# CHAPTER 14.

# Impact of Bark Beetle Infestation on Fuel Loads and Fire Behavior in "Old-Stage" Southwestern Ponderosa Pine

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## INTRODUCTION

Bark beetle (Coleoptera: Curculionidae, sf. Scolytinae) infestations modify fuels and, consequently, modeled fire behavior in conifer ecosystems of the Western United States (Hicke and others 2012, Jenkins and others 2014). Changes in fuels will vary with space and time since infestation, and impacts on fire behavior will be correspondingly complex (Simard and others 2011). Multiple studies have focused on quantifying fuels and modeled or observed fire behavior in currently infested (known as "red-stage" because killed trees still retain fading yellow-red needles) and recently infested (known as "gray-stage" because all needles have fallen, revealing the tree boles and branches) pine stands, particularly in lodgepole pine type (*Pinus contorta*). Less research has been conducted in "old-stage" stands (wherein beetle-killed trees have mostly fallen, the fallen needles have mostly decomposed, and advance regeneration forms ladder fuels), especially for relatively arid types such as ponderosa pine (*Pinus ponderosa*) (Hicke and others 2012).

Since 1995, we have monitored permanent plots in ponderosa pine type on the Colorado Plateau that experienced a bark beetle outbreak c. 1992–1996. Infested trees were killed by a suite of bark beetles including mountain pine beetle (*Dendroctonus ponderosae*), round-headed pine beetle (*D. adjunctus*), western pine beetle (*D. brevicomis*), larger Mexican pine beetle (*D. approximatus*), red turpentine beetle (*D. valens*), and pine engraver beetles (*Ips pini, I. knausi*). Data from these plots were originally used to analyze factors that influence the transition from endemic to epidemic beetle population phases and to parameterize a stand-level, bark beetle risk rating model (Chojnacky and others 2000). We remeasured these plots in 2012 and added planar intercept sampling to characterize surface fuels as a function of infestation severity. Fuel load data were used in a fire simulation model, the Fire and Fuels Extension of the Forest Vegetation Simulator (FFE-FVS) (Dixon 2002, Rebain 2010). Our objectives were to quantify the effects of infestation severity on fuels and modeled fire behavior in old-stage ponderosa pine (i.e., 15–20 years after infestation).

## METHODS

Forty-five ponderosa pine-dominated sites with varying degrees of bark beetle-caused host mortality were identified during 1995–1996 in southern Utah, northern Arizona, and southwestern Colorado. At each site, we installed two parallel transects, each with 10 contiguous 405-$m^2$ circular plots. For each tree ≥ 7.6 cm diameter at breast height (d.b.h.), we measured species d.b.h., crown ratio, and Keen tree class (Keen 1943). A subset of trees was measured for age, total height, and crown base height. Year of attack was estimated for all bark beetle-infested stems, and beetle species were identified by egg gallery patterns and sizes (Chojnacky and others 2000). Trees < 7.6 cm d.b.h. were measured with a 13.5-$m^2$ plot centered on the overstory plot. Pre-outbreak stand conditions were estimated by recoding recently killed trees as live. We remeasured these plots in 2012 and added planar intercept sampling to quantify surface fuel loads based on Fire Effects Monitoring and Inventory System (FIREMON) protocols (Lutes and others 2006) (fig. 14.1). This was done to 321 of the original 900 plots, randomly selected from 3 strata defined by beetle-infested basal area (BA) (0, 0.01–0.37, or > 0.37 $m^2$ $plot^{-1}$); these classes were chosen based on the distribution of killed BA among the plots. Planar intercept data were entered into FIREMON software to summarize surface fuel loads. These outputs, along with the over- and understory tree data, were used to create input files for FFE-FVS (Utah variant).

FVS is a growth and yield model (our simulations did not include tree growth) and FFE adds fuel dynamics and potential fire behavior. As with all U.S. operational fire models, FFE-FVS calculates surface fire behavior using the equations of Rothermel (1972) and Albini (1976), which consider factors such as slope, fuel loads, and environmental conditions. Based on Scott and Reinhardt's (2001) rules and using surface and aerial fuels, FFE-FVS output includes torching index (the 6.1 m wind speed predicted to initiate a crown fire) and crowning index (the 6.1 m wind speed predicted to sustain an active crown fire). Note that lower values of these indices indicate increased crown fire hazard. Predictions of fire type are based on an algorithm comparing the user-defined wind speed with the torching and crowning indices. There are four possible fire types: surface (crowns do not burn), passive (individual trees or groups of trees torch), conditional-crown (surface fire from an adjacent stand will continue as a surface fire or crown fire from an adjacent stand will continue as a crown fire), and active crown (fire moves through tree crowns, burning all crowns and killing all trees). For each plot, we modeled fire behavior with custom fuel models that represent the observed fuel loads and dynamic, FFE-selected fuel models that have

*Figure 14.1—Measuring surface fuels with planar intercept sampling, Kaibab National Forest, Arizona, 2012. The fallen ponderosa pine snags were killed by* Dendroctonus *bark beetles c. 1992–1996. (photo by Barbara J. Bentz, U.S. Department of Agriculture, Forest Service)*

been previously defined and calibrated. (Note: we only report results from custom models herein; results from dynamically selected models are comparable and are reported in Hansen and others 2015.) "Extreme" weather conditions, used to model fire type, were calculated from a centrally located fire weather station and represent the 90th percentile temperature and wind conditions and the 10th percentile fuel moisture conditions.

Statistical analyses were conducted using generalized linear mixed models (fuel loads and fire behavior parameters) and multinomial logistic regression models (categorical fire types) (see Hansen and others 2015 for full details including parameter value estimates). Explanatory variables were infested tree density (i.e., trees per ha) and BA from the c. 1992–1996 outbreak, and we report the best fitting for each response variable. Tested covariates included infestation severity (infested tree density or BA per ha) from intervals other than 1992–1996, elevation, slope, aspect, pre-outbreak stand conditions, and time since last fire. To produce figures 14.2–14.5, we used median dataset values of significant covariates. Changing the covariate values modifies the scale, but not the character, of the relationships between the response and explanatory values.

## RESULTS AND DISCUSSION

*Dendroctonus* bark beetles generally infest larger diameter trees, leaving a residual live stand of smaller trees (Hansen 2014). These changes were reflected in our data, which showed significantly reduced live total BA, ponderosa pine BA, canopy cover, and ponderosa pine diameter as a function of infestation severity (infested tree density or BA; data not shown, but see Hansen and others 2015). The density of live trees ≥ 7.6 cm d.b.h. increased as a function of infestation severity. Presumably, advance regeneration measured in the original surveys grew into that size class by 2012, more than replacing the density of infested trees. Likewise, seedling density was positively related to infestation severity, suggesting successful recruitment into beetle-caused canopy gaps. Regarding fuels that support crown fires, the increase in ladder fuels (reflected by reduced canopy base heights) is countered by the beetle-caused decrease in canopy bulk density (fig. 14.2).

Similarly, fuel component loading showed different trends with increasing infestation severity. Litter depth and loads decreased with increasing infestation severity (fig. 14.3) (note that litter is a primary carrier of fire among many fuel models; Scott and Burgan 2005). This is because of the reduced live foliar biomass after bark beetle infestation, with commensurate reductions in litterfall. Moreover, sufficient time had lapsed since infestation that the pulse of fallen needles from killed trees had mostly decomposed. In contrast, fuel loads of woody materials increased as a function of infestation severity, especially among the largest diameter material (1000-hour fuels; i.e., ≥ 7.6 cm diameter) (fig. 14.3). This reflects snagfall of beetle-killed trees.

A fuels-relevant feature of bark beetle outbreaks is the degree of spatiotemporal variation in infestation. In red-stage stands, there might be 5 or more years' difference in timing of attack among killed trees. Thus, an infested red-stage stand will contain a mix of trees: uninfested, currently infested with green needles, recently infested with fading needles, and previously infested with fallen needles. Although this temporal variability is less important in old-stage stands, the role of spatial variability continues. That is, there is considerable variation in infestation severity among stands in an infested forest or landscape,

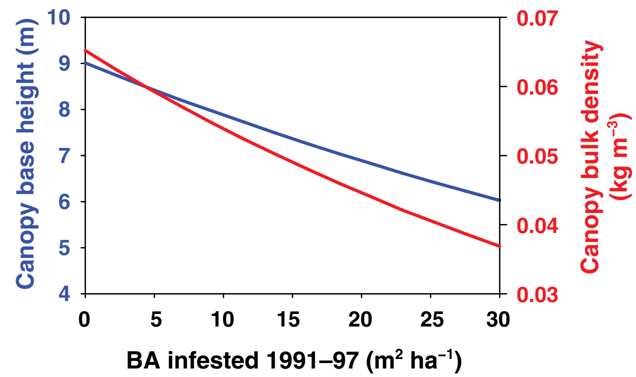


*Figure 14.2—Canopy base height and canopy bulk density as a function of bark beetle infestation severity during an outbreak 15–20 years before measurements. Note: BA = basal area.*

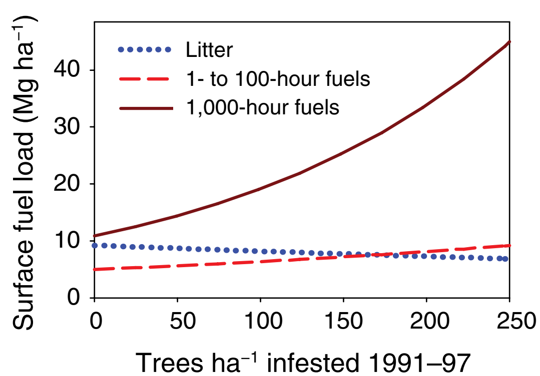


*Figure 14.3—Surface fuels as a function of infestation severity 15–20 years after a bark beetle outbreak.*

with few stands experiencing complete overstory mortality (Hansen 2014). This variation occurred even at the substand scale among our plots. For example, one of our sites averaged 133 infested pines per ha, but the plots within the site varied from 25 to 790 infested pines per ha.

From the FFE-FVS simulations, torching index was negatively related to infestation severity from the c. 1992–1996 outbreak (i.e., torching is more likely with increasing beetle severity; fig. 14.4). This result is related to the decreased canopy base heights resulting from post-outbreak seedling recruitment and release of advance regeneration. Conversely, crowning index was predicted to increase as a function of infestation severity (i.e., crown fire behavior is less likely with increasing beetle severity; fig. 14.4). This outcome is related to the reduced canopy bulk density after the beetle-caused deaths of the largest overstory trees. Moreover, the resulting canopy gaps decrease continuity in canopy fuels. Surface fire rate of spread was predicted to increase as a function of infestation severity (results not shown). Modeling by Page and Jenkins (2007) in lodgepole pine indicated that this behavior is mostly related to increased within-canopy wind speeds due to the loss of canopy sheltering; drying of surface fuels minimally affected rate of spread, and surface fuel loads had no effect.

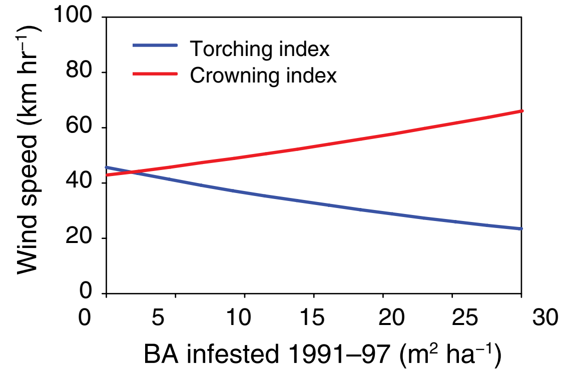


*Figure 14.4—Torching and crowning indices (the 6.1 m wind speeds predicted to initiate and sustain a crown fire, respectively) as a function of infestation severity 15–20 years after a bark beetle outbreak. Lower values of these indices indicate higher crown fire hazard. Note: BA = basal area.*

The net result of these beetle-related changes in fire behavior is captured by predictions of fire type as a function of infestation severity (fig. 14.5). Under the "extreme" fire weather conditions used in the simulations, surface fires are most probable in uninfested stands, whereas increasing infestation severity results in heightened probability of passive fires. The simulations predict that the probability of conditional or active crown fire in these old-stage ponderosa pine stands is low, under the simulated weather conditions, regardless of bark beetle infestation. Conceivably, active crown fires observed elsewhere in southwestern ponderosa pine have been affected by even higher wind speeds and lower fuel moistures.

These simulated fire behavior results should be interpreted cautiously. All operational fire models, including FFE-FVS, are limited by the underlying assumptions of the Rothermel (1972) and Van Wagner (1977) models. These assumptions are questionable even under ideal conditions (Cruz and Alexander 2010), and application of these models is further compromised when applied to spatially variable stands, such as from bark beetle infestation. Moreover, previous modeling applications in beetle-infested lodgepole pine have produced variable results, especially for red-stage stands where assumptions vary widely regarding the amounts and moisture levels of foliage on beetle-killed trees. Finally, 1,000-hour fuels are the fuel class most conspicuously affected in old-stage stands (fig. 14.3) and these fuels are not considered in the Rothermel and Van Wagner models. Although attempts to include these fuels in simulations of old-stage lodgepole pine resulted in predictions of greatly increased combustion energy (Page and Jenkins 2007, Schoennagel and others 2012), it is uncertain to what extent 1,000-hour fuels affect rate of spread or probability of active crown fire (Hansen and others 2015). Although flawed, operational models are the only practical

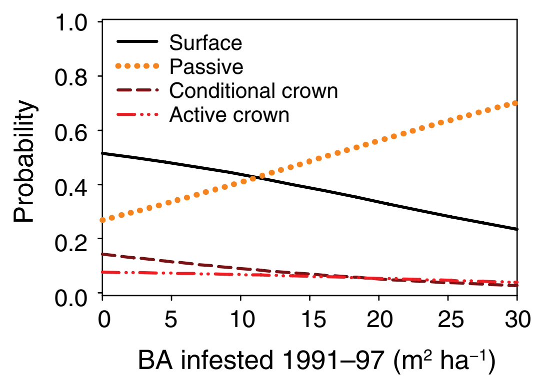


*Figure 14.5—Fire type probabilities as a function of infestation severity 15–20 years after a bark beetle outbreak. These results were simulated using extreme weather conditions (i.e., 90th percentile temperature and wind speed and 10th percentile fuel moistures from a centrally located fire weather station). Note: BA = basal area.*

method for assessing changes in fire behavior as a function of modifications to fuel profiles, even for research purposes. Researchers and managers are aware of model limitations and use the simulations to inform fuelbed changes on fire behavior. We advise the reader to consider relative, rather than absolute, differences in fire behavior as a function of infestation severity.

## CONCLUSIONS

Stand structure and fuelbed conditions in old-stage ponderosa pine stands of the Colorado Plateau were modified by bark beetle infestation similar to previous descriptions for ponderosa and lodgepole pine (Hansen 2014, Hicke and others 2012, Hoffman and others 2012, Jenkins and others 2014). For example, quadratic mean diameter, BA, canopy bulk density, and canopy base heights were reduced following the loss of large-diameter host trees. Litter, a primary carrier of fire in many fuel models, was reduced in old-stage stands because of decreased litterfall and decomposition of fallen needles from killed trees. In contrast, woody fuels of all size classes increased after infestation, especially among the largest sizes.

These beetle-caused changes in ponderosa pine fuel profiles modified simulated fire behavior similar to previous descriptions for old-stage lodgepole pine (Hicke and others 2012, Page and Jenkins 2007, Simard and others 2011). The hazard of torching behavior increased in conjunction with lowered canopy base heights, but the hazard of active crown fire decreased in conjunction with reduced canopy fuels. Thus, increasing infestation severity resulted in heightened probability of passive fire (torching of individual crowns or groups of crowns) concomitant with reduced probability of surface fire. These results are partially supported by modeling, using the NEXUS model, in gray-stage ponderosa pine stands of Arizona (Hoffman and others 2012). In that case, decreased canopy fuels similarly increased predicted crowning indices. Unlike our study, however, canopy base heights were also increased in infested stands, resulting in increased torching indices. This difference reflects the insufficient stand developmental time, in the case of Hoffman and others, for recruitment of new seedlings and release of advance regeneration.

Our simulations indicated that active crown fires are not probable, using the extreme weather conditions simulated, in these stands regardless of infestation severity. It is possible that even more extreme weather conditions would shift this outcome, but we see no evidence that bark beetle history will affect the probability of active or conditional-crown fires given current stand conditions (fig. 14.5). Moreover, spatial variability in beetle-caused tree mortality will result in diminished beetle-driven effects on fire behavior at increasing spatial scales.

## CONTACT INFORMATION

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