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30

Impact of Forest Restoration Treatments on Southwestern Ponderosa Pine Tree Resistance to Bark Beetles

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Intermountain West Frequent-Fire Forest Restoration

Ecological restoration is a practice that seeks to heal degraded ecosystems by reestablishing native species, structural characteristics, and ecological processes. The Society for Ecological Restoration International defines ecological restoration as "an intentional activity that initiates or accelerates the recovery of an ecosystem with respect to its health, integrity and sustainability….Restoration attempts to return an ecosystem to its historic trajectory" (Society for Ecological Restoration International Science and Policy Working Group 2004).

Most frequent-fire forests throughout the Intermountain West have been degraded during the last 150 years. Many of these forests are now dominated by unnaturally dense thickets of small trees, and lack their once diverse understory of grasses, sedges, and forbs. Forests in this condition are highly susceptible to damaging, stand-replacing fires and increased insect and disease epidemics. Restoration of these forests centers on reintroducing frequent, low-severity surface fires—often after thinning dense stands—and reestablishing productive understory plant communities.

The Ecological Restoration Institute at Northern Arizona University is a pioneer in researching, implementing, and monitoring ecological restoration of frequent-fire forests of the Intermountain West. By allowing natural processes, such as low-severity fire, to resume self-sustaining patterns, we hope to reestablish healthy forests that provide ecosystem services, wildlife habitat, and recreational opportunities.

The Southwest Fire Science Consortium (SWFSC) is a way for managers, scientists, and policy makers to interact and share science. SWFSC's goal is to see the best available science used to make management decisions and scientists working on the questions managers need answered. The SWFSC tries to bring together localized efforts to develop scientific information and to disseminate that to practitioners on the ground through an inclusive and open process.

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Cover Photo: Ponderosa pine forests of the Southwest are home to multiple bark beetle species. Bark beetles can have a wide range of positive and negative effects on ponderosa pine ecosystems. *Photo courtesy of the Wagner Lab, Northern Arizona University*

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Introduction

Insects can have a wide-range of both positive and negative effects on forest ecosystems. Positive impacts include serving as pollinators, creating snags for cavity nesting birds and bats, helping to increase forest heterogeneity, and aiding in decomposition and nutrient cycling. Negative impacts can range from relatively minor impacts at the individual tree level, such as reductions in growth or form defects, to landscape-level tree mortality (Coulson and Witter 1984, Raffa et al. 2008). In the ponderosa pine forests of the southwestern United States, the bark beetle has been the insect most often associated with widespread tree mortality.

Restoration efforts in ponderosa pine ecosystems have the overarching goal of making these forests more healthy and resilient by reducing fuel loads and restoring ecosystem functions. Stand restoration in these ecosystems usually involves varying intensities of thinning or prescribed burning treatments or, more often, some combination of both. These same treatments may also alter tree susceptibility to disturbance events, such as insect attacks and wildfire. This working paper will highlight current research about the effects of restoration treatments on ponderosa pine tree resistance/susceptibility to bark beetles.

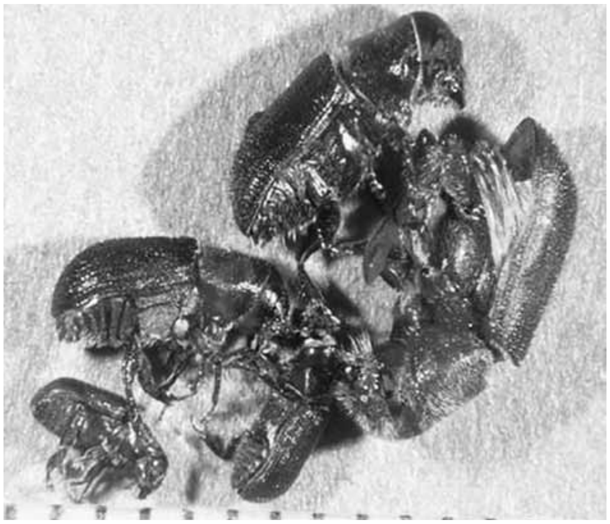

Figure 1: Bark beetles. *Photo courtesy of the Wagner Lab, Northern Arizona University*

Key Information about Bark Beetles

- Native to ponderosa pine ecosystems
- Natural disturbance agents
- Range in size from (0.008-0.33 inches/2.0-8.3 mm) (Figure 1)
- Black to reddish-brown in color
- Kill trees by using a mass attack strategy that can overwhelm the tree's defensive capabilities
- Lifecycle depends on species and location; may have multiple generations per year or only one generation every two years
- Active when ambient temperatures begin to exceed 59°F (15°C), although this varies by species and lifecycle
- Majority of the lifecycle occurs under the bark of the tree, which protects the beetle from predation and environmental extremes
- Resin is a tree's primary defense against bark beetles (Smith 1972)
- Bark beetle success is measured by its ability to reproduce; for most beetle species, tree death is a prerequisite for beetle success

Evidence of attack

- Pitch tubes (Figure 2) form on tree trunk
- Woodpeckers often flake off the outer portion of bark
- Sawdust-like material will collect in bark crevices
- Needles often do not turn yellow until many months after attack
- Beetles create "galleries" on the surface of the wood and in the bark (Figure 3)

Bark Beetles

Although bark beetles are often viewed negatively because they cause tree mortality, bark beetles are native to forest ecosystems and play an important ecological role. They serve as a disturbance agent and play a vital role as a food source for other insects and birds. Tree mortality due to bark beetles increases forest structural diversity and creates habitat for cavity-nesting birds and bats. Therefore, complete eradication of these insects is not desirable and, based on past efforts, not feasible at the landscape scale. That said, recent outbreaks of bark beetles in North America are unprecedented and appear to be driven by human-caused factors, such as increasing tree density (due to past management decisions), and environmental factors, such as increasing temperatures and more frequent and extreme droughts (Raffa et al. 2008, Bentz et al. 2010).

Ponderosa pine forests of the Southwest are home to multiple bark beetle species, most of which belong to either the *Dendroctonus* or *Ips* genera (Table 1). Of the two genera present in ponderosa pine forests, the species in the *Dendroctonus* genus are generally considered to be primary bark beetles: beetles capable of attacking and killing vigorous trees. *Ips* beetles, also called engraver beetles, are known as secondary beetles: beetles which generally attack only weakened or even recently dead trees. However, large populations of *Ips* beetles have been known to attack and kill vigorous trees. Pine engraver outbreaks often occur after beetle populations have increased due to an abundance of slash piles or if many stressed trees are present on the landscape. For instance, *Ips* beetles were implicated in widespread tree mortality of both ponderosa and piñon pine trees during the drought years of 2002 and 2003 (USDA 2013).

Genus species	Common name
Dendroctonus adjunctus	Roundheaded pine beetle
Dendroctonus approximatus	Larger Mexican pine beetle
Dendroctonus brevicomis	Western pine beetle
Dendroctonus frontails	Southern pine beetle
Dendroctonus ponderosae	Mountain pine beetle
Dendroctonus valens	Red turpentine pine beetle
Ips calligraphus	six spined ips
Ips knausi	
Ips lecontei	Arizona five spined ips
Ips pini	Pine engraver

Table 1: List of bark beetles most commonly found in ponderosa pines in Arizona.

Effects of Tree Thinning on Bark Beetle Activity

For almost 90 years, forest researchers have suggested that tree stands with higher tree densities and/or basal area (BA) are more susceptible to damage from bark beetles (reviewed in Fettig et al. 2007). The origin of this hypothesis comes from multiple studies that surveyed stands after bark beetle outbreaks. These studies found that stands with higher BAs or stand density have higher rates of bark beetle attacks and subsequent tree mortality than comparable stands in the same geographic area with lower BAs/densities (Table 2).

Although these studies seem to provide strong correlative evidence that trees in thinned stands are less likely to be attacked by bark beetles, the reasons why these stands/trees are not attacked as frequently are still being investigated. Most researchers think that forest thinning treatments increase tree resistance to bark beetles by reducing tree competition for resources and increasing tree vigor (as often indicated by increased growth rates) (Sartwell and Stevens 1975). Other research indicates that tree/stand susceptibility to bark beetles changes after thinning is due to differences in microclimate (temperature, wind movement, stand structure) (Bartos and Amman 1989, Schmid et al. 1995, Amman and Logan 1998).

Stand Density/Basal Area Studies

Multiple studies from ponderosa pine ecosystems have compared individual trees or forest stands after bark beetle attacks. These studies show that stands/trees with higher BAs, higher stand density, and/or trees with lower growth rates are more likely to have higher amounts of bark beetle-driven tree mortality (reviewed in Fettig et al. 2007). Some of these studies establish threshold BAs below which beetle attacks are less likely (Table 2), while others examine the relationship using more complex techniques. For instance, Negrón (1997) conducted surveys in the Sacramento Mountains of New Mexico and concluded that initial BA was a good predictor of the probability of attack by the roundheaded pine beetle (*Dendroctonus adjunctus*). Furthermore, in the Pinaleño Mountains of Arizona, Negrón et al. (2000) developed a model that found a 72% probability of roundheaded pine beetle infestations in ponderosa pine when BA was greater than 105 ft^2/acre. In the Pine Valley Mountains of Utah, these models predicted that trees in stands with ponderosa pine BA greater than 250 ft^2/acre had a 91% probability of infestation compared to a 32% chance in stands with a lower BA. Since tree death is a prerequisite for beetle success, increased infestation and increased likelihood of attack all suggest an increased likelihood of tree mortality. An additional study, conducted after the severe drought of 2002, found that thinning ponderosa pine stands might help to decrease the amount of tree mortality even during extreme drought events (Negrón et al. 2009). While these studies have found varying thresholds (see Table 2), they provide strong evidence that thinning stands decreases the amount of ponderosa pine mortality due to bark beetles.

Figure 2: Bark beetle trapped in pitch tube on a ponderosa pine tree.

Figure 3: Bark beetle galleries. Formed when beetles lay eggs.

Changes in Stand Microclimate

The microclimate hypothesis suggests that thinned stands may be less susceptible to bark beetle attacks due to changes in stand structure and microclimate, both of which could affect the ability of the bark beetles to find susceptible hosts and/or reproduce successfully. Of particular interest to managers is the fact that changes in microclimate would occur immediately after thinning treatments, whereas changes in host resistance may take a year or longer. Research from other areas of the United States shows that thinning changes air temperature, as well as the temperature in the phloem of the tree, especially those areas exposed to direct sunlight. This increased solar exposure may affect beetle development (generally more heat accelerates their development) or speed phloem drying rate making it more difficult for beetles to reproduce successfully (Amman and Logan 1998). Accelerated development could increase the number of generations beetles produce in a year, although it could also force the beetles to overwinter in stages that are not as resistant to freezing temperatures (reviewed in Bentz et al. 2010). Little research has been done in the Southwest about differences in microclimate or beetle performance in thinned compared to unthinned stands in standing trees. Two studies have looked at beetle reproductive success in slash under different light intensities. Both studies found that the pine engraver beetle (*Ips pini*) had lower reproductive

Authors	**Species Tree/Beetle**	**Location**	**Relevant BAs (ft^2/acre)**	**Notes**
Gaylord et al. 2010	Ponderosa/ multiple	Northern Arizona	160	Increased likelihood of attacks above this threshold
McCambridge et al. 1982	Ponderosa/ MPB	Colorado	120 and 95	More mortality in higher density stands
Negrón et al. 2000	Ponderosa/ RPB	Arizona and Utah	170 and 130*	Infested and uninfested, respectively
Negrón and Popp 2004	Ponderosa/ MPB	Colorado	75	Stands with BAs above this threshold had 50% greater likelihood of attacks
Sartwell and Stevens 1975	Ponderosa/ MPB	Pacific Northwest and Black Hills, SD	150	Increased likelihood of attacks above this threshold
Schmid and Mata 1992	Ponderosa/ MPB	Black Hills, SD	120	Increased likelihood of attacks above this threshold

MPB = Mountain pine beetle
RPB = Roundheaded pine beetle
* See text for further results from this study

Table 2: Relevant studies about thinning and bark beetle attacks in ponderosa pine forests. Variation in results is likely due to differences in the beetle species being examined, levels of beetle populations, or variability in site indices or environmental factors.

success and/or the logs were attacked less frequently in slash exposed to more sunlight/light intensity, although the effect varied by diameter of the log (Villa-Castillo and Wagner 1996, Hayes et al. 2009).

Making Host Trees More Difficult To Locate

The microclimate hypothesis also suggests that thinning makes it harder for beetles to locate host trees. How the first group of beetles selects a host tree is complex, varies by beetle species, and is still not fully understood. It appears that beetles probably use a number of different factors to select potential hosts, including visual orientation toward tree silhouettes, olfactory cues from trees (tree volatiles), and other sensory cues (Raffa and Berryman 1982, Wood 1982, Mattson and Haack 1987, Strom et al. 2001, Seybold et al. 2006). Use of these different cues may allow the beetles to select the most vulnerable or optimal host, possibly based on the tree's vigor/defense. Alternatively, the pioneer beetles may select hosts at random and successful (tree-killing) bark beetle reproduction may be chance events. Once the initial selection is made, the pioneering beetles begin to emit pheromones that attract other beetles to the same host tree.

Thinning appears to disrupt some of the sensory cues used by the beetles. Most obviously, thinning reduces the number of tree silhouettes and could affect the beetles' ability to visually locate a host tree (Strom et al. 2001). Furthermore, thinning appears to allow more wind into the stand, which might make it more difficult for the beetles to locate either the pheromones produced by the other beetles or the olfactory cues from susceptible trees (Thistle et al. 2004). However, two different studies in northern Arizona, which used traps baited with pheromone lures in stands of different BAs, found no significant difference in trap catches among BA treatments for *Ips* beetles (Zausen et al. 2005, Gaylord et al. 2010), although catches of *Dendroctonus* beetles were higher in unmanaged stands than in managed stands (Zausen et al. 2005). These studies suggest that regardless of thinning intensity, there is no significant impact on *Ips* bark beetles ability to locate and orient toward pheromone cues in ponderosa pine forests, but *Dendroctonus* beetles may be able to locate pheromone cues better in stands of higher densities.

Increasing Host Tree Defenses

The most prevalent hypothesis regarding stand thinning suggests that thinning increases stand resistance to bark beetles because it reduces tree competition and, thus, residual trees have greater vigor and more resilience to bark beetles. Multiple studies in northern Arizona have shown that water stress is lower in thinned stands than in unthinned stands and that insect resistance (i.e., amount of resin produced) increased as stand BA decreased (Feeney et al. 1998; Kolb et al. 1998, reviewed in Fettig et al. 2007; McDowell et al. 2007). These results all support the hypothesis that trees in stands with lower BAs are healthier and more resistant to insect attacks.

In contrast, there are some studies that found no differences in tree resin flow between thinned and unthinned stands (Feeney et al. 1998) or even increased resin in unthinned stands relative to thinned stands, (Zausen et al. 2005). Thus, while studies suggest that changes in water availability occur within one year after thinning treatments for trees in several different size/age classes (Stone et al. 1999, Feeney et al. 1998, Skov et al. 2004, Gaylord 2009), how long it takes for a tree to respond to thinning treatments in terms of increased resin production or other measures of tree vigor, such as growth, may depend on several factors, including size or age of the residual tree. In summary, there is no clear-cut answer about how quickly tree defense to bark beetle attacks will increase, if at all, after thinning treatments. Furthermore, the continued effects of the thinning treatments also depend on residual tree density/BA as well as how often the stand is retreated.

Management Implications

While some research is contradictory regarding the effects of thinning on tree defense to bark beetle attacks, overall most evidence suggests that thinning treatments are effective in increasing resistance. Fettig and colleagues (2007) provide a very comprehensive review of the effects of thinning treatments on stand and tree resistance to bark beetles. They examined studies in multiple forest types and came to the conclusion that thinning treatments are an effective method to decrease the likelihood of bark beetle attacks.

Nonetheless, while all the research suggests that thinning stands makes them more resistant to bark beetles, it is impossible to clearly define a threshold BA below which a stand is immune to bark beetle attacks. There are several reasons this is the case. First, when beetle populations are high, there are sufficient numbers of beetles to overcome and kill even the most vigorous trees. Second, the threshold BA will most likely vary by other factors, including which bark beetle species is the most abundant, abiotic conditions (drought, temperature), site index, and the proximity to unmanaged stands (Schmid and Mata 2005). Third, may be the degree of spacing between trees. For instance, in eastern Oregon, researchers found that stands thinned with either 18 ft. x 18 ft. or 21 ft. x 21 ft. spacing experienced little mortality compared to stands with tighter spacing (Sartwell and Dolph 1976). It is likely that researchers simply do not understand all the multiple factors associated with thinning, or how they interact, that ultimately determine bark beetle success at the tree, stand, or landscape level.

Effects of Prescribed Fire on Bark Beetle Activity

Prescribed burning, either used alone or after thinning treatments, is a key management tool for restoring ponderosa pine forests, and is generally acknowledged to help improve forest health and resiliency. In general, the effect of a prescribed fire on a tree's or stand's vulnerability to successful bark beetle attack depends on multiple factors, including the condition of the tree prior to the burn and the amount of damage sustained by the tree from the fire. Trees that are killed by fires are typically infested after the fire by woodwasps (*Hymenoptera: Siricidae*) or woodborers (*Coleoptera*; *Buprestidae* and *Cerambycidae*), but not bark beetles. On the other hand, trees that are infected by pathogens, such as mistletoe or root rot, prior to prescribed burning may be more susceptible to post-fire bark beetle infestations (Parker et al. 2006).

Time Since Treatment and Season of Measurement

As mentioned earlier, resin is a tree's primary defense response to bark beetle attacks. Research from Crater Lake, Oregon indicates ponderosa pines that had been burned showed higher resin flow than unburned controls up to two years after treatment (Perrakis and Agee 2006). In a follow-up study (Perrakis et al. 2011), researchers found bole resin flow remained higher in trees in burned stands than those in the unburned controls four years after the burn treatment. Interestingly, this same study (Perrakis et al. 2011) also reported that while burned stands produced the greatest resin flow they did not have the greatest overstory ponderosa pine survival. The authors suggest that by damaging live trees or volatizing the resin in consumed woody debris, fire may increase the release of host volatiles, which are known to attract bark beetles (reviewed in Seybold et al. 2006). This, in turn, makes fire-damaged trees more attractive to bark beetles and, thus, more likely to incur bark beetle-induced mortality. The researchers suggested that the increased resin volume was inadequate to defend the tree due to the amplified attraction of beetles (Perrakis et al. 2011).

In contrast, in another study conducted in northern Arizona in stands that had been thinned eight to 15 years prior to the study initiation and broadcast burned within eight years after the thinning treatments were conducted, researchers found no difference in resin volume between stands that had been thinned-and-burned and untreated stands and the researchers found the lowest resin volume in stands that had only been thinned (Zausen et al. 2005). While these results suggest that any benefits of the restoration treatments on resin flow may have dissipated with time, the implications of this study should be interpreted with caution as it should be noted that resin was only sampled once per year for the two years of the study and the sample size (four replicates/treatment) was fairly small.

In northern Arizona, the effect of burning on resin volume in ponderosa pine appears to be affected not only by the time since treatment, but also the season during which the resin is measured. Various studies (Feeney et al. 1998, Wallin et al. 2004, Wallin et al. 2008) report that when resin is measured during the dry season (June), trees in areas that have been thinned and burned produce more resin, and have a lower chance of being attacked by beetles, than trees in the controls or thin-only treatments. Moreover, they observed that the effect of the thin-and-burn treatment on resin lasts up to seven years. In contrast, the same treatments do not seem to confer the same benefit when resin was measured during the wet monsoon season, with trees in the control stand producing the same amount, or even more, resin than trees in either of the restoration treatments seven years post treatment (Wallin et al. 2004). Since beetles in the southwestern ponderosa pine system are active as soon as temperatures exceed 59 degrees Fahrenheit (15 degrees Celsius) (Williams et al. 2008, Gaylord et al. 2008), these results suggest that trees in thinned-and-burned stands may have increased resistance to bark beetle attacks during the dry season but not during the monsoon season.

Crown Damage

In ponderosa pine forests, the probability of a tree being attacked and killed by bark beetles after a fire appears to be strongly correlated to the amount of damage sustained by the crown of the tree (Miller and Keen 1960, Breece et al. 2008, Perrakis et al. 2011). Research in northern Arizona suggests that fires that produce significant amounts of crown scorch and crown consumption increase the likelihood of successful beetle attacks. One study found that 1) higher crown scorch decreased resin flow four months after burning treatments and 2) bark beetle colonization attempts increased with increased crown scorch (Wallin et al. 2003). A study by McHugh and colleagues (2003) examined trees in both prescribed fires and two wildfires. In all cases, they found the trees that showed evidence of bark beetle attacks had significantly more crown scorch and total crown damage than trees without evidences of beetles. Furthermore, trees that were dead and with evidence of beetle attacks had significantly more crown scorch and total crown damage than trees that had survived with evidence of beetle attacks. Overall McHugh et al. (2003) observed that mortality was low in trees that had no evidence of beetle attacks unless crown damage exceeded 70–80%. However, when beetles were present, tree mortality occurred with only 30–40% crown damage.

Season of Burning

Research has been conducted to assess how the season of burning affects the susceptibility of trees to insect attacks. Researchers have hypothesized that crown scorch early in the growing season may have more impact than dormant-season crown scorch (Fischer 1980). However, more recent studies in the Sierra Nevada and Oregon concluded that

the probability of bark beetle attack on pines did not differ between early and late-season burns. Instead, these studies found tree mortality was related to the amount of fire-related damage and not the season during which the burn occurred (Thies et al. 2005, Schwilk et al. 2006, Perrakis et al. 2011).

Effects of Burning on Subsequent Bark Beetle Attacks
Much of our initial understanding of the interaction between fire and bark beetles came from chapters in Miller and Keen (1960), which suggest increased susceptibility to bark beetle attacks after both wildfire and prescribed burning in ponderosa pine stands in California, Oregon, Idaho, and Montana. However, a more recent study by Fettig et al. (2010) in the southern Cascades of northern California reported that there was relatively little bark beetle-associated mortality on plots that had been thinned or thinned-and-burned when compared to plots that had received a burn-only treatment. In addition, on the burn-only plots, much of the mortality occurred to smaller diameter trees. Our understanding has also been increased by multiple studies that have shown that increased bark beetle attacks occur when there is more damage to crown. Thus, to reduce the likelihood of bark beetle attacks post-fire, and the potential for undesirable tree mortality, land managers should attempt to keep crown scorch to a minimum during prescribed burning treatments.

Land managers should also recognize that the amount of tree mortality from bark beetles varies with beetle population levels (Breece et al. 2008). Thus, while crown damage does increase the likelihood of attacks, when beetle populations are at low, subsequent tree mortality from bark beetle attacks will likely be low and often within acceptable management guidelines (Breece et al. 2008). Furthermore, in many cases after fires, the red turpentine beetle (*Dendroctonus valens*) is the most likely bark beetle to be present. This insect generally attacks only the lower bole of the tree, which results in very large, distinctive pitch tubes (Figure 4). In North America, this beetle is not considered very aggressive. However, red turpentine beetle attacks are often followed by attacks from other bark beetles. Thus, trees with evidence of red turpentine beetle should be closely monitored (Parker et al. 2006).

While fire damage to a specific tree may increase the chances of that individual tree being attacked by bark beetles, there is currently no research in southwestern pine forests to indicate how likely it is that the beetle infestations will spread to adjacent, unburned stands. Older research from Oregon, with western pine beetle in ponderosa pine, suggests that fire scorched trees may act as a sink for beetles, rather than a source (Miller and Patterson 1927). More recent research in California found little evidence of beetle populations building up in fire-injured white fir (*Abies concolor*) and several species of pines, including ponderosa, and expanding to healthy, green trees (Fettig et al. 2010). However, research after the Yellowstone fires of 1988 (Rasmussen et al. 1996) in Douglas-fir (*Pseudotsuga menziesii*), lodgepole pine (*Pinus contorta*), and Engelmann spruce (*Picea engelmannii*) trees suggest that beetle populations are able to build up in fire-injured trees and, subsequently, move to uninjured trees in the surrounding forested area.


Figure 4: Pitch tubes from red turpentine beetles near the bottom of a ponderosa pine tree. *Photo courtesy of J. McMillin*

Management Recommendations

The research studies highlighted in this working paper suggest the following points for land managers to consider when planning restoration treatments to reduce bark beetle problems:

- In general, thinning forest stands appears to decrease the susceptibility of trees to bark beetle attacks either due to increased tree vigor/defense, changes in microclimate, a combination of the two, or some other unexamined set of variables.
- There is no clear threshold BA below which no bark beetle attacks will occur.
- Bark beetle populations fluctuate and when they are at high levels even vigorous trees can be attacked and killed.
- Under the predicted climate change scenarios of increasing droughts (Seager et al. 2007), thinning stands may help to mitigate the amount of water stress trees experience and, thus, lessen the likelihood of bark beetle-driven tree mortality.
- Since most beetles tend to perform better in trees of specific diameters, thinning stands, and simply increasing the heterogeneity across the landscape will help to decrease the likelihood of landscape-level bark beetle attacks.
- The prompt disposal of slash will reduce the potential for bark beetle infestations. Likewise, chipping operations, because they release odors that may attract beetles and lead to increased beetle

activity, are best done in areas away from vulnerable trees (Fettig et al. 2006).

- The impact of prescribed fire on the likelihood of bark beetle attacks appears to be affected by the amount of crown scorch on the residual trees.
- Managers would be advised to limit the amount of crown scorch during prescribed burns in order to minimize the likelihood of post-fire bark beetle outbreaks (Fowler et al. 2010).
- Although more research is needed, there is some evidence to support that fire will increase resin production in trees, especially during dry seasons.
- In particular, if management objectives of restoration treatments include maintaining old ponderosa pine trees from fire, it would be best to rake leaf litter away from the base of trees (Egan 2011). This will help limit damage to the tree that could further weaken trees making them more susceptible to bark beetles. Removing understory trees to limit crown scorch is also advisable (reviewed in Kolb et al. 2007).

References

Amman, G.D. and J.A. Logan. 1998. Silvicultural control of mountain pine beetle: prescriptions and the influence of microclimate. *American Entomologist* 44:166-177.

Bartos, D.L. and G.D. Amman. 1989. Microclimate: an alternative to tree vigor as a basis for mountain pine beetle infestations. USDA Forest Service. Res. Pap. INT-400. Intermountain Research Station.

Bentz, B.J., J. Regniere, C.J. Fettig, E.M. Hansen, J.L. Hayes, J.A. Hicke, R.G. Kelsey, J.F. Negrón, and S.J. Seybold. 2010. Climate change and bark beetles of the western United States and Canada: Direct and indirect effects. *BioScience* 60:602-613.

Breece, C.R., T.E. Kolb, B.G. Dickson, J.D. McMillin, and K.M. Clancy. 2008. Prescribed fire effects on bark beetle activity and tree mortality in southwestern ponderosa pine forests. *Forest Ecology and Management* 255:119-128.

Coulson, R.N. and J.A. Witter. 1984. *Forest entomology: Ecology and management*. New York: John Wiley and Sons.

Egan, D. 2011. *Protecting old trees from prescribed burning*. Ecological Restoration Institute Working Paper 24. Flagstaff, AZ: Ecological Restoration Institute.

Feeney, S.R., T.E. Kolb, W.W. Covington, and M.R. Wagner. 1998. Influence of thinning and burning restoration treatments on presettlement ponderosa pines at the Gus Pearson Natural Area. *Canadian Journal of Forest Research* 28:1295-1306.

Fettig, C., R. Borys, and C. Dabney. 2010. Effects of fire and fire surrogate treatments on bark beetle-caused tree mortality in the southern Cascades, California. *Forest Science* 56:60-73.

Fettig, C.J., K.D. Klepzig, R.F. Billings, A.S. Munson, T.E. Nebeker, J.F. Negrón, and J.T. Nowak. 2007. The effectiveness of vegetation management practices for prevention and control of bark beetle infestations in coniferous forests of the western and southern United States. *Forest Ecology and Management* 238:24-53.

Fettig, C.H., J.D. McMillin, J.A. Anhold, S.M. Hamud, R.R. Borys, C.P. Dabney, and S.J. Seybold. 2006. The effects of mechanical fuel reduction treatments on the activity of bark beetles (Coleoptera: Scolytidae) infesting ponderosa pine. *Forest Ecology and Management* 230:55-68

Fischer, W.C. 1980. Prescribed fire and bark beetle attack in ponderosa pine forests. USDA Forest Service. Fire Management Notes 41:10-12.

Fowler, J.F., C.H. Sieg, J. McMillin, K.K. Allen, J.F. Negrón, L.L. Wadleigh, J.A. Anhold, and K.E. Gibson. 2010. Development of post-fire crown damage mortality thresholds in ponderosa pine. *International Journal of Wildland Fire* 19:583-588.

Gaylord, M.L. 2009. Factors impacting management of pine bark beetles in ponderosa pine forests in northern Arizona. Ph.D. dissertation. School of Forestry, Northern Arizona University, Flagstaff, AZ.

Gaylord, M.L., R.W. Hofstetter, and M.R. Wagner. 2010. Impacts of silvicultural thinning treatments on beetle trap captures and tree attacks during low bark beetle populations in ponderosa pine forests of northern Arizona. *Journal of Economic Entomology* 103:1693-1703.

Gaylord, M.L., K.K. Williams, R.W. Hofstetter, J.D. McMillin, T.E. DeGomez, and M.R. Wagner. 2008. Influence of temperature on spring flight initiation for southwestern ponderosa pine bark beetles (Coleoptera: Curculionidae, Scoytinae). *Environmental Entomology* 37:57-69.

Hayes, C.J., R.W. Hofstetter, T.E. DeGomez, and M.R. Wagner. 2009. Effects of sunlight exposure and log size on pine engraver (Coleoptera: Curculionidae) reproduction in ponderosa pine slash in northern Arizona, U.S.A. *Agricultural and Forest Entomology* 11:341-350

Kolb, T.E., K.M. Holmberg, M.R. Wagner, and J.E. Stone. 1998. Regulation of ponderosa pine foliar physiology and insect resistance mechanisms by basal area treatments. *Tree Physiology* 18: 375-381.

Kolb, T.E., J.K. Agee, P.Z. Fulé, N.G. McDowell, K. Pearson, A. Sala, and R.H. Waring. 2007. Perpetuating old ponderosa pine. *Forest Ecology and Management* 249:141-157.

Mattson, W.J. and R.A. Haack. 1987. The role of drought in outbreaks of plant-eating insects. *BioScience* 37:110-118.

McCambridge, W.F., F.G. Hawksworth, C.B. Edminster, and J.G. Laut. 1982. Ponderosa pine mortality resulting from a mountain pine beetle outbreak. USDA Forest Service, RP-RM-235. Rocky Mountain Research Station.

McDowell, N.G., H.G. Adams, J.D. Bailey, and T.E. Kolb. 2007. The role of stand density on growth efficiency, leaf area index, and resin flow in southwestern ponderosa pine forests. *Canadian Journal of Forest Research* 37:343-355.

McHugh, C.W., T.E. Kolb, and J.L. Wilson. 2003. Bark beetle attacks on ponderosa pine following fire in northern Arizona. *Environmental Entomology* 32:510-522.

Miller, J. and F.P. Keen. 1960. Biology and control of the western pine beetle. USDA, Misc. Publication 800.

Miller, J.M. and J.E. Patterson. 1927. Preliminary studies on the relation of fire injury to bark beetle attack in western yellow pine. *Journal of Agricultural Research* 34:597-613.

Negrón, J. 1997. Estimating probabilities of infestation and extent of damage by the roundheaded pine beetle in ponderosa pine in the Sacramento Mountains, New Mexico. *Canadian Journal of Forest Research* 27:1936-1945.

Negrón, J. F. and J.B. Popp. 2004. Probability of ponderosa pine infestation by mountain pine beetle in the Colorado Front Range. *Forest Ecology and Management* 191:17-27.

Negrón, J.F., J.D. McMillin, J.A. Anhold, and D. Coulson. 2009. Bark beetle-caused mortality in a drought-affected ponderosa pine landscape in Arizona, USA. *Forest Ecology and Management* 257:1353-1362.

Negrón, J., J.L. Wilson, and J.A. Anhold. 2000. Stand conditions associated with roundheaded pine beetle (Coleoptera: Scolytidae) infestations in Arizona and Utah. *Environmental Entomology* 29:20-27.

Parker, T.J, K.M. Clancy, and R.L. Mathiasen. 2006. Interactions among fire, insects and pathogens in coniferous forests of the interior western United States and Canada. *Agricultural and Forest Entomology* 8:167-189.

Perrakis, D.D.B. and J.K. Agee. 2006. Seasonal fire effects on mixed-conifer forest structure and ponderosa pine resin properties. *Canadian Journal of Forest Research* 36:238-254.

Perrakis, D.D.B., J.K. Agee, and A. Eglitis. 2011. Effects of prescribed burning on mortality and resin defenses in old growth ponderosa pine (Crater Lake, Oregon): Four years of post-fire monitoring. *Natural Areas Journal* 31:14-25.

Raffa, K.F. and A.A. Berryman. 1982. Gustatory cues in the orientation of *Dendroctonus ponderosae* (Coleoptera: Scolytidae) to host trees. *Canadian Entomologist* 114:97-104.

Raffa K.F., B.H. Aukema, B.J. Bentz, A.L. Carroll, J.A. Hicke, M.G. Turner, and W.H. Romme. 2008. Cross-scale drivers of natural disturbances prone to anthropogenic amplification: the dynamics of bark beetle eruptions. *BioScience* 58:501-517.

Rasmussen, L.A., G.D. Amman, J.C. Vandygriff, R.D. Oakes, A.S. Munson, and K.E. Gibson. 1996. Bark beetle and wood borer infestation in the greater Yellowstone area during four postfire years. USDA Forest Service, INT-RP-487, Intermountain Research Paper.

Sartwell, C. and R.E. Dolph, Jr. 1976. Silvicultural and direct control of mountain pine beetle in second growth ponderosa pine. USDA Forest Service, RN-PNW-268.

Sartwell, C. and R.E. Stevens. 1975. Mountain pine beetle in ponderosa pine: Prospects for silvicultural control in second-growth stands. *Journal of Forestry* 73:136-140.

Schmid, J.M. and S.A. Mata. 1992. Stand density and mountain pine beetle-caused tree mortality in ponderosa pine stands. USDA Forest Service, RM-515.

Schmid, J.M. and S.A. Mata. 2005. Mountain pine beetle-caused tree mortality in partially cut plots surrounded by unmanaged stands. USDA Forest Service, Res. Note, RMRS-RP-54.

Schmid, J.M., S.A. Mata, and W.K. Olsen. 1995. Microclimate and mountain pine beetles in two ponderosa pine stands in the Black Hills. USDA Forest Service, RM-RN-532.

Schwilk, D.W., E.E. Knapp, S.M. Ferrenberg, J.E. Keeley, and A.C. Caprio. 2006. Tree mortality from fire and bark beetles following early and late season prescribed fires in a Sierra Nevada mixed-conifer forest. *Forest Ecology and Management* 232:36-45.

Seager R., M. Ting, I. Held, Y. Kushnir, J. Lu, G. Vecchi, H. Huang, A. Leetmaa, N. Lau, C. Li J.Velez, and N. Naikl. 2007. Model projections of an imminent transition to a more arid climate in southwestern North America. *Science* 316: 1181-1184.

Seybold, S.J., D.P.W. Huber, J.C. Lee, A.D. Graves, and J. Bohlmann. 2006. Pine monoterpenes and pine bark beetles: A marriage of convenience for defense and chemical communication. *Phytochemistry Review* 5:143-178.

Skov, K.R., T.E. Kolb, and K.F. Wallin. 2004. Tree size and drought affect ponderosa pine physiological response to thinning and burning treatments. *Forest Science* 50:81-91.

Smith, R.H. 1972. Xylem resin in the resistance of the Pinacea to bark beetles. USDA Forest Service, General Technical Report PSW-1.

Stone, J.E., T.E. Kolb, and W.W. Covington. 1999. Effects of restoration thinning on presettlement Pinus ponderosa in northern Arizona. *Restoration Ecology* 7:172-182.

Strom, B.L., R.A. Goyer, and P.J. Shea. 2001. Visual and olfactory disruption of orientation by the western pine beetle to attractant-baited traps. *Entomologia Experimentalis et Applicata* 100:63-67.

Thies, W.G., D.J. Westlind, and M. Loewen. 2005. Season of prescribed burn in ponderosa pine forests in eastern Oregon; impact on pine mortality. *International Journal of Wildland Fire* 14:223-231.

Thistle, H.W., H. Peterson, G. Allwine, B. Lamb, T. Strand, E. H. Holsten, and P.J. Shea. 2004. Surrogate pheromone plumes in three forest trunk spaces: composite statistics and case studies. *Forest Science* 50:610-625.

United States Department of Agriculture (USDA). 2013. Aerial survey information. http://www.fs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb5238439.pdf.

Villa-Castillo, J. and M.R. Wagner. 1996. Effect of overstory density of *Ips pini* (Coleoptera: Scolytidae) performance in ponderosa pine slash. *Journal of Economic Entomology* 89:1537-1545.

Wallin, K.F., T.E. Kolb, K.R. Skov, and M.R. Wagner. 2003. Effects of crown scorch on ponderosa pine resistance to bark beetles in northern Arizona. *Environmental Entomology* 32:652-661.

Wallin, K.F., T.E. Kolb, K.R. Skov, and M.R. Wagner. 2004. Seven-year results of thinning and burning restoration treatments on old ponderosa pines at the Gus Pearson Natural Area. *Restoration Ecology* 12:239-247.

Wallin, K.F., T.E. Kolb, K.R. Skov, and M.R. Wagner. 2008. Forest management treatments, tree resistance, and bark beetle resource utilization in ponderosa pine forests of northern Arizona. *Forest Ecology and Management* 255:3263-3269.

Williams, K.K., J.D. McMillin, T.E. DeGomez, K.M. Clancy, and A. Miller. 2008. Influence of elevation on bark beetle (Coleoptera: Curculionidae: Scolytinae) community structure and flight periodicity in ponderosa pine forests of Arizona. Environmental Entomology 37: 94-109.

Wood, D.L. 1982. The role of pheromones, kairomones and allomones in the host selection and colonization behavior of bark beetles. *Annual Review Forest Entomology* 27:411-446.

Zausen, G.L., T.E. Kolb, J.D. Bailey, and M.R. Wagner. 2005. Long-term impacts of stand management on ponderosa pine physiology and bark beetle abundance in northern Arizona: A replicated landscape study. *Forest Ecology and Management* 218:291-305.

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