Fire and Bark Beetle Interactions[1]

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Abstract

Bark beetle populations are at outbreak conditions in many parts of the western United States and causing extensive tree mortality. Bark beetles interact with other disturbance agents in forest ecosystems, one of the primary being fires. In order to implement appropriate post-fire management of fire-damaged ecosystems, we need a better understanding of relationships between bark beetles and wildfire. Interactions can be one of two primary types: Fires can influence bark beetle populations directly by providing significant amounts of susceptible trees which may precipitate serious outbreaks; and effects of bark beetle outbreaks may influence likelihood and behavior of future fires. We examine various aspects of these interactions.

Keywords: Bark beetles, fire, fire-insect interactions.

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Introduction

The collective wildfire seasons over past decade have been some of the most widespread and damaging in recorded history. As such, wildfires unquestionably have had both short- and long-term effects on management activities in forested stands of the intermountain West. Some of those effects may be initiation of bark beetle outbreaks. In other cases, existing outbreaks may be prolonged. Land managers need to determine, to the extent possible, which trees are likely to succumb to fire damage, which might survive fire effects but be killed by bark beetles, and which others may survive them both. The sooner those assessments can be made and preventive or corrective measures implemented, the more successfully adverse effects will be avoided (Missoula Field Office 2000). The relationship between bark beetle-caused mortality and resultant effects on fire behavior continue to generate questions. These relationships will also be discussed.

Other authors in these proceedings have discussed current bark beetle conditions, in western coniferous forests, where extreme tree mortality occasionally occurs due to elevated insect populations (*see* Cain and Hayes 2008). If we want to develop and implement appropriate post-fire management of fire-damaged forest ecosystems, we will need a better understanding of relationships between bark beetles and wildfire. This interaction can take two primary forms: Fires can have a significant impact on population dynamics of bark beetles which in turn can cause tree injury; and occurrence of bark beetles have many effects in coniferous forest ecosystems—one of which may be influencing the likelihood and behavior of future fires through changes in stand structure, transformation of live fuels into dead fuels, and fuel arrangements. In this paper, we examine two commonly held assumptions—fires have a significant impact on population dynamics of beetles; and that bark beetle-caused mortality, likewise, has a significant impact on wildfire behavior.

Post-fire tree survivability and bark beetle interactions

Recently obtained research results can make prognoses of tree survival and appropriate management responses to both fire and threats from bark beetles more effective. Ryan (1982, 1989) has shown that the probability of tree survival is related to damage to crown, stem, or roots. Furthermore, amount of damage individual trees can sustain and still survive is dependent upon characteristics of its species (needle length and bark thickness), its size (diameter and height), and site factors on which it is growing. Research by Ryan, Harrington and Reinhardt has provided helpful means of predicting post-fire mortality based on species-specific characteristics (Harrington 1996, Reinhardt and Ryan 1989, Ryan and Amman 1994). Studies recently completed by Hood et al. (2007) and Sieg et al. (2006) have greatly helped answer survivability questions for two coniferous tree species—Douglas-fir and ponderosa pine, respectively.

In some cases, effects of earlier fires and management responses to bark beetle-induced mortality have served as valuable information sources. Included here are summaries of pertinent research results, useful historic precedents, and projects involving management activities implemented during previous post-fire evaluations. We have learned that recommendations must be general enough to have widespread applicability, yet specific enough to be locally worthwhile. Still, recommendations are subject to site-specific conditions that are often difficult to predict: fire effects on bark beetle hosts, weather one or two years post-fire, extant populations of host-specific bark beetle species, and interactions between all three.

Within the past decade, forested stands in the West, of all ownerships, have been both extensively and intensely affected. Fire damage, of varying severity, has extended to several million acres in each of the past ten years. Yearly, fires rage in some parts of the West from April through November. Even as fires burn, post-fire planning to deal with their aftermath must proceed. There is, and will continue to be, a need to address wildfire effects in forested stands, and perhaps even more critically, in the more-populated wildland-urban interface. What short- and long-term management decisions will be implemented and how; and how bark beetles will interact with fire-damaged trees are questions that must be answered—and the sooner the better.

Bark Beetle Considerations

Following wildfires, land managers are naturally concerned about tree survivability. We have also learned, in some situations, there is a high likelihood of bark beetles infesting fire-weakened trees (Parker et al. 2006). Bark beetle outbreaks following wildfires are not unprecedented, but neither are they certain. Several conditions must exist for bark beetles to take advantage of fire-damaged hosts:

1. There must be a sufficient supply of undamaged inner bark in fire-affected trees. If beetles' food supply, the bark and inner bark (phloem), becomes dry or scorched—often the case in stand-replacing fires or in thin-barked tree species—beetles will neither feed nor lay eggs in it.
2. Fires must occur at a time when beetles either are, or soon will be, in the adult stage and capable of infesting susceptible trees. Fires in late summer or early fall may occur after beetles have flown or may be colonized by wood borers and may therefore not be as suitable to bark beetles the following year. A recently killed tree's inner bark remains usable to beetles for a relatively short time. If not attacked while still "green," phloem may become too dry or otherwise unusable before the next flight season.
3. There must be a population of beetles within a reasonable distance to take advantage of weakened trees which become available.
4. Post-fire weather must be conducive to beetle survival and propagation.

Fire Survivability Case Studies

Because several conditions must be met for outbreak development, beetle epidemics following wildfires are not a foregone conclusion; but a few such outbreaks are well-documented. Douglas-fir beetle (*Dendroctonus pseudotsugae* Hopkins), spruce beetle (*D. rufipenis* (Kirby)), and pine engraver beetle (*Ips* spp.) outbreaks following wildfires in 1988, 1994, and 2000 became extensive and quite damaging in parts of Yellowstone National Park and Montana (Amman and Ryan 1991; Rasmussen et al. 1996; Ryan and Amman 1996; FHP, Northern Region, unpublished office reports).

Following 1988 Yellowstone National Park fires, Amman and Ryan (1991) concluded “The 1988 fires in the Greater Yellowstone Area killed many trees outright. Many more were subjected to sublethal injuries resulting in increased susceptibility to insect attack. Still other trees escaped fire injury but are exposed to the spread of insect attack from nearby injured trees.” Rasmussen et al. (1996) showed “that bark beetle and delayed tree mortality due to fire injury significantly alter mosaics of green and fire-injured trees, that insect infestation increases with the percent of basal circumference killed by fire, and that bark beetle populations appear to increase in fire-injured trees and then infest uninjured trees.”

Ryan and Reinhardt (1988) demonstrated that post-fire mortality can be predicted as a function of crown scorch and bark thickness for most western conifers and that probability of mortality increased with percentage of crown killed and decreased as bark thickness increased. Weatherby et al. (1994) used those relationships in an effort to evaluate tree survivability following the 1989 Lowman, ID fire. They found 82% of the ponderosa pine and 52% of the Douglas-fir survived the fire; but a significant portion was killed by bark beetles as opposed to direct fire effects.

Observations made following wildfires in western Montana have shown that Douglas-fir is likely to be killed by Douglas-fir beetles if cambium has been killed on half or more of the bole circumference. Occasionally, that damage may occur on large, lateral roots at or below the duff (Hood et al. 2007). Amman and Ryan (1991) showed that 71% of the Douglas-fir on their Yellowstone plots died—over twice as many as predicted by the model using crown scorch and bark thickness characteristics. They surmised, “… unmeasured root injury may have contributed to the higher than expected mortality. However, because several of the dead Douglas-firs received minimal heating, insects appear to be responsible for part of the additional mortality.” Ryan and Amman (1996) showed after Yellowstone Park fires of 1988, 77% of the Douglas-fir; 61% of the lodgepole pine; 94% of the Engelmann spruce and 100% of the subalpine fir had been killed by a combination of fire injury and/or bark beetles.

Weatherby (1999) established a study to follow the fate of selected trees in two areas burned in 1994 on the Payette National Forest, Idaho. Her work illustrated the feasibility of predicting survivability based on breast-height diameter, percent crown scorch, and percent of circumference of bole (or roots) charred. In one area (French Creek), of 121 grand fir and 82 Douglas-fir monitored following the 1994 wildfire, 41% of the grand fir and 13% of the Douglas-fir had died. Of these, about half the mortality for each tree species was attributed to bark beetles. In another (Pony Creek), 36% of the Douglas-fir and 16% of the ponderosa pine had died by 1998. Bark beetles killed slightly more than two-thirds of the dead Douglas-fir (67%) and one-fourth (27%) of the dead ponderosa pines.

Burn Intensity Categories and Bark Beetle Responses

Previous post-fire evaluations in the Northern Region have varied somewhat from area to area, but most are similar to ones developed following the Little Wolf Fire (Tally Lake

Ranger District, Flathead National Forest) in 1994. Fire-affected forested areas were assigned “burn intensity” categories using aerial photographs taken soon after the fire and knowledge of pre-fire stand conditions. They were refined by post-fire surveys and field verification within burned areas. Ground-char classes were based on ones described by Ryan and Noste (1985). Burn intensity (BI) classes were as follows:

BI 1: All vegetation blackened—foliage destroyed, boles deeply charred and understory vegetation burned. Approximate distribution of ground char: Unburned 0%, Light 15%, Moderate 70%, Deep 15%.

BI 2: Stems predominantly blackened, some foliage only scorched. Understory vegetation mostly burned. Ground char: Unburned 0%, Light 25%, Moderate 60%, Deep 15%.

BI 3: Most vegetation scorched with few blackened stems; small amounts of green vegetation. Ground char: Unburned 0%, Light 40%, Moderate 50%, Deep 10%.

BI 4: Predominantly, but temporarily green with scorched or blackened areas. Ground char: Unburned 15%, Light 65%, Moderate 15%, Deep <5% (Anonymous 1996).

In order to help define the likelihood of bark beetle population buildups in those areas, Gibson (1994) made the following assessments according to identified burn intensity categories:

BI 1: Few severely burned trees will be infested by bark beetles which will later damage uninjured trees. Some may attract wood wasps (horntails, family Siricidae) or wood borers (families Cerambycidae [longhorned beetles or roundheaded wood borers] and Buprestidae [flatheaded or metallic wood borers]) but they are of little threat to adjacent green trees. Where charring has destroyed or dried the phloem, no bark beetle food remains. Even most wood borers which ultimately feed within the sapwood, require relatively fresh inner bark for newly hatched larvae. Thin-barked tree species burned to the extent that inner bark is destroyed will provide little food for insects. Thicker barked species may attract some wood-inhabiting insect species or bark beetles, depending on depth and height of charring.

BI 2: Some thicker barked species—such as Douglas-fir, western larch and ponderosa pine—may survive immediate effects of fire. In the case of Douglas-fir, however, bole scorch on more than about half of the tree’s circumference will likely produce a strong attraction for Douglas-fir beetles. Large-diameter, and older ponderosa pines in this category may be attacked by western pine beetles (*D. brevicomis* LeConte), or red turpentine beetles (*D. valens* LeConte); however, outbreak development of these beetles in this situation would not be expected. Severely weakened western larch may be infested by several species of wood borers. Thin-barked species in this group—lodgepole pine, Engelmann spruce, and subalpine fir—may have been burned too severely to attract bark beetles or wood borers.

BI 3: This group likely will attract the most bark beetles. Douglas-fir in this category may be less affected, depending upon degree of bark and root collar scorch, as noted earlier. Most second-growth ponderosa pine, lodgepole pine, Engelmann spruce and subalpine fir will almost certainly be attacked by bark beetles or wood borers. Smaller diameter ponderosa pines and lodgepole pines will be infested by one or more species of engraver beetles (*Ips* spp.), other secondary bark beetles (*Pityogenes* spp. and *Pityophthorus* spp.) and wood-boring beetles. We have learned that mountain pine beetles (*D. ponderosae* Hopkins) are seldom attracted to fire-weakened trees. Engelmann spruce will be attacked by spruce beetles and subalpine fir will support populations of several beetles, the most dominant being western balsam bark beetle (*Dryocoetes confusus* Swaine).

BI 4: In this latter group, bark beetle attraction will be dependent mostly upon amount of root collar damage. Most Douglas-fir, western larch and ponderosa pines will survive and not attract beetles unless smoldering ground fires significantly damaged roots or root collars. Other tree species are more likely to be infested, even though severe damage may not be readily apparent. Observations in other burned areas have shown thin-barked trees can withstand only a small amount of damage at ground level without becoming so weakened they eventually succumb to bark beetle attacks. In these areas, it is common to find trees with little apparent bole or crown damage that have been completely girdled at the root collar.

Tree Responses to Fire and Management Alternatives

Beyond the likelihood of individual trees dying directly from fire damage, there is great interest in determining which trees are at risk of subsequently being killed by bark beetles—both dependent upon, and independent from, fire effects. Ryan and Reinhardt (1988) have described the survivability of seven coniferous species, relative to crown scorch and bark thickness. Except for ponderosa pine and grand fir, they have provided a basis for defining the probability that any particular tree would survive fire injury. As noted, however; some trees "predicted" to survive might be subsequently attacked by bark beetles. On the other hand, trees directly killed by fire, may be too severely damaged to be infested by bark beetles.

Scott et al. (2002) developed a method for determining post-fire probability of survival of several coniferous species in the Blue Mountains of Washington and Oregon that has been useful as a tree-marking guide for post-fire salvage operations. Sieg et al. (2006) reported on a multi-year study, following a series of wildfires in the West. They determined the best predictors of post-fire ponderosa pine mortality—specifically, crown scorch and consumption volume. Hood et al. (2007) demonstrated the relationship between fire-damaged Douglas-fir and subsequent attack by Douglas-fir beetles. Their model can help determine not only what fire-affected Douglas-fir may ultimately die; but more importantly, which ones are most likely to attract Douglas-fir beetles within the next year or so.

Gibson et al. (1999) documented buildups of both spruce beetle and Douglas-fir beetle populations following a wildfire, and expedient management responses used to forestall significant outbreaks on the Flathead National Forest, Montana. In most cases, timing of treatments is important. Damaged trees may be infested from shortly after fires are out (within a few days) until trees either recover or phloem becomes unsuitable (as long as

1-2 years post-burn). Some treatments, such as the use of anti-aggregative pheromones, may provide critical protection for injured trees until beetle populations decline or tree vigor improves. The availability and use of these techniques are discussed in this volume by Gillette and Munson (2009). In determining what actions may be most appropriate, an estimate of tree survivability and susceptibility to bark beetles will be essential.

Fire Survivability and Likelihood of Beetle Infestation of Common Coniferous Species in the Intermountain West

Douglas-fir: Reporting results from a multi-year, post-fire study in the Greater Yellowstone Area, Ryan and Amman (1996) showed that four years following the fires, 79% of 125 Douglas-fir in their survey plots had been attacked by one or more species of insects, and 77% were dead. Seventy-one percent of the insect attacks were by Douglas-fir beetles. Dead trees had suffered greater crown scorch and bole injury; however, trees attacked by Douglas-fir beetles had more than 50% basal girdling, ample green phloem, and less than 75% crown scorch. Beetles initially attacked severely injured trees, then attacked more lightly injured trees in subsequent years. Mortality immediately following fires occurred in trees with both severe crown scorch and bole injury. The majority of subsequent mortality, however, was found in trees with little crown injury but more than 50% basal girdling. Of dead Douglas-fir, 83% had been infested by insects. In a similar survey of fire-damaged trees in central Idaho, Weatherby et al. (1994) showed that Douglas-fir which died from fire effects had 74% crown scorch, whereas those that were killed by beetles had 39% crown scorch.

Ponderosa Pine: Burns and Honkala (1990) noted, “Survival and growth of ponderosa pine usually are little affected if 50 percent or less of the crown is scorched in a fire. Six years after a fire in Arizona, however, no poles and only 5 percent of the sawtimber-size trees were living if more than 60 percent of the crown had been destroyed. Low tree vigor and cambium damage increase the likelihood of mortality.” Wagener (1961) noted that extent of fire damage in ponderosa pines was at least partly a function of time of burn. Early season fires were more damaging than ones which occurred in late summer or early autumn. Likewise, time of year greatly affected subsequent bark beetle activity; and both directly affected a tree’s probability of survival. He showed young, fast-growing trees on good sites were more likely to survive than old, overmature trees on poor sites. He also noted that trees with complete crown scorch will likely survive if buds and twigs are not damaged extensively and are thus capable of producing foliage the following year. An additional criterion was damage to bark and cambium—trees with both heavy foliage scorching and moderate to severe cambium kill were more likely to die later from bark beetle attacks. Though mature ponderosa pine has thick, fairly fire-resistant bark; permanent damage and death will be influenced by amount and distribution of fuels on the forest floor and other site and stand conditions. In uneven-aged stands, injury to the cambium will vary considerably from site to site. Resultant cambium damage will greatly determine tree’s survivability, and cambium killing which extends for more than a few feet up the trunk will significantly reduce a tree’s probability of survival. In their study, Weatherby et al. (1994) showed that few ponderosa pines greater than 4 inches diameter-at-breast-height (d.b.h.) died if crown scorch was less than 80%. Seig et al. (2006) noted the probability of a tree's survival was predominantly associated with percent of crown scorch and amount of crown consumed; but when bark beetles and d.b.h. were considered, predictive ability increased significantly.

Lodgepole Pine: According to Burns and Honkala (1990), lodgepole pine is more susceptible to fire than Douglas-fir and some of its other associates, because of its relatively thin bark. But it is less susceptible to fire than either Engelmann spruce or subalpine fir. On the other hand, success of lodgepole pine is directly affected by the role fire plays in its regeneration. Overmature lodgepole pine's susceptibility to mountain pine beetle, a beetle-killed stand's proclivity to burn, and fire's role in opening serotinous cones, has made the lodgepole pine/mountain pine beetle/fire/stand replacement cycle a well-established relationship throughout the tree's range. Although attracted to over-mature and slow-growing individuals, mountain pine beetles infrequently colonize fire-damaged lodgepole pine. Ryan and Amman (1996) showed of 151 lodgepole pine surveyed, 62% were attacked by insects and 61% (of the total) had died. Most dead trees had been extensively girdled by fire (greater than 75% of bole circumference) and had been infested by beetles. Majority of the beetles were engraver beetles (*Ips* spp.); but a few had been infested by secondary bark beetles and wood borers. Engraver beetles preferentially attacked trees with more than 75% basal girdling, but less than 50% crown scorch.

Engelmann Spruce: Probably because of their typically wetter habitats, fewer fire-effects studies have been done in Engelmann spruce stands than many other species. In their study following the 1988 fires in Yellowstone National Park, Ryan and Amman (1994) found only 17 spruce on their plots. By 1991, however, 83% of them were dead. They noted that as might be expected for thin-barked species, mortality did not vary by tree diameter. Trees which received most apparent damage, in the form of crown and bole injury, were ones most likely to die. Sixteen of 17 trees had been more than 90% girdled by fire and 82% of them had been infested by spruce beetles. In addition, because spruce is a shallow-rooted species, slow-burning fires causing significant root damage create trees which are easily windthrown. In turn, windthrown spruce on which there is little bole charring are quite likely to be infested by spruce beetles.

Subalpine Fir: Ryan and Amman (1994) noted that subalpine fir is known for its lack of fire resistance, primarily because of thin bark. They commented, "Virtually any fire vigorous enough to scorch the bark will cause cambium injury, followed by sloughing of the dead bark." In their study they found 17 subalpine fir, all of which died following the fires. Eighty-eight percent were eventually infested by woodborers, although bark damage was initially significant enough to preclude bark beetle infestations. We have noticed, however, subalpine fir with root damage is easily windthrown, as previously noted for spruce. Such trees, with little additional bole damage, are quite susceptible to western balsam bark beetles. Beetle populations building in downed trees are then likely to infest nearby green trees not affected by fires (K.E.G. and J.N. personal observations and unpublished data).

Western Larch: Ryan and Reinhardt (1988) described conditions most often affecting tree survivability following prescribed burns. They concluded that coniferous species in the northwestern United States vary widely in their resistance to fire injury, and that deeper-rooted trees tend to have thicker bark which renders them relatively resistant to fire-related damage. Burns and Honkala (1990) recorded, "Larch develops a deep and extensive root system…" and further, "Mature larches are the most fire-resistant trees in the Northern Rockies because of their thick bark, their high and open branching habit, and the low flammability of their foliage." Mature western larch is relatively fire resistant, wind firm, and have few insect pests—particularly bark beetles—which take advantage of weakened individuals or stands. Younger larch, with thinner bark and growth habits, may be more susceptible to fire injury; especially cambial damage and crown scorch, as described by Ryan and Reinhardt (1988).

Grand Fir: Little research has been conducted on the effects of wildfire in grand fir stands; however, its morphological characteristics are similar to white fir which is rated moderate in fire resistance, becoming more resistant as it ages. In both species, fire injuries may provide entry courts for significant decay organisms (Parker et al. 2006). Burns and Honkala (1990) rate grand fir as "medium" in fire resistance—less resistant than larch, ponderosa pine and Douglas-fir; but more resistant than subalpine fir and spruce. They note that its resistance to fire is based largely on habitat. On moister sites it is readily killed by ground fires. On drier sites grand fir is more fire resistant due to deeper root systems and thicker bark which develop in those environments.

Bark Beetles and Fire Interactions in Western Conifer Forests

Little is known about the topic of bark beetle outbreaks and the likelihood or fire behavior of a subsequent fire in western forest ecosystems. Most information available on this topic comes from anecdotal information and few scientific studies. This is an issue of great relevance at the present time when we consider the extensive eruptive populations of bark beetles that we have observed in recent years. Wildland-urban interface and the proliferation of private property in these areas further exacerbate the problem as fire control operations are of utmost necessity to protect residents from personal injury and loss of assets.

As indicated above, few studies have addressed this problem. Kulakoski and Veblen (in press) indicated that a 2000 spruce beetle outbreak did not appear to influence fire extent or severity in a subsequent fire in 2000 in spruce-fir forests in northern Colorado. Bebi et al. (2003) reported that a 1940s spruce beetle outbreak in central Colorado outbreak did not affect subsequent fire susceptibility. However, Bigler et al. (2005) working is the same areas as Kulakowski and Veblen (in press) concluded that the spruce beetle outbreak slightly increased the probability of high severity fire in 2002. In Alaska, Berg and Anderson (2006) concluded that there was no relationship between spruce beetle-caused tree mortality and subsequent wildfire occurrence. Lynch et al. (2006) working in lodgepole pine after the 1988 Yellowstone Fire indicated that a 1972–1975 mountain pine outbreak increased probability of burning but a 1980–1983 mountain pine beetle had no effect. Page and Jenkins (2007) suggested rates of fire spread and intensity were higher in lodgepole pine stands currently infested by mountain pine beetles, but lower in post-epidemic stands when compared to non-infested stands. Jenkins et al. (2008) described varying fire behavior with length of time following bark beetle outbreaks. It can be seen that most of the available studies come from spruce-fir and lodgepole pine forests. Forest types such as ponderosa pine and piñon-juniper woodlands remain unaddressed. It should be mentioned that in some forest types such as lodgepole pine and spruce-fir forests, infrequent high-intensity fires are part of the ecology of these forests with bark beetles not being needed for these fires to occur. Bark beetle outbreaks, however, can and do influence both fire hazard and behavior in areas where they have occurred.

Here we present some characteristics that may influence fire[3] and how bark beetles may influence those factors using examples from a mountain pine beetle outbreak in lodgepole pine forests of north-central Colorado and from a roundheaded pine beetle outbreak, *D. adjunctus* (Blandford), in south-central New Mexico. The Colorado outbreak has been causing extensive mortality in these forests since about 2001. Mortality levels are so extensive that stands normally considered less susceptible to mountain pine beetle, less than 80 ft^2/acre, are being decimated.

Here we briefly discussed some of the changes in foliar moisture, effects in stand structure, and the accumulation of downed woody debris during and after a bark beetle outbreak. These are factors known to influence fire in forest ecosystems. We discuss some preliminary modeling efforts underway.

Foliar Moisture: Dry needles play a role in crown fires (Van Wagner 1977, Chrosciewicz 1986, Agee et al. 2002). One of the short term effects of bark beetles is altering foliar moisture caused by the simple death of the tree.

We have conducted foliage sampling of beetle-killed trees and live trees to determine foliar moisture content. Reduction in foliar moisture is evident already in the early spring and by the middle of the summer is very pronounced (Table 1). The dry needles that are on trees, in effect, lower the crown base height of the tree facilitating transition to a crown fire under a lower flame length and fire line intensity (Keyes 2006).

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[3] Hereafter in this paper when discussing “fire” we mean likelihood of fire occurrence or potential fire behavior.

Table 1—Percent foliar moisture content in live and beetle-killed trees in 2005 at different sampling dates, Fraser Experimental Forest, Fraser, CO

Sampling Date	Live Trees	Beetle-killed trees
mid-May 2006	104	64
end-July 2006	127	9
early-December 2006	114	14

Stand Structure: Among other studies, Lentile et al. (2006), and Jain and Graham (2004) discuss how forest structure influence fire severity. Bark beetles effect changes in forest structure in a variety of ways including changing stocking levels and diameter classes of remaining live trees in the affected forest. These changes directly influence canopy bulk density and can stimulate the development of fuel ladders. In north central Colorado, about 6 years into a bark beetle outbreak, we are seeing reductions in mean tree diameters of lodgepole pine from about 20 cm down to about 12 cm (fig. 1) and in stocking levels from about 28 m^2/ha down to 9 m^2/ha (fig. 2).

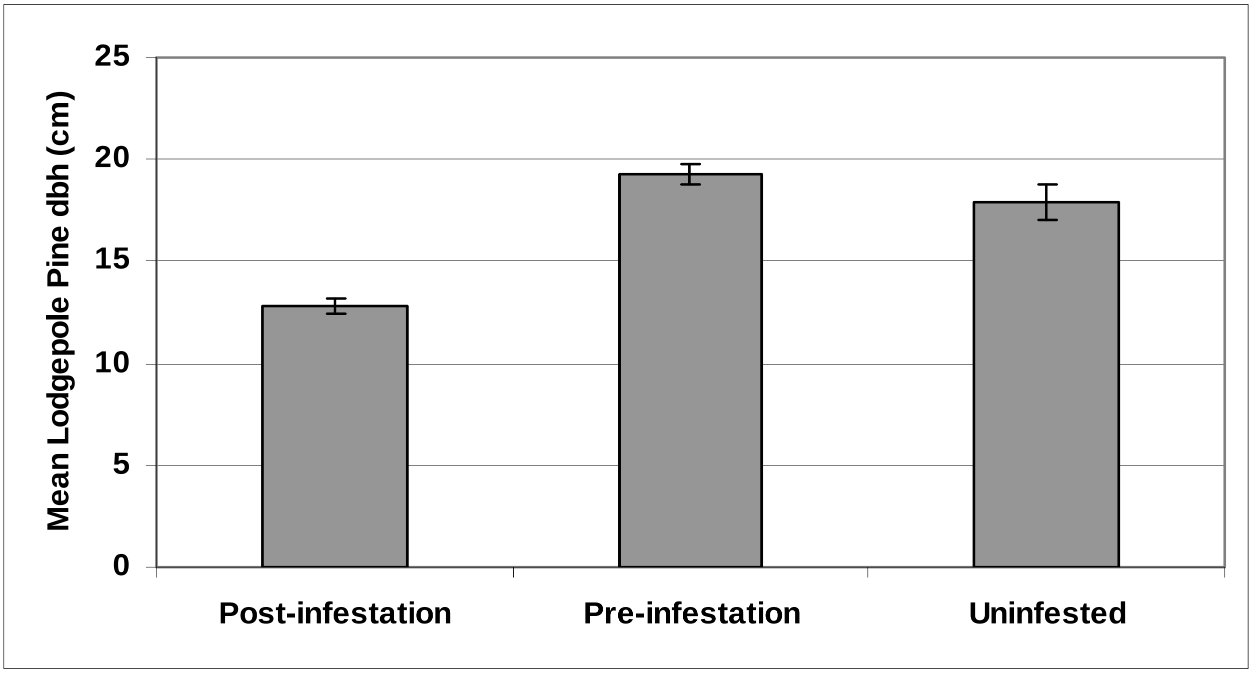

Figure 1—Mean dbh of lodgepole pine in post-infestation, pre-infestation, and uninfested, Arapahoe NF, Colorado. Error bars are standard errors.

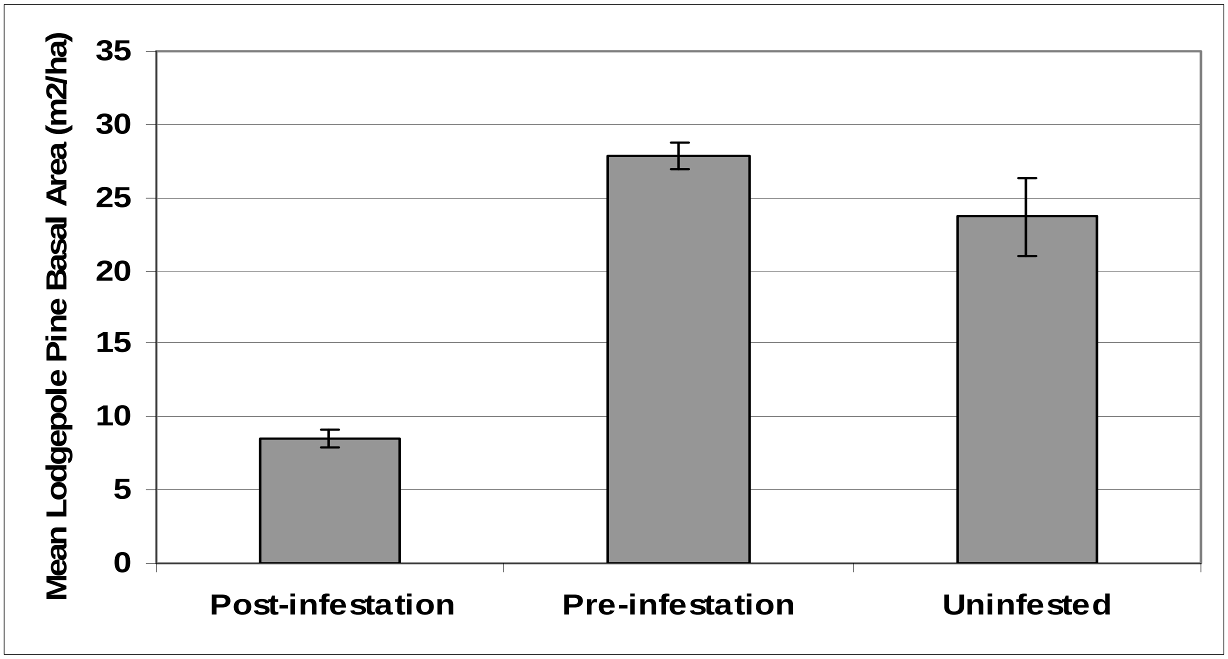

Figure 2—Basal area of lodgepole pine in post-infestation, pre-infestation, and uninfested, Arapahoe NF, Colorado. Error bars are standard errors.

Downed Wood: Another factor directly influencing fire is the type, amount, and distribution of forest fuels (Van Wagner 1977; Agee 1993). Bark beetles, through tree mortality, transform live fuels to dead fuels which will also vary spatially across the landscape following the spatial distribution of tree mortality. In the short term, less than 6 years, bark beetle-induced mortality increases the duff and litter depth, the accumulation of dead woody material less than ¼ inch but not downed wood greater than ¼ inch nor the total amount of downed woody debris.

A study by Mitchell and Preisler (1998) indicated that in an unthinned lodgepole pine stand, little tree fall occurs within the first 3 years after mortality, with about 10% and 80% of trees on the ground by 6 and 12 years, respectively. Similar fall rates have been reported for ponderosa pine, *Pinus ponderosa* (Keen 1955). The fall rate, however, can be strongly influenced by tree diameters, moisture availability in the site, and the occurrence of strong wind among others. Nevertheless the data presented by Mitchell and Preisler (1998) can be used to make some projections for the accumulation of large woody material over time. Projections made from tree mortality data by mountain pine beetle in lodgepole pine forests in Colorado result in large increases in total fuel loading 12 years after the outbreak (fig. 3). These increases in fuel accumulations may result in more intense fires with excessive soil heating.

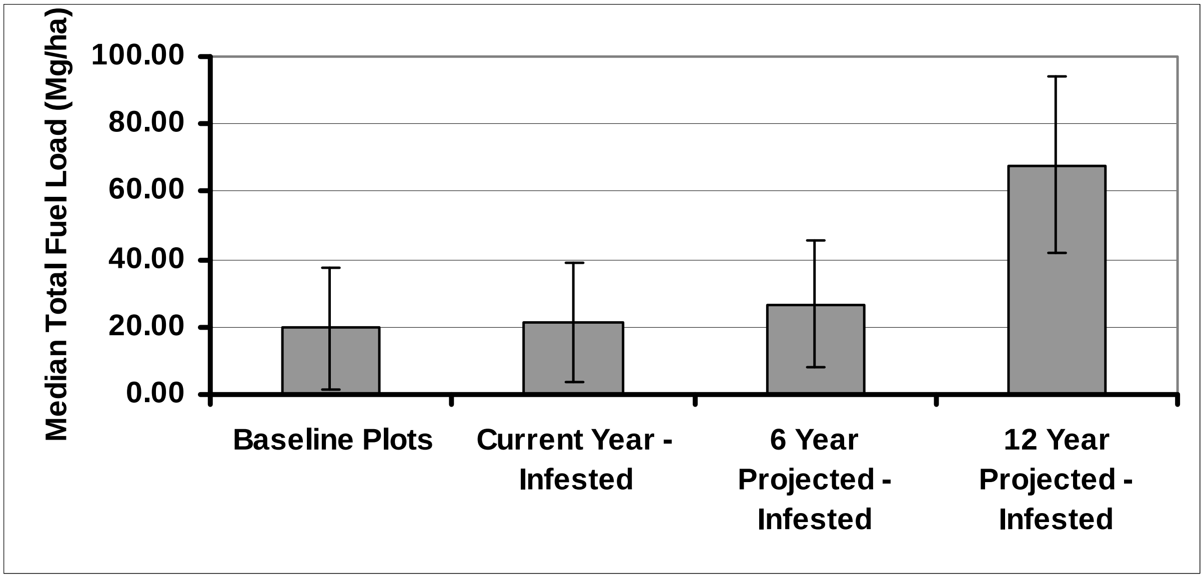

Figure 3—Median total downed woody debris accumulations in uninfested and currently infested plots, and 6- and 12-year projections, Arapaho NF, Colorado. Error bars are median absolute deviations.

During the late 1980s to early 1990s, eruptive populations of the roundheaded pine beetle caused extensive mortality in ponderosa pine. Stand susceptibility plots were established in 1994–1995. These plots were revisited 10 years after the original establishment, which represents approximately 14 years after the outbreak. Downed woody debris accumulations in mixed conifer and ponderosa pine forests increased from 6 to 40 and from 4 to 20 metric tons/hectare in mixed conifer forests and ponderosa pine forests, respectively (fig. 4).

Fire Modeling: Through preliminary modeling using the Forest Vegetation Simulator / Fire and Fuels Extention and fire models such as Behave, we have obtained projected increases in total flame length and the area affected by passive crown fires. Also obtained were decreases in crowning index, and the area affected by active crown fires. The increase in flame length may be associated with the increase in downed woody debris and the increase in passive crown fire is due to the nature of the patchy forests left after a bark beetle outbreak. A lower crowning index value means it takes a lower wind speed for fire to move within the crown. and the decrease of area affected by active crown fire may be due to the loss of crown continuity.

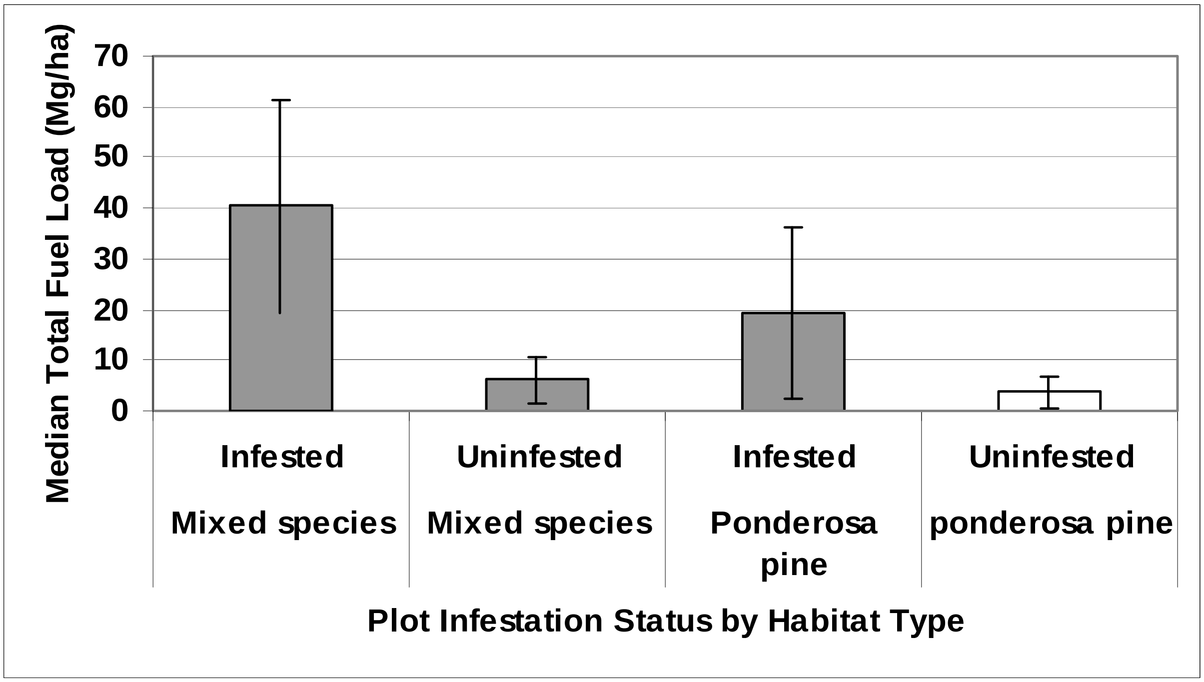

Figure 4—Median total downed woody debris accumulations in infested and uninfested plots about 14 years after a roundheaded pine beetle outbreak, Lincoln National Forest, New Mexico. Error bars are median absolute deviations.

Additional studies are underway to continue examination of downed woody debris after the occurrence of bark beetles in different forest types, to continue the study of foliar moisture dynamics, and to better clarify the changes in forest structure caused by bark beetles that can influence fire characteristics. Finally a particularly valuable resource is the availability of historical aerial detection flights of insect and disease conducted annually by Forest Health specialists and data on the location of historical fires. We are currently using GIS approaches combined with weather data to examine if and under what conditions fire may occur subsequently to a bark beetle outbreak. This information will provide the opportunity to include time since bark beetle outbreak and the occurrence of fire-conducive weather as potentially important considerations in assessing fire hazard.

Summary

We note that much remains to be learned before we will be able to accurately predict which trees will succumb to effects of a wildfire or prescribed fire, which will survive, and which of those may ultimately be killed by bark beetles. Some of the more severely affected trees will unquestionably die; some of the least affected will no doubt survive. Trees between the two extremes are ones most difficult to predict because of their varying susceptibility to bark beetles, the effects of post-fire weather, and other site/stand factors difficult to measure and not well-understood.

As previously noted, a fire-damaged tree's susceptibility to bark beetles is determined by: (1) Amount of damage and tree's response, (2) time of year fire occurs, (3) populations of bark beetles in tree's vicinity, and (4) weather for several months both pre- and post-fire.

A complex of factors is involved in any one tree's survivability. Not the least of those are pre-fire physiological condition, an array of abiotic site factors, a host of potentially damaging biotic agents, and interactions between them all. We may never unfailingly predict either post-fire survival or death for fire-damaged trees. But reasonable estimates, sufficient for most management decisions, are possible if measurable parameters are adequately considered.

Because of the area burned throughout the West since 2000, total area in the millions of acres; dealing with fire effects on all affected resources will undoubtedly extend well into the future. Yet the need to assess as quickly as possible where site rehabilitation and stabilization is most critical, and in some cases where economic values can be captured in a timely manner, will be paramount.

Bark beetles could influence subsequent fire behavior if fire occurs and depending on time since bark beetle outbreak fire and weather conditions among other factors. Reductions in foliar moisture could facilitate movement of a fire into the crown. Changes in stand structure such as reduced stocking and tree diameters can change the availability of fuel ladders, changes in understory vegetation and arrangement of fuels. Bark beetles also transform fuels from live fuels in the canopy to dead fuels on the ground. These fuel accumulations can be of significance a decade after the mortality event which will result in different fire characteristics compared to unaffected stands.

Literature Cited

Agee, J.K. 1993. Fire ecology of Pacific Northwest forests. Washington, DC: Island Press. 493 p.

Agee, J.K.; Wright, C.S.; Williamson, N.; Huff, M.H. 2002. Foliar moisture content of Pacific Northwest vegetation and its relation to wildland fire behavior. Forest Ecology and Management.167: 57–66.

Amman, G.D.; Ryan, K.C. 1991. Insect infestation of fire-injured trees in Greater Yellowstone Area. Research Note INT-398. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 9 p.

Bebi, P.; Kulakowsi, D.; Veblen, T.T. 2003. Interactions between fire and spruce beetles in a subalpine rocky mountain forest landscape. Ecology. 84: 362–371.

Berg, E.E.; Anderson R.S. 2006. Fire history of white and Lutz spruce forests on the Kenai Peninsula, Alaska, over the last two millennia as determined from soil charcoal. Forest Ecology and Management. 227: 275–283.

Bigler, C.; Kulakowski, D.; Veblen T.T. 2005. Multiple disturbance interactions and drought influence fire severity in Rocky Mountain subalpine forests. Ecology. 86: 3018-3029.

Burns, R.M.; Honkala, B.H., tech. coords. 1990. Silvics of North America, Volume 1, Conifers. Agriculture Handbook 654. Washington, DC: U.S. Department of Agriculture, Forest Service. 673 p.

Chrosciewicz, Z. 1986. Foliar moisture variations in four coniferous tree species of central Alberta. Canadian Journal of Forest Research. 16: 157–162.

Gibson, K.E. 1994. Trip Report, Unpublished office report, October 17, 1994. Missoula, MT: US Department of Agriculture, Forest Service, Northern Region, Forest Health Protection, Missoula Field Office, Federal Building, 200 E. Broadway. 3 p.

Gibson, K.; Lieser, E; Ping, B. 1999. Bark beetle outbreaks following the Little Wolf Fire, Tally Lake Ranger District, Flathead National Forest. FHP Report 99-7. Missoula, MT: U.S. Department of Agriculture, Forest Service, Northern Region. 15 p.

Gillette, N.E.; Munson A.S. 2009. Semiochemical sabotage: behavioral chemicals for protection of western conifers from bark beetle. In: Hayes, J.L.; Lundquist, J.E., comps. Western Bark Beetle Research Group—a unique collaboration with Forest Health Protection symposium, Society of American Foresters Conference, 23–28 October 2007, Portland, OR. Gen. Tech. Rep. PNW-GTR-784, Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 85–109.

Harrington, M.G. 1996. Fall rates of prescribed fire-killed ponderosa pine. Res. Paper INT-RP-489. Missoula, MT: U.S. Department of Agriculture, Forest Service. Intermountain Research Station. 7 p.

Hood, S.; Bentz, B.; Gibson, K.; Ryan, K.; Denitto G. 2007. Assessing post-fire Douglas-fir mortality and Douglas-fir beetle attacks in the northern Rockies. Gen.Tech. Rep. RMRS-GTR-199. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 32 p. (plus supplement).

Jain, T.B.; Graham, R.T. 2004. Is forest structure related to fire severity? Yes, no, maybe: methods and insights in quantifying the answer. In: Shepperd, W.D.; and Eskew, L.G., comps. Proceedings, Silviculture in Special Places. RMRS-P-34. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 217–234.

Jenkins, M.J.; Hebertson, E.; Page, W.; Jorgensen, C.A. 2008. Bark beetles, fuels, fires and implications for forest management in the intermountain West. Forest Ecology Management. 254: 16–34.

Keen, F.P. 1955. The rate of natural falling of beetle-killed ponderosa pine snags. Journal of Forestry. 55: 720–723.

Keyes, C.R. 2006. Role of foliar moisture content in the silvicultural management of forest fuels. Western Journal of Applied Forestry. 21: 228–231.

Lentile, L.B.; Smith, F.W.; Shepperd, W.D. 2006. Influence of topography and forest structure patterns of mixed severity fire in ponderosa pine forests of the South Dakota Black Hills, USA. International Journal of Wildland Fire. 15: 557–566.

Lynch, H.J.; Renkin, R.A.; Crabtree, R.L.; Moorcroft, P.R. 2006. The influence of previous mountain pine beetle (*Dendroctonus ponderosae*) activity on the 1988 Yellowstone fires. Ecosystems. 9: 1318–1327.

Mitchell, R.G.; Preisler, H.K. 1998. Fall rate of lodgepole pine killed by the mountain pine beetle in central Oregon. Western Journal of Applied Forestry. 13: 23–26.

Missoula Field Office., comps. 2000. Survivability and deterioration of fire-injured trees in the northern Rocky Mountains. Forest Health Protection Report 2000–13. Missoula, MT: U.S. Department of Agriculture, Forest Service, Northern Region, State and Private Forestry. 49 p. (plus appendices).

Page, W.G.; Jenkins, M.J. 2007. Mountain pine beetle induced changes to selected lodgepole pine fuel complexes within the Intermountain Region. Forest Science. 53: 507–518.

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

Rasmussen, L.A.; Amman, G.D.; Vandygriff, J.C.; Oakes, R.D.; Munson, A.S.; Gibson. K.E. 1996. Bark beetle and wood borer infestation in the Greater Yellowstone Area during four postfire years. Res. Paper INT-RP-487. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 9 p.

Reinhardt, E.D.; Ryan, K.C. 1989. Estimating tree mortality resulting from prescribed fire. In: Baumgartner, D.M.; Breuer, D.W.; Zamora, B.A.; Neuenschwander, L.F.; and Wakimoto, R.H., comps. and eds. Symposium proceedings: Prescribed fire in the Intermountain Region. Pullman, WA: Washington State University: 41–44.

Ryan, K.C. 1982. Evaluating potential tree mortality from prescribed burning. In: Baumgartner, D.M., ed. Symposium proceedings: Site preparation and fuels management on steep terrain. Pullman, WA: Washington State University: 176–179.

Ryan, K.C. 1990. Predicting prescribed fire effects on trees in the Interior West. In: Alexander M.E.; Bisgrove G.F., tech. coords. Proceedings, 1st Interior West Fire Council annual meeting and workshop; 1988 October 24–27. The art and science of fire management. Kananaskis Village, AB. Information Report NOR-X-309. Edmonton, AB: Northern Forestry Centre: 148–162.

Ryan, K.C.; Amman, G.D. 1994. Interactions between fire-injured trees and insects in the Greater Yellowstone Area. In: Despain, D.G., ed. Plants and their environments: proceedings of the first biennial scientific conference of the Greater Yellowstone ecosystem. Technical Report NPS/NRYELL/NRTR/93XX. Denver, CO: U.S. Department of the Interior, National Park Service: 259–271.

Ryan, K.C.; Amman, G.D. 1996. Bark beetle activity and delayed tree mortality in the Greater Yellowstone Area following the 1988 fires. In: Keane, R.E.; Ryan, K.C.; Running, S.W., eds. Proceedings Ecological implications of fire in Greater Yellowstone, 1996. Birmingham, AL: International Association of Wildland Fire: 151–158.

Ryan, K.C.; Noste, N.V. 1985. Evaluating prescribed fires. In: Lotan, J.E., ed. Proceedings, Symposium and workshop on wilderness fire. Gen. Tech. Rep INT-GTR-182. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station: 230–238.

Ryan, K.C.; Reinhardt, E.D. 1988. Predicting postfire mortality of seven western conifers. Canadian Journal of Forest Research. 18:1291–1297.

Scott. D.W.; Schmitt, C.L.; Spiegel, L. 2002. Factors affecting survival of fire injured trees: A rating system for determining relative probability of survival of conifers in the Blue and Wallowa Mountains. Report BMPMSC-03-01. La Grande, OR: U.S. Department of Agriculture, Forest Service, Blue Mountains Pest Management Service Center, Wallowa-Whitman National Forest. 39 p.

Sieg, C.H.; McMillin, J.D.; Fowler, J.F.; Allen, K.K.; Negron, J.F.; Wadleigh, L.L.; Anhold, J.A.; Gibson, K.E. 2006. Best predictors for postfire mortality of ponderosa pine trees in the intermountain West. Forest Science. 52: 718–728.

U.S. Department of Agriculture. 1996. Environmental assessment, spruce beetle control project. U.S. Department of Agriculture, Forest Service, Flathead National Forest, Tally Lake Ranger District. 203 p.

Van Wagner, C.E. 1977. Conditions for the start and spread of crown fire. Canadian Journal of Forest Research. 7: 23–34.

Wagener, W.W. 1961. Guidelines for estimating the survival of fire-damaged trees in California. Miscellaneous Paper No. 60. Berkeley, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station. 11 p.

Weatherby, J.C.; Mocettini, P.; Gardner, B.R. 1994. Biological evaluation of tree survivor-ship within the Loman Fire boundary, 1989–1993. Report No. R4-94-06. Boise, ID: U.S. Department of Agriculture, Forest Service, Intermountain Region. 10 p.

Weatherby, J. 1999. Inter-office memo to Forest Supervisor, Payette National Forest, January 20, 1999. Boise, ID: U.S. Department of Agriculture, Forest Service, Intermountain Region. 2 p.