortality-only	S	S	A	A
2 year mortality/TH	S	S	P	P
5 year mortality-only	S	P	P	A
5 year mortality/TH	S	S	P	P

S = surface fire; A = active crown fire; P = passive crown fire.

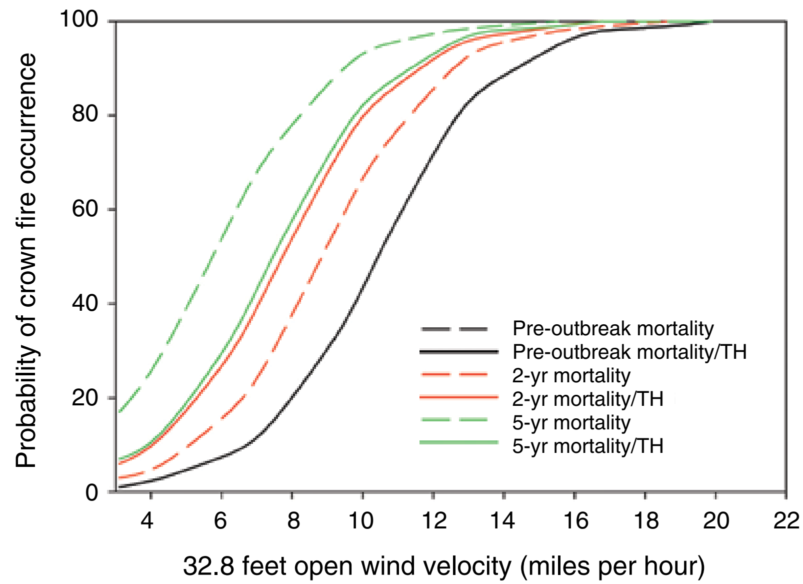

Figure 12.2—Probability of crown fire occurrence by wind speed for pre-outbreak, and 2 and 5 years post-outbreak for mortality-only and mortality/timber-harvested stands. Pre-outbreak mortality-only and mortality/timber-harvested stands have the same crown fire probability, and thus these lines appear as a single line. Note: TH = timber-harvested.

and the probability of crown fire occurrence was higher in mortality-only stands than in mortality/TH stands (fig. 12.2).

DISCUSSION

This study documented dramatic changes in forest structure, surface fuels, and predicted fire behavior within 5 years following a mountain pine beetle outbreak in Black Hills ponderosa pine forests. In addition to time since outbreak, initial tree densities and level of mortality influenced post-outbreak attributes. Within 2 years post-outbreak, tree density and basal area were reduced 60–80 percent. Residual post-outbreak trees had smaller diameters and lower crown base heights due to the mortality of the larger trees, which left shorter trees with crowns closer to the ground. By 5 years post-outbreak, the basal area of all stands was below the threshold of 120 square feet per acre for high susceptibility to mountain pine beetle infestations (Schmid and others 1994).

Snagfall proceeded quickly, resulting in a shift from most plots having CWD loadings below recommended levels 2 years post-outbreak to most of the mortality-only stands having loadings above recommended levels by 5 years post-outbreak. Two years post-outbreak, total CWD loadings in mortality-only and mortality/TH stands were below (65–66 percent of the stands) or within (33–34 percent of the stands) recommended levels for dry coniferous forests (5–20 tons per acre; Brown and others 2003); no stands had loadings above recommended levels. Five years post-outbreak, none of the mortality-only stands had woody fuel loadings below recommended levels; 53 percent of the stands had levels within and 47 percent of the stands had levels above recommended levels. In contrast, at 5 years post-outbreak, CWD fuel loadings in mortality/TH stands were mostly (59 percent) below or within (38 percent) recommended levels; only one stand (3 percent) had CWD loadings above recommended levels. In a previous study in Arizona, 20 percent of the stands killed by both ips and *Dendroctonus* beetles had CWD loadings above recommended levels 5 years post-outbreak (Hoffman and others 2012b). We attributed the greater proportion of plots with higher CWD loadings at 5 years in our study compared to those in the Southwest study to higher pre-outbreak tree densities in the Black Hills. Mortality stands in Arizona averaged 162 ponderosa pine trees per acre compared to an average range of between 178 and 327 trees per acre in the Black Hills. The generally low level of woody surface material on the mortality/TH stands was a reflection of the harvesting techniques used. Trees were whole-tree harvested when the needles were still green and limbed at landings adjacent to the stands. Thus logging prevented the buildup of woody surface fuels following the bark beetle outbreak, similar to model projections following whole-tree harvest of dead trees in other forest types (Donato and others 2013).

The combination of lower CBD and CBH plus higher woody fuel loadings has several implications for predicted crown fire potential following bark beetle-induced tree mortality in

Black Hills ponderosa pine stands. Lower CBH is predicted to allow surface fires to transition into the crowns more readily. Heavy woody surface fuel loadings by 5 years post-outbreak in mortality-only stands were predicted to provide an additional avenue for fires to transition into crowns. With time, as downed wood becomes rotten and more ignitable and herbaceous fine fuels increase, high severity surface fires are likely to occur and result in additional tree mortality and severe soil heating (Brown and others 2003, Hyde and others 2012). Prescribed burning under moderate weather conditions and high 1000-hour fuel moistures has the potential to reduce woody surface fuel loading with fewer detrimental consequences (Stevens-Rumann and others 2012).

Post-outbreak timber harvest of dead trees in the mortality/TH stands prevented the type of surface fuel buildup that occurs without timber harvest following bark beetle-induced tree mortality, thus resulting in a lower crown fire potential, and crown fires were predicted to be mostly passive. However, on both mortality-only and on mortality/TH stands, high tree seedling densities will eventually increase crown fire risk if allowed to grow. Prescribed burning can be an effective tool in reducing seedling numbers, but as seedlings mature they become less resistant to fire mortality (Battaglia and others 2009). Prescribed burning could be useful in suppressing pine regeneration and preventing the development of hyper-dense stands in the future and it could easily be accomplished in stands where dead trees have been removed by timber harvest.

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