

Ecological Restoration Institute
Working Paper No. 31

31

Climate Change Impacts on Bark Beetle Outbreaks and the Impact of Outbreaks on Subsequent Fires

June 2014

NORTHERN
ARIZONA
UNIVERSITY



Ecological
Restoration Institute



SOUTHWEST
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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.

This publication would not have been possible without funding from the USDA Forest Service and the Southwest Fire Science Consortium. The views and conclusions contained in this document are those of the author(s) and should not be interpreted as representing the opinions or policies of the United States Government. Mention of trade names or commercial products does not constitute their endorsement by the United States Government or the ERI.

Author: Monica Gaylord

Reviewers: Barbara Benz, Chris Fettig, David Huffman, Andrea Thode, and Barb Satink Wolfson, Amy Waltz

Series Editor: Tayloe Dubay

Please use the following citation when referring to this Working Paper:

Gaylord, M.L. 2014. Climate Change Impacts on Bark Beetle Outbreaks and the Impact of Outbreaks on Subsequent Fires. ERI Working Paper No. 31. Ecological Restoration Institute and Southwest Fire Science Consortium, Northern Arizona University: Flagstaff, AZ. 7 p.

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Introduction

The Insect

Bark beetles are small insects that can have profound impacts on forests. While some species of bark beetles primarily attack trees that are recently dead or dying, others attack live, vigorous trees and can cause tree mortality across extensive areas. The Southwest is home to multiple species of bark beetles (Gaylord et al. 2006, Williams et al. 2008). In southwestern ponderosa pine forests the most notable bark beetle species belong to the genus *Ips* or *Dendroctonus*.

Ecological Role and Impacts

Bark beetles and fire share similar roles in southwestern ponderosa pine forests. Similar to fire, bark beetles are natural disturbance agents and help with nutrient redistribution. Tree mortality from bark beetles helps with snag formation, providing vital habitat for cavity nesting birds and bats, among other wildlife. Bark beetles are a food source for other insects and birds. At low bark beetle populations, tree mortality ranges from individual trees to small groups of trees leading to gap formation and increasing forest heterogeneity. Epidemics, or outbreaks, are also part of the natural cycle. In some ecosystems, such as mountain pine beetle in lodgepole pine, the forests are homogenized after these outbreaks, helping to perpetuate lodgepole pine stands (Brown 1975). Historically, epidemics would subside due to excessively cold temperatures or because suitable host material (tree species or preferred diameter range) becomes depleted.

Current bark beetle outbreaks in some forest systems are considered unprecedented (Raffa et al. 2008, Bentz et al. 2009). Recent outbreaks appear to be driven by warmer/drier climate, an abundance of overstocked and homogeneous stands caused by past management decisions, or a combination of these and other factors (Raffa et al. 2008, Bentz et al. 2010, Fettig et al. 2013). In essence, large-scale outbreaks are a result of many of the same factors driving catastrophic fires and, consequently, both disturbance agents are having impacts on ecosystems that are often outside of their historic range of variability.

Climate Change and Bark Beetle Outbreaks

Historically, tree mortality from bark beetles in southwestern forests is often correlated with drought events (Kleinman et al. 2012, USDA 2013). Climate models for the southwestern U.S. forecast more frequent and severe drought events (Seager et al. 2007). Given past associations between drought events and bark beetle outbreaks it appears likely that bark beetle-driven tree mortality could also increase. In addition to water deficits, most models for the Southwest indicate this area will experience increased temperatures (Seager et al. 2007). During the most recent drought event in the Southwest (2002), temperatures were warmer than normal (Breshears et al. 2005). Both of these factors (higher temperatures and increased water stress) could impact bark beetle populations. Changes in

Key Information about Bark Beetles

- Native to pine ecosystems in the Southwest
- Natural disturbance agents
- Range in size from 0.008-0.33 inches (2.0-8.3 mm)
- Adults are 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; can 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
- Majority of the lifecycle occurs under the bark of the tree
- 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

- Resin is a tree's primary defense against beetles
- Pitch tubes will form on the tree bole (Fig. 1)
- Woodpeckers often flake off the outer portion of bark
- Sawdust-like material (frass) will collect in bark crevices (Fig. 1)
- Needles often do not turn yellow until many months after attack
- Beetles create "galleries" on the surface of the wood and in the bark (Fig. 2)

temperature will likely have a direct impact on the beetle itself whereas water stress (exacerbated by increased temperatures and periods of drought) will indirectly impact the beetle via impacts on the host trees (Bentz et al. 2010).



Figure 1: Pitch tube and frass in bark crevices on a ponderosa pine tree.





Figure 2: Bark beetle galleries.

Direct Impacts of Temperature on Bark Beetles

Because temperature is a major driver of their physiological processes, all bark beetle species will be affected in some way by climate change. Depending on the species and their geographic location, the generation time for beetles can range from multiple generations per year to one generation every one to two years. Increased temperatures generally accelerate the rate of bark beetle development. Accelerated development may have positive or negative impacts on beetle populations depending on the circumstances (reviewed in Bentz et al. 2010). For instance, quicker beetle development and warmer temperatures earlier in the spring and/or later in the fall could allow beetles to increase the number of generations completed. This could allow for faster buildups of populations and a greater likelihood of beetle epidemics. On the other hand, accelerated development could cause increased beetle mortality. Because some stages of beetle development are much cold hardier than others (Bentz and Mullins 1999, Tran et al. 2007), accelerated development may cause the beetles to enter winter in a developmental stage that is not as resistant to freezing temperatures. This could lead to a decline in beetle populations due to higher mortality rates during winter. Similarly, beetles with only one generation a year are dependent on a relatively synchronous emergence in order to mass attack trees. Loss of synchrony could occur due to changing temperatures and this could be detrimental to these beetle species (Logan and Bentz 1999, Bentz et al. 2010).

Impact of Temperature Changes on Range Expansion or Contraction of Bark Beetles

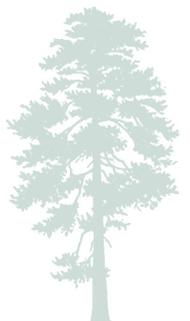
Increased temperatures could also allow beetles to spread farther north or to higher elevations than their historic range (Logan and Bentz 1999, Williams and Liebhold 2002, Tran et al. 2007, Sambaraju et al. 2011). Beetles entering new geographic regions will encounter different beetle and predator complexes and it is unknown how these novel interactions will be resolved. In addition, beetles may be encountering new hosts. While these hosts likely have well developed defenses against those bark beetle species that

already occur in their respective ranges, they may not be as well defended against the new beetle species. Furthermore, recent work in Canada suggests that host trees growing in regions that historically have been climatically inhospitable to bark beetles, may be less resistant to beetle attacks than trees of the same species growing in areas where outbreaks have historically occurred (Cudmore et al. 2010). Thus, with climate change beetles may move to new geographic areas where hosts may be less well-defended, leading to increased beetle populations. Conversely, if suitable hosts are restricted to a smaller range, or are not able to survive under changing climate conditions, the beetles may perish due to the loss of their food source (Williams and Liebhold 2002).

Indirect Effects on Bark Beetles: Impact of Climate Change on the Host

An additional indirect impact of climate change on beetle populations is the impact warming temperatures and droughts could have on the host tree. Trees that are water stressed may be more susceptible to bark beetle attacks. Drought has well-established physiological impacts on trees (McDowell et al. 2008, McDowell 2011). In both ponderosa and piñon pine trees, water stress has been shown to reduce or even shut down photosynthesis, this leads to less carbon assimilation and eventual carbon limitation (Gaylord et al. 2007, Plaut et al. 2012). Resin is the first line of defense that bark beetles encounter when attacking a tree. Since resin is carbon based, lower amounts of carbon assimilation by the tree is hypothesized to lead to less resin production (Herms and Mattson 1992, McDowell et al. 2008). Lethal bark beetle attacks also can occur during drought due to reasons other than lower resin production. For instance, volatile and auditory emissions from trees during drought may attract beetles (Mattson and Haack 1987, Kelsey et al. 2014). In fact, a recent study in piñon pine in New Mexico found that plots subjected to an experimental drought treatment had a much higher percentage of tree mortality than ambient and irrigated plots. The majority of piñons that died in this study had evidence of piñon ips attacks, despite the fact that resin volume did not decline (Gaylord et al. 2013). After beetle populations have built up in stressed trees, some beetle populations, such as mountain pine beetle and spruce beetle begin to attack and kill even vigorous trees, while other outbreaks, such as piñon ips, subside once the trees are no longer stressed.

Past management actions may increase the impacts of climate change. For example, in ponderosa pine forests of the Southwest, years of fire suppression have led to forests with higher stand densities; these increased densities also lead to increased competition among trees, particularly for limited resources such as water (Kolb et al. 1998). Increased temperatures could increase the level of water stress the trees experience (i.e., increased evaporation and transpiration with increased temperatures), that could accelerate the rate of tree mortality (Williams et al. 2013).



Conclusions

- Climate change will most likely increase the frequency and severity of bark beetle outbreaks in the Southwest.
- Increased beetle populations could occur due to the shortened generation times and longer developmental periods caused by increasing temperatures. However not all species will be able to successfully adapt to the increased temperatures (Bentz et al. 2014).
- Drought and increased temperatures will likely lead to more stressed trees and thus more susceptible hosts.
- Due to warming temperatures, beetles may be able to expand their range and encounter trees with lower resistance to bark beetle attacks.
- Beetles distribution is dependent on the range of suitable host trees. If the suitable host-tree range contracts due to climate change, the bark beetle range will also contract. Conversely, if the host-tree range expands, the beetle range may also expand.
- In addition, while we understand some of the interactions and feedbacks that might occur between bark beetles and their host, it is impossible to model all of the interactions that occur in an ecosystem, such as the impact of climate change on bark beetle predators or competing herbivores. Furthermore, when bark beetles enter the trees they bring along specific fungi as well as other organisms including mites and nematodes. Many of these other organisms are thought to play a role in beetle success. How these other organisms respond to changing temperatures could also influence the impact of climate change on beetle success (Six et al. 2011).

Management Implications

- Thinning appears to reduce water stress in southwestern forests, thus thinning treatments may help to mitigate some of the impacts of climate change (reviewed in Fettig et al. 2007).
- Managers should attempt to maintain or improve forest resilience through restoration, such as mechanical thinning and prescribed burning, or other management activities. These preventative treatments are the best option. After bark beetle populations build up, beetles are much more difficult to control. Options include sanitation, salvage, and the use of insecticides and semiochemicals. These methods are generally only used on a small scale for individual, high-value trees or areas and are generally impractical at the landscape level (Gaylord 2014).

Impact of Beetle Outbreaks on Future Fires

Landscape-level tree mortality from bark beetle epidemics is a concern for land managers in terms of future fire risk and behavior. The widely held assumption has been that bark beetle associated tree mortality increases fire risk and severity. Intuitively this makes sense. High tree mortality leads to an increase in dry fuels on the landscapes. However, several recent papers (Romme et al. 2006, Kulakowski and Veblen 2007, Jenkins et al. 2008,

Bond et al. 2009, DeRose and Long 2009, Klutsch et al. 2011, Simard et al. 2011, Jenkins et al. 2012) as well as comprehensive literature reviews (Hicke et al. 2012, Jenkins et al. 2014) have suggested that the relationship is not as straightforward as first thought. What is evident is that tree mortality from bark beetles is likely to impact fire risk and behavior for many years after the actual outbreak has ended.

After a beetle outbreak, affected stands will undergo changes in tree species, fuel structure, fuel type, and canopy and surface fuel loads. All of these factors can impact future fire risk and behavior. Many different researchers have attempted to model the impact of the tree mortality and stand regrowth on future fires. Although there is some disagreement among the different models, there is general consensus that stand fire susceptibility does not increase or decrease in a strictly linear fashion post-bark beetle outbreaks (reviewed in Hicke et al. 2012). Time since outbreak appears to be an important variable in determining stand susceptibility to fire post-outbreak; however, because different stand types will change at different rates post-outbreak (rate of needle drying, snag fall, and understory regrowth are all variable and depend on multiple factors), most studies will address what “phase” a stand is in post-outbreak in addition to, or rather than just, “years” post-fire (Box 1).

Green phase	Healthy, uninfested trees
Red phase	Needles still on the tree. Low foliar moisture content *Note: Needle color depends on tree species, may be greenish
Gray phase	After needle drop Trees appear gray Fine twigs still remain on trees early in this phase, but will drop in the latter part
Older or Old phase	Snags fall Understory vegetation increases Seedlings establish

Box 1. Stands are categorized in “phases” in relation to bark beetle outbreaks (from Hicke et al. 2012).

There are also some acknowledged shortcomings of modeling potential fire in stands post-bark beetle epidemics (Jenkins et al. 2012). For instance, the majority of the work on fire models has been conducted in cooler, moister forest types such as lodgepole pine and spruce, little work has been done in drier, southwestern pine forests such as piñon and ponderosa. Since different stand types can have very different structures and fire behavior, translating results from system to system should be done with caution. Clearly more research is needed in southwestern systems. In addition, most fire models are based on live fuels. Dead fuels tend to be drier than live fuels and they have different chemical composition; in particular they do not contain as many volatile oils, and thus their flammability varies from live fuels (Jolly



et al. 2012). In fact, one study in lodgepole pine used a range of moisture scenarios and wind speeds to model fire behavior (Schoennagel et al. 2012). The researchers found that more active crown fire was possible at lower wind speeds and with less extreme crown conditions in the stands with dead or dying needles versus the green stands. Moreover, the more open canopy and large surface fuel loads in stands in the gray phase and older lead to an increase in surface fireline intensities. In fact, under extreme burning conditions the minimum wind speed for active crown fires were 15.5-22 miles per hour (mph) lower for red, gray and older- stands compared to the green. To complicate matters further, in stands with an ongoing epidemic, there will likely be a range of stages of tree death with some trees with red or brown needles, others still fading, and others still green. The percentage of trees within each of these categories will impact the potential for fire and fire behavior (Jenkins et al. 2008, 2012). For instance, studies of lodgepole pine in Yellowstone found that the likelihood of crown fire increased in areas of heavy bark beetle associated tree mortality (>50%) relative to areas with less tree mortality (Turner et al. 1999). Finally, modeling stand susceptibility to fire post-beetle outbreaks over the longer term requires some inputs about snag fall and decomposition rates. Snag fall rates are variable or unknown for many forest types in the West.

Changes in Fuels Post-Outbreaks

Different studies disagree slightly about the amount of fuels present early in the red phase, and again, results probably vary from system to system. Most of the studies conducted to date, primarily in moist, cool forest types, agree that 1-10 hour fuels increase during the latter half of the red phase and into the gray phase and then gradually decrease as these small fuels begin to break down and decompose (Jenkins et al. 2008, reviewed in Hicke et al. 2012, Figure 3). There is also a fair amount of agreement that both ladder fuels and 100-1,000-hour fuels begin to increase steadily as the gray phase ends. During this time, snag fall begins as does understory regrowth and development (Hicke et al. 2012).

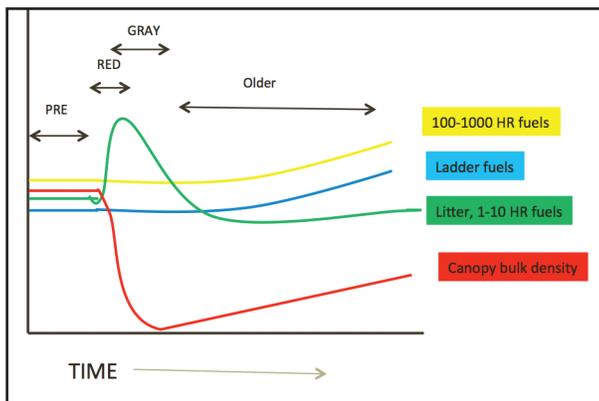


Figure 3: Conceptual framework for change in fuels post-beetle outbreaks (modified from Hicke et al. 2012).

Changes in Fire Behavior Post-Outbreaks

With regard to fire behavior, there is less agreement among the various models on what happens in the red and gray phase than in the older phase (reviewed in Hicke et al. 2012). In the framework developed by Hicke et al. (2012), based on research primarily conducted in spruce and lodgepole forest types, they indicated an increase in active crown fire potential early in the red phase and then a swift decrease midway through the red phase leading to a gradual increase again as the stand begins to regrow. In addition, for surface fire and torching potential, this study proposed a relatively uniform increase from the beginning of tree mortality through stand regrowth, although torching potential is proposed to have a slightly greater increase during the red phase than surface fire does during this same time frame (Figure 4).

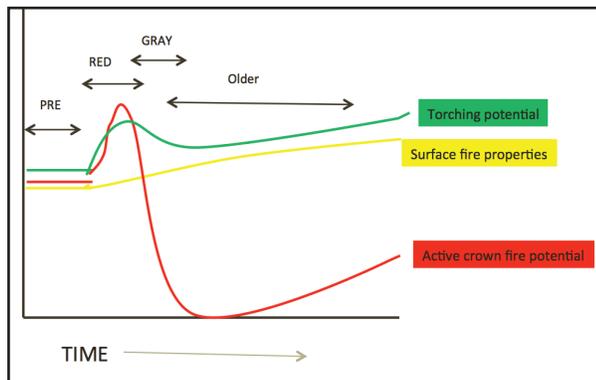
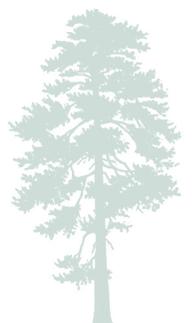


Figure 4: Conceptual framework for changes in fire behavior post-beetle outbreaks (modified from Hicke et al. 2012).

Attacked Stands Versus Unattacked Stands

There has also been interest in the difference in fire potential and severity in stands attacked by bark beetles versus unattacked stands. A recent study, based primarily on work in lodgepole and spruce forests, reported the probability of crown fires increases during the red phase as does crown fire severity (assuming other conditions are favorable for fire: climate, ignition, etc.) but the probability and intensity of surface fire is not increased (Hicke et al. 2012). In the gray and older phases, the probability of surface fire may increase but crown fire probability and severity most likely decreases. This same team went on to say that, because crown fire and surface fire respond differently, it is difficult to predict what the combined response will be within a stand. Furthermore, it is important to point out that crown fire spread is controlled by more factors than just dead fuel quantity. For instance, live fuel moisture, wind speed, and canopy density also play a role. Romme et al. (2006) emphasized that once needle drop occurs, new gaps exist in the canopy and canopy bulk density is decreased, that may reduce the risk of crown fires. In fact, a study conducted in lodgepole pine in Yellowstone suggested that mountain pine beetle outbreaks in these forests may actually



reduce the probability of active crown fire in the short term because the canopies have been thinned (Simard et al. 2011), similarly, windspeeds predicted to sustain active crown fire in lodgepole pine stands in Colorado were predicted to be lower in uninfested plots than infested plots (Klutsch et al 2011). In addition, in the San Bernardino Mountains of California, researchers found no evidence that pre-fire tree mortality influenced fire severity. This latter study was conducted in mixed conifer stands that experienced fire approximately one year post bark beetle mortality (Bond et al. 2009).

Research from Southwestern Forests

Although the majority of the research discussed above is from lodgepole or spruce ecosystems, research conducted in New Mexico piñon and ponderosa pine systems found similar results. Allen (2007) suggested that vegetation dieback interacts with fire activity by modifying fuel amounts and configurations. Essentially, bark beetle-caused tree mortality alters the type of fuel available (dead versus live). Similarly, trees killed by beetles will initially exist as standing trees with lots of fine fuels in the canopy (dead twigs and needles); however, these needles are generally shed fairly rapidly and the tree will eventually deteriorate to a larger fuel on the forest floor. In addition, after tree death, trees will lose many of their flammable biochemicals. These standing, woody fuel structures no longer sustain running crown fires, so the risk of crown fires may initially decrease (Allen 2007); however, surface fine fuels increase rapidly from needle drop and also increased understory growth. Eventually, the dead trees fall and woody vegetation regenerates, leading to a high amount of both surface and ladder fuels (Allen 2007).

A more recent study (Floyd-Hanna et al. 2012) investigated changes in fuel structures after the widespread mortality in 2002–2004 in piñon-juniper woodlands of southwestern Colorado. This study looked at how the widespread tree mortality (caused by drought and bark beetles) impacted the continuity of horizontal and vertical fuels. The study started six years after the majority of tree death had occurred. Their study found that piñon-juniper stands were considerably less dense after this disturbance event with lower structural complexity. Fire models found that while most characteristics of surface fires (spread rate, flame length) did not vary with different levels of tree mortality, there was increased heat per unit area in stands with high mortality, most likely due to the increased amount of 100-hour fuels and litter. Furthermore, since stands with high mortality will have a larger amount of 1,000-hour fuels, the researchers felt that this could lead to longer fire residence time, in turn drying out canopy fuels and thus these stands might be more prone to torching fire behavior despite the reduction in canopy. Nonetheless, the overall conclusion was that the majority of surface fire characteristics were not changed substantially by the disturbance event and the likelihood of active crown fire

was likely reduced in most stands. One note of caution for managers is that the researchers predicted that surface fires in these stands may be more difficult to control under adverse weather conditions due to the increased surface fuel loads.

Management for Post-Beetle Outbreaks

Salvage logging post-beetle outbreaks has been suggested as a method to reduce stand susceptibility to fire. The ability to remove accumulated fuels after bark beetle outbreaks is often constrained by economics or other management objectives. There are studies that have suggested that there is little ecological justification to remove beetle-killed trees (Romme et al. 2006) and that removal of dead trees may not reduce high severity fire (Bond et al. 2009). Conversely, a more recent study by Collins et al. (2012) found that harvesting decreased the amount of subalpine fir in the lower canopy and increased the amount of lodgepole pine and aspen. These changes were thought to hinder torching and increase post-fire tree survival in mature stands. In addition, coarse woody fuels were predicted to increase in the untreated stands within 30 years as the snags would begin to fail and fall to the forest floor. While this study suggested that salvage harvesting would change post-outbreak fire behavior in stands, the authors also acknowledged that there are still many variables that are unknown with regards to fire modeling. In addition, the authors pointed out that since treatment could only be done on a small percentage of the forest, it was unknown how treating small patches would impact fire behavior across the larger landscape. Little research on this topic has been conducted in southwestern pine forests.

Conclusions

- Due to multiple factors, the fire risk, fire behavior, and changes in fuels after bark beetle outbreaks are still somewhat difficult to model.
- Time since outbreak and the amount of tree mortality are both key factors in subsequent fire risk and fire behavior and the relationship is not linear, i.e., there is neither a consistent increase in fire risk/intensity nor a consistent decline.
- The most recent literature reviews suggest that the probability of active crown fire increases in the red phase. In the gray and old phases, surface fire probability increases due to increased surface fuel loads but active crown fire probability in these phases may decrease because of reduced canopy bulk density.
- More research is needed to model fire behavior in southwest forests. For instance, managers need to adequately quantify the rate of snag fall and decomposition in different forest types across the Southwest. How quickly the understory responds to the disturbance event is also important in determining subsequent fire risk.
- Due to the beetles' preference for certain tree



species and size, changes in stand structure and fuel characteristics, and hence future fire risk/behavior, after beetle outbreaks are dependent on stand composition (species, tree size) prior to outbreak.

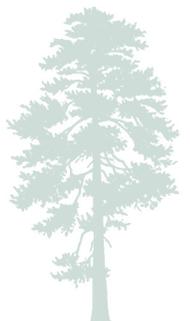
- In all habitats, the likelihood of fire and fire behavior will depend on current weather conditions even when fuels loads are high.

Management Implications

- Managers should also consider other factors in bark beetle infested stands. For instance, it has been reported that bark beetle attacked trees have an increased tendency to snap off or uproot more easily than unattacked trees. Snag mitigation in attacked stands may also require more effort (reviewed in Jenkins et al. 2012) and increased surface fuels may make surface fires harder to contain (Floyd-Hanna et al. 2012).
- It is important to remember that stands have different historical fire regimes. Some stands, and particularly lodgepole pine forests and other higher elevation forests, historically have had stand-replacing fires. For instance in high elevation spruce stands, there is evidence to support that stands which have experienced a spruce beetle outbreak do not support higher intensity fires relative to stands with no outbreaks (reviewed in Jenkins et al. 2008). Fires in these systems appear to be driven by climate and, thus, changes in the fuels do not impact frequency or intensity of fires. Similar results have been reported for lodgepole pine forests (Kulakowski and Jarvis 2011). It must be noted that in the summer of 2013, Colorado experienced several large wildfires and to our knowledge no one has investigated the contribution of recent beetle mortality to those fires.

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PO Box 15017
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