Chapter 19. Influence of Bark Beetle-Caused Mortality on Fuel Loadings and Crown Fire Hazard in Southwestern Ponderosa Pine Stands

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Bark beetles (*Coleoptera: Scolytinae*) are important biotic agents of conifer mortality in forests of western North America (Furniss and Carolin 1977) and play an important role in the disturbance ecology of these ecosystems (Fettig and others 2007). Bark beetle outbreaks affect subsequent fire behavior in part by influencing the spatial distribution and state of fuels [see review by Jenkins and others (2008)]. Crown fire hazard following a bark beetle outbreak likely varies as a function of time (Romme and others 2006) with increased risk of crown fire initiation immediately following outbreak, reduced crown fire spread and initiation after needle drop, and increased crown fire initiation and spread after snags fall. There is a paucity of "scientifically and statistically sound studies" on this topic; therefore, a better understanding of the fate of fuels after bark beetle outbreaks is needed to develop management options related to treating fuels (Negrón and others 2008). Furthermore, because rates of needle drop, tree fall, and surface fuel decomposition vary across elevation gradients and forest types (Cahill 1977, Jenkins and others 2008), it is important to quantify relationships between bark beetle outbreaks and potential fire behavior across this variability. In contrast to higher-elevation forest types, relationships between bark beetle outbreaks, fuel loading, and fire behavior have not been reported for ponderosa pine forests (Jenkins and others 2008).

A drought-induced bark beetle outbreak resulted in high levels of ponderosa pine mortality throughout much of Arizona between 2001 and 2003 (Negrón and others 2009, Williams and others 2008). Although ponderosa pine mortality approached 100 percent in some stands, reductions in tree density (stems·ha^{-1}) averaged < 25 percent across five national forests monitored between 2001 and 2004 (Negrón and others 2009). The goal of our study was to quantify how canopy and surface fuels changed through time following this outbreak and to better understand the implications of these changes in terms of predicted fire behavior. The objectives were to (1) quantify effects of bark beetle outbreaks on canopy and surface fuels in ponderosa pine forests of the Southwest, (2) model potential fire behavior in stands with tree mortality caused by bark beetles, and (3) examine relationships between amount of bark beetle-caused tree mortality and both fuel loadings and fire hazard.

Methods

We utilized a network of plots established in 2003–04 across five national forests (Apache-Sitgreaves, Coconino, Kaibab, Prescott, and Tonto) in Arizona to quantify overstory impacts

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of bark beetle outbreaks in ponderosa pine stands (Negrón and others 2009). We selected 37 plots with at least 10 percent ponderosa pine mortality (basal area killed) and paired them with plots without mortality. Pairing was based on proximity, elevation, and percent ponderosa pine. We quantified tree stand attributes and canopy and surface fuels 4–5 years post-outbreak during June–August 2007. We modeled crown fire hazard using NEXUS (Scott and Reinhardt 1999), plus torching index, which is the wind speed at which a surface fire is expected to transition into the canopy, and crowning index, which is the wind speed at which active crowning is possible (Scott and Reinhardt 2001).

We ran three separate sets of fire behavior simulations for each plot. In the first simulation, fire behavior fuel model was held constant for all plots (model 9, see Anderson 1982 for description of standardized fuel models) to quantify the influence of bark beetle-caused tree mortality on the canopy stand structure and potential fire behavior while ignoring the effects of tree mortality on surface fire properties and windflow within a stand. In the second simulation we used fire behavior fuel model 10 for all plots that had surface fuel loadings > 22.4 Mg/ha to account for changes in quantity and position of canopy fuel and quantity of surface fuels. The third simulation adjusted the wind reduction factor for stands with basal areas of <11.5 m^2/ha, to account for differences caused by tree mortality. Fuel moisture and slope were held constant in all simulations. Crown fire hazard was predicted for upper 97.5th percentile weather conditions to represent severe fire weather conditions during the fire season. We analyzed the effects of bark beetle-caused tree mortality on fuel loadings and crown fire hazard by comparing means for mortality and no-mortality plots using an unequal variance Student's two-tailed t-test ($\alpha = 0.05$).

Results

Bark beetle-caused tree mortality resulted in significant changes in several stand variables which affect the vertical and horizontal distribution of canopy fuels (table 19.1). Stands

Table 19.1—Comparison of stand structural characteristics in mortality and no-mortality plots in ponderosa pine stands of north-central Arizona

Stand variables	No mortality	Mortality
Total stems·ha^{-1}	378 (35.7)	314 (32.7)
Stems·ha^{-1} ponderosa pine	282 (28.7)	123 (24.4)[a]
Stems·ha^{-1} other species	96 (20.2)	191 (26.9)[a]
Total basal area ($m^2 \cdot ha^{-1}$)	26.5 (2.5)	16.4 (2.2)[a]
Basal area ponderosa pine ($m^2 \cdot ha^{-1}$)	18.0 (2.5)	11.0 (2.2)[a]
Basal area other species ($m^2 \cdot ha^{-1}$)	8.5 (1.9)	5.4 (1.2)
Stand density index	181.2 (15.4)	117.5 (13.9)[a]
Tree height (m)	10.5 (0.6)	10.8 (1.0)
Quadratic mean diameter (cm)	29.5 (1.6)	30.2 (0.9)
Crown base height minimum (m)	1.3 (0.3)	2.7 (0.003)[a]
Crown base height 20 percent (m)	2.0 (0.3)	3.3 (0.002)[a]
Crown base height average (m)	3.2 (0.3)	4.2 (0.03)[a]
Crown base height calculated (m)	1.2 (1.8)	2.0 (0.02)[a]

Values in parentheses are standard errors.
[a] Means within a row are significantly different (α=0.05).

with mortality had lower ponderosa pine density (stems·ha^{-1}) and higher density of other species than stands with no mortality. However, these differences did not equate to a significant difference in total tree density. Stands with mortality also had significantly lower stand density index, total basal area, and basal area of ponderosa pine, but basal area of other species did not differ from stands without mortality. All measures of canopy base height were significantly higher in mortality plots compared to the no-mortality plots.

Bark beetle-caused tree mortality resulted in significant increases for all surface fuels except total 1,000-hour rotten fuels, and increases in litter depth (table 19.2). Total surface fuel loading was, on average, two times greater in mortality plots compared with no-mortality plots. Surface fuel loadings in 1-, 10- and 100-hour fuels averaged more than two times higher those of no-mortality plots.

Mortality plots had lower canopy foliage biomass, canopy 10- and 100-hour fuel load, and total canopy fuel loading with and without foliage compared with no-mortality plots (table 19.3). The total available canopy fuel loading was also significantly lower in the mortality stands. Canopy bulk density estimates did not differ significantly between no-mortality and mortality plots despite significant differences in the amount of available canopy fuel loadings.

In our first simulation with weather, topographic and surface fuel conditions held constant, torching index (fig. 19.1) and

Table 19.2—Surface fuel loadings by fuel classes and duff and fuel bed depth in mortality and no-mortality plots in ponderosa pine stands of north-central Arizona

Surface fuel measurements	No mortality	Mortality
1-hr (Mg·ha^{-1})	0.4 (0.1)	1.1 (0.2)[a]
10-hr (Mg·ha^{-1})	1.9 (0.2)	3.2 (0.4)[a]
100-hr (Mg·ha^{-1})	1.4 (0.3)	3.9 (0.6)[a]
1000-hr sound (Mg·ha^{-1})	0.0 (0.0)	10.7 (3.7)[a]
1000-hr rotten (Mg·ha^{-1})	6.9 (3.2)	6.1 (1.5)
Total fuel loading (Mg·ha^{-1})	10.6 (3.3)	25.2 (4.1)[a]
Litter depth (cm)	5.8 (.2)	13.6 (0.2)[a]
Duff depth (cm)	1.6 (1.0)	1.7 (1.1)

Values in parentheses are standard errors.
[a] Means within a row are significantly different (α=0.05).

Table 19.3—Canopy fuel loadings by size class, total and available canopy fuel, and canopy bulk density of mortality and no-mortality plots in ponderosa pine stands of north-central Arizona

Canopy measurements	No mortality	Mortality
Foliage (Mg·ha^{-1})	8.7 (0.8)	5.8 (0.7)[a]
1-hr (Mg·ha^{-1})	1.6 (0.2)	1.2 (0.2)
10-hr (Mg·ha^{-1})	9.8 (0.8)	6.5 (0.9)[a]
100-hr (Mg·ha^{-1})	10.3 (1.4)	6.5 (1.1)[a]
Total canopy fuel (Mg·ha^{-1})	33.4 (3.3)	21.5 (2.9)[a]
Available canopy fuel (Mg·ha^{-1})	9.4 (0.8)	6.4 (0.7)[a]
Canopy bulk density (kg·m^{-3})	0.127 (0.003)	0.092 (0.002)

Values in parentheses are standard errors.
[a] Means within a row are significantly different (α=0.05).

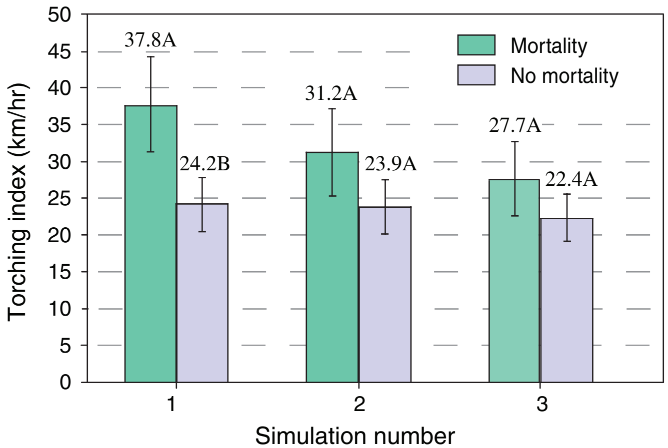

Figure 19.1—Simulated torching index (mean with standard error) for plots with tree mortality and with no mortality for three sets of assumptions in ponderosa pine stands of north-central Arizona. Simulation 1 shows changes in torching index based only on changes in the canopy fuels complex; simulation 2 shows changes in torching index based on combined effects of changes in canopy and surface fuels complex; and simulation 3 shows changes in torching index based on a combination of changes in canopy and surface fuels complex as well as a reduction in wind adjustment factor. Means within a group followed by a different letter are significantly different (α = 0.05).

crowning index (mortality: 39.7 km·h^{-1} ± 6.4 SE, no mortality: 27.8 ± 2.8; $p = 0.02$) were significantly higher in mortality plots compared to no-mortality plots. These results reflect the increased canopy base height estimates and decreased tree densities and canopy fuels in the mortality plots. In the second simulation, the torching index was not significantly different between the no-mortality and mortality plots. Three out of 37 (8 percent) no-mortality plots had surface fuel levels high enough to be classified as fuel model 10, while 15 out of 37 (40 percent) mortality plots were classified as fuel model 10. In the third simulation, torching index did not differ significantly between mortality and no-mortality plots given that seven no-mortality plots and 16 mortality plots had their wind reduction factor increased to represent less vegetative drag in the canopy fuel stratum due to lower basal areas.

Discussion

Our preliminary results suggest that crown fire hazard was not higher in mortality stands despite 2.5 times higher surface fuel loadings 4–5 years after mortality occurred. This finding is based on crown fire hazard being comprised of two components: first, the ability of a surface fire to transition into the canopy of a stand, and second, the ability of a crown fire to spread through a stand. In stands with mortality, a surface fire was predicted to need about three times as much energy release per unit area per minute to promote the surface fire into the canopy compared to stands without mortality. If fuel loadings and moisture were held constant, this increase in energy would require an increase in wind speed of about 13 km·h^{-1} (fig. 19.1–simulation 1). However, the effect of epidemic insect outbreaks is not limited just to changes in vertical fuel distributions. As the canopy fuels from the dead trees fall, an increase in the surface fuel loading and composition along with corresponding changes in fire behavior can be expected. In our simulations, this increase counteracted the effect of bark beetle-caused mortality on the vertical distribution of fuels (fig. 19.1–simulation 2). Accounting for the decrease in drag caused by a reduction in canopy biomass further reduced any effect the changes in the vertical distribution of fuels had on the ability of surface fire to transition in mortality stands (fig. 19.1–simulation 3). These preliminary modeling results suggest a tradeoff between increased canopy base heights and increased surface fuel loadings. The end result of this tradeoff was that a surface fire can transition into the canopy, but physical properties driving this mechanism have switched from low surface fuels and low crown base heights to higher surface fuels and higher crown base heights.

Although this work provides insights into the effect of bark beetle-caused mortality on fuels and potential fire behavior in ponderosa pine, it is limited to 4–5 years post-mortality. Questions remain about effects of bark beetle-caused mortality at other points in time, such as immediately following mortality or many years after mortality, to fully assess the model proposed by Romme and others (2006).

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