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Mitigating Old Tree Mortality in Long-Unburned, Fire-Dependent Forests: A Synthesis

Sharon M. Hood

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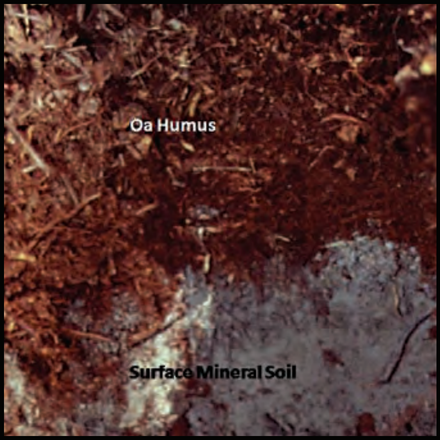

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Abstract

This report synthesizes the literature and current state of knowledge pertaining to reintroducing fire in stands where it has been excluded for long periods and the impact of these introductory fires on overstory tree injury and mortality. Only forested ecosystems in the United States that are adapted to survive frequent fire are included. Treatment options that minimize large-diameter and old tree injury and mortality in areas with deep duff and methods to manage and reduce duff accumulations are discussed. Pertinent background information on tree physiology, properties of duff, and historical versus current disturbance regimes are also discussed.

Keywords: smoldering, fire effects, tree mortality, duff mounds, fire exclusion, fuel treatment, prescribed fire, monitoring, old-growth, heat injury, reintroduction of fire, duff consumption

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Preface

Forest managers around the country have expressed concerns about large-diameter and old tree mortality when prescribed burning in long-unburned forests. The synthesis herein suggests recommendations for maintaining and perpetuating old trees in fire-dependent ecosystems. It expands on efforts funded by the Joint Fire Science Program (JFSP) to define the issues surrounding burning in fire-excluded forests of the United States that are adapted to survive frequent fire. When the JFSP initially funded this synthesis, two JFSP projects were examining the effect of raking on reducing old ponderosa and Jeffrey pine (subsequently published in Fowler and others 2010; Hood and others 2007a). Another JFSP project examined the effect of prescribed burning under different duff moisture conditions on long-unburned old longleaf pine mortality (Varner and others 2007). Two other syntheses were also recently published on this subject: *Perpetuating old ponderosa pine* (Kolb and others 2007) and *The conservation and restoration of old growth in frequent-fire forests of the American West* (Egan 2007). The scope of the synthesis herein focuses only on limiting overstory tree mortality in species adapted to survive frequent fire; therefore, the implications of fire suppression and fuel treatments on other ecosystem components are not discussed.

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Mitigating Old Tree Mortality in Long-Unburned, Fire-Dependent Forests: A Synthesis

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Introduction

Historically, many forested ecosystems in the United States burned frequently, both from lightning ignited fires and from Native American burning. Frequent fire maintained low fuel loadings and shaped forests composed of tree species adapted to survive low-intensity frequent fire. Longleaf pine (*Pinus palustris* Mill.) forests burned as frequently as every 2 to 8 years (Christensen 1981; Frost 1993), and historical records and dendrochronological studies provide evidence that ponderosa pine (*Pinus ponderosa* C. Lawson), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), western larch (*Larix occidentalis* Nutt.), giant sequoia (*Sequoiadendron giganteum* (Lindl.) J. Buchholz), red pine (*Pinus resinosa* Aiton), and many other forests also burned regularly. In the early 1900s, the United States government initiated a program to suppress all fires, both natural and anthropogenic. Many unintended consequences have resulted from over a century of fire suppression, such as increased tree densities and fuel, increased stress on older trees from competition, and greater risk of bark beetle attacks. These consequences are especially apparent in forests that historically burned frequently and have thus missed many fire cycles.

Maintaining old trees and perpetuating large-diameter trees is an increasing concern. Stands of old trees that were historically common across vast landscapes in the United States are now relatively rare on the landscape because of harvesting (Noss and others 1995). Though logging is no longer the principal threat to most old-growth forests, they now face other risks (Vosick and others 2007). Prescribed fire has become a major tool for restoring fire-dependent ecosystem health and sustainability throughout the United States and use will likely increase in the future. However, increased mortality of large-diameter and old trees following fire has been reported in many areas around the country, and there is increased concern about maintaining these on the landscape (Kolb and others 2007; Varner and others 2005). As early as 1960, Ferguson and others (1960) reported high longleaf pine mortality after a low-intensity prescribed burn consumed the majority of heavy duff accumulations around the base of the trees. Mortality of pre-settlement ponderosa pines in prescribed burn areas in Grand Canyon National Park was higher than in control plots (Kaufmann and Covington 2001). After beginning a forest restoration program that reintroduced fire by prescribed burning at Crater Lake National Park, excessive post-fire mortality of larger ponderosa pine was observed in the burn areas, and early season burns had an even higher mortality than late season burns (Swezy and Agee 1991). Both Swezy and Agee (1991) and McHugh and Kolb (2003) reported a U-shaped mortality distribution for ponderosa pine following wildfires, with smaller- and larger-diameter trees having higher mortality than mid-diameter trees.

Litter and duff accumulation around large-diameter trees has reached unprecedented levels in many areas as a result of 100+ years of fire exclusion. Abnormally high litter and duff accumulations after extended fire-free periods in fire-dependent ecosystems are well documented (Covington and others 1997; Dodge 1974; Haase and Sackett 1998; Sackett and Haase 1998; Sackett and others 1996; Swezy and Agee 1991; Varner and others 2005). Even with mechanical thinning to reduce ladder fuels and thus, the likelihood of crown injury, deep duff mounds remain, as does the potential for stem and root injury. Because flames are not typically associated with smoldering duff, forest floor consumption after the flaming front passes draws little attention, and its consequences are easily overlooked. However, restoration burns in areas with deep basal duff around trees may result in greater duff consumption and higher soil temperatures than trees subject to periodic low-intensity fires with shallower basal duff (Swezy and Agee 1991).

Several studies have attributed large-diameter tree mortality to basal injury caused by duff mound smoldering. Long-term smoldering can cause extended high soil heating, frequently above 140 °F (60 °C), which is the temperature required to kill living tissue. Hartford and Frandsen (1992) reported soil temperatures under smoldering duff mounds of 750 °F (400 °C), with duff temperatures above 212 °F (100 °C) for over 16 hours, compared to soil temperatures of less than 176 °F (80 °C) and duff temperatures above 212 °F (100 °C) for 1 hour under burning slash. Temperatures in smoldering duff mounds exceeded 572 °F (300 °C) for 2 to 4 hours during a prescribed burn in Glacier National Park, resulting in 45 percent mortality of the cambium sampled (Ryan and Frandsen 1991).

Basal tree injury from smoldering duff can attract bark beetles that can greatly influence post-fire delayed tree mortality. Rust (1933) reported for the 1928 Tubb's Hill ground fire at Coeur d'Alene, ID, that bark beetles attacked a greater percentage of ponderosa pines containing severe basal injury (from long-duration smoldering of accumulated basal duff) than trees with severe crown injury. This type of fire injury, and subsequent insect attack, resulted in heavy losses in larger trees in more open stands (Rust 1933). Bradley and Tueller (2001) stated that a burned tree was nearly 25 times more likely to be attacked by bark beetles than an unburned tree, and trees with deep soil charring were nearly 10 times more likely to be attacked than all other trees combined.

Although some work has been done on the effect of duff and litter removal from the base of trees (Covington and others 1997; Feeney and others 1998; Laudenslayer and others 2008; Swezy and Agee 1991), little is known about the factors that determine its success or failure as a practical management tool. Successful removal treatments could widen the window of opportunity for prescribed burning to achieve management goals already constrained by weather, fuel conditions, air quality concerns, societal constraints, fire resource availability, and concern about potential large-diameter tree mortality. Sample sizes in most of these studies were small and there were no controls or raking-only treatments. Fowler and others (2010) reported that raking reduced cambium kill at the bases of old ponderosa pine. However, the cambium kill did not result in tree mortality, and three years after burning, no trees, either raked or unraked, died in the study.

It is important to distinguish between first-entry, initial burns and subsequent maintenance burns in areas that have not burned for long periods. Long-unburned stands usually have substantially higher fuel loadings and greater duff to litter ratios than more frequently burned stands. Therefore, extra care must be taken when reintroducing fire to forests after decades of fire absence (Wade and Johansen 1986). In areas with deep basal duff mounds, the initial prescribed burn will likely have the greatest impact on tree mortality compared to subsequent burns. In these areas, utmost precaution to limit duff consumption at the base of large trees is required. It will likely take either multiple low-severity fires to slowly reduce fuel loadings to historical levels or mechanical removal methods such as raking to maintain the large tree component (Arno 2000; Harrington and Sackett 1990). Fires that consume litter but little duff may create an environment that speeds up residual duff decomposition (Zeleznik and Dickmann 2004; S. Haase, personal communication; T. Jain, personal communication). Because litter is consumed very quickly during passage of the flaming front, residence times are short and do not cause basal injury to trees with thick bark.

Organization and Scope

Maintaining large-diameter and old trees is only one aspect of forest restoration. Restoring and maintaining historic disturbance patterns and ecosystem functions is the larger goal of most restoration efforts. However, perpetuating the large-diameter tree component is key to restoring historical stand structure and many ensuing processes because old trees take longer than any other ecosystem component to replace (Kaufmann and Covington 2001). The forest restoration literature discusses in detail these broader issues for several fire-frequent ecosystems in the United States (Apostol and Sinclair 2006; Clewell and Aronson 2008; Friederici 2003; Stanturf and Madsen 2004). This report focuses on maintaining existing large and/or old trees and perpetuating future old trees when reintroducing fire into long-unburned areas. Old-growth forest definitions abound and vary by ecosystem. Rather than trying to define and limit the volume to only old-growth forests, I discuss the impact of fire on all large-diameter and/or old trees for species that current knowledge leads us to believe survived frequent low-intensity surface fire regimes. Only tree species that are adapted to survive frequent low-to-moderate intensity surface fire are included. The majority of the literature focuses on ponderosa and longleaf pine, but many other pertinent species are discussed (Table 1).

Table 1—Trees species included in this volume. Mature trees listed historically survived under a frequent, low-intensity fire regime.

Species	
Eastern U.S.	**Western U.S.**
Red pine	Ponderosa pine
	Douglas-fir
	Sugar pine
	Western larch
	Incense cedar
Southern U.S.	White fir
Longleaf pine	Red fir
	Giant sequoia

This synthesis is organized into seven sections: (1) Fire Impacts on Trees and Causes of Tree Death; (2) Properties of Soil and Duff; (3) Historical and Current Fire Frequencies and Stand Characteristics; (4) Treatment Effects on Old Tree Resilience; (5) Management Options; (6) Monitoring the Effects of Fire on Overstory Tree Mortality; and (7) Knowledge Gaps. The first two sections provide a background for fire-related tree injury and ground fuels in fire-excluded stands. The third section contrasts historical and current stand conditions and disturbance regimes for fire-dependent forest types. The fourth and fifth sections provide information on treatment options at various scales based on pertinent studies and makes general treatment recommendations by forest type. *Management Options* also discusses defining treatment objectives, treatment prioritization, no action, and monitoring techniques. Differences between stand and individual tree monitoring, what variables to monitor, and appropriate monitoring time lengths are discussed in the *Monitoring* section. The last section identifies gaps in the scientific literature and recommends topics for future research.

Fire Impacts on Trees and Causes of Tree Death

When discussing fire effects on trees, it is helpful to first define some key terms. Injury and damage are not synonymous. Smith and Sutherland (2001) make the distinction: injury is an impairment or loss of function; damage involves loss of property, value, or usefulness. Damage is relative to management goals (Sutherland and Smith 2000), while injury is not.

The three basic types of fire are: crown fire, surface fire, and ground fire. Crown and surface fires consume surface and canopy fuels by active flaming. These two types can cause crown injury through convective and radiant heating, but typically cause little to no soil heating (Byram 1959; Hartford and Frandsen 1992). Ground fires burn through duff and organic soils by smoldering combustion. Smoldering combustion is a much slower process with higher residence times, more smoke production, and lower temperatures than active flaming (Hartford and Frandsen 1992). No flames are visible during smoldering and only wisps of smoke or a small, glowing front is visible during the glowing combustion phase (DeBano and others 1998). Ground fires and consumption of large-diameter surface fuels can cause root and basal stem injury by consuming fine roots growing in the duff layer and through long-term heating of the soil and cambium at the tree base (Hungerford and others 1994; Ryan and Frandsen 1991).

Trees can be killed immediately by fire, die several years post-fire from either direct fire injuries or indirectly though biotic or abiotic agents, or survive despite injuries (Loomis 1973). Fire injuries to a tree's crown, cambium, and roots are first order fire effects. These injuries often lead to tree death, depending on the extent of injury, and influence the tree's ability to withstand other factors such as post-fire bark beetle attacks and drought (Ryan 1982; Wade and Johansen 1986). These secondary factors that result from the interaction with the fire and the tree's response to fire-caused injuries are called second order fire effects.

First Order Tree Responses to Heat Injury

Crown injury—Crown injury is typically cited as the most important factor determining post-fire tree survival (Fowler and Sieg 2004; Wagener 1961). Crown injury reduces a tree's photosynthetic capacity by reducing the volume of the live crown. However, this reduction in photosynthetic capacity is not directly proportional to the percentage of crown volume lost because the lower one-third of the crown is less photosynthetically productive than the upper two-thirds (Ryan 1998). Wallin and others (2003) found that ponderosa pine trees with greater than 50 percent crown scorch increased net photosynthetic rate, suggesting improved water relations in the remaining unscorched foliage after a prescribed burn in Arizona; Ryan (2000) also supported this finding.

Crown injury can be grouped into two major types: needle scorch and bud kill (Figure 1). Crown needle scorch is a measure of the amount of pre-fire crown where needles are killed by heated air (scorched) and can include areas with live and dead buds. Crown bud kill is the amount of pre-fire crown where buds are either killed by heated air or consumed by direct flame contact (Figure 2). These measurements are usually expressed as either percentage of pre-fire crown volume scorched/killed or percentage of pre-fire crown length scorched/killed.

For most species, the areas of the crown with needle scorch and bud kill are equal. However, the difference can be substantial for species with large buds, such as the southern pines, ponderosa pine, red pine, and Jeffrey pine (*Pinus jeffreyi* Balf.), or for those with protective features around the buds, such as the spur shoots on western larch branches. Larger buds require longer heat exposure to kill meristematic tissue; therefore, species with large buds are more resistant to crown injury. Long needles also form a protective sheath around the buds, offering additional protection (Ryan 1982; Wade and Johansen 1986). These species are capable of surviving very high levels of crown

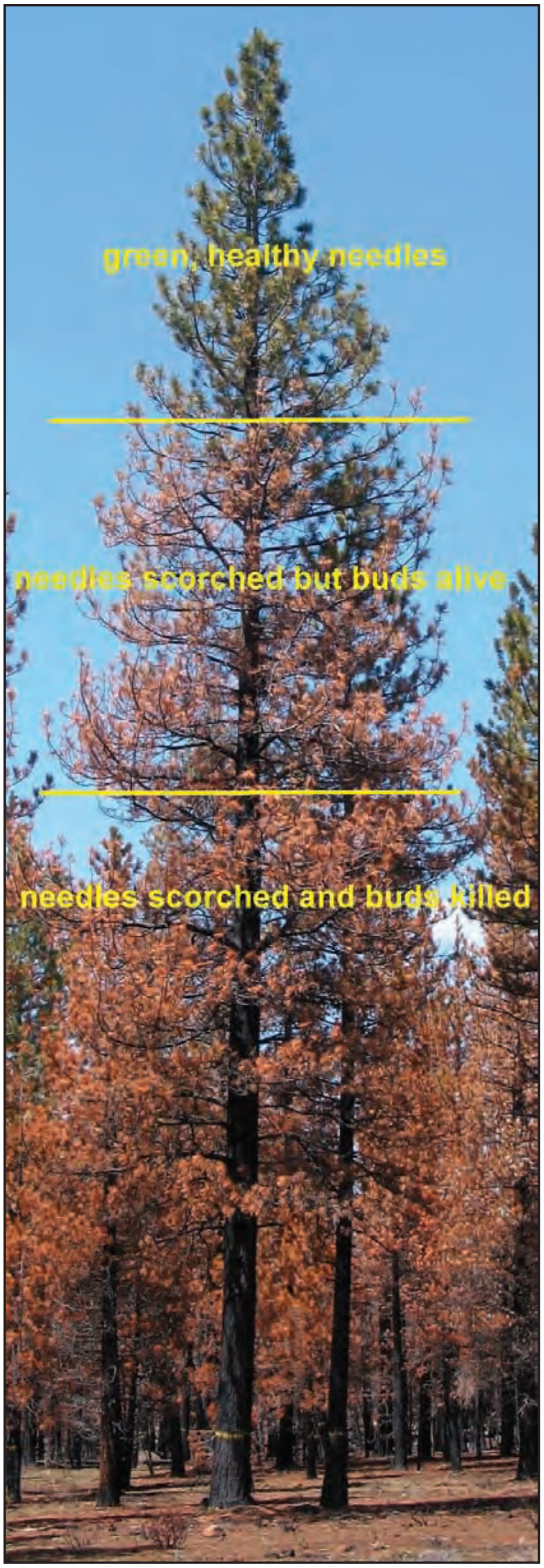

Figure 1. Ponderosa pine showing the different types of crown injury. The uppermost, green portion of the crown was unaffected by the fire. The middle portion of the crown's needles were scorched and killed, but the buds survived. The lower portion of the crown's needles was scorched and both the needles and buds were killed.

Figure 2. Crown consumption from direct flame contact.

scorch if bud kill is minimal (Dieterich 1979; Wade and Johansen 1986; Wagener 1961). Burning during the dormant season may reduce bud kill more than burning during the growing season when buds are actively growing and ambient air temperature is lower (Ferguson 1955; Harrington 1993; Wade and Johansen 1986). Southern pines also undergo multiple needle flushes during the growing season. This ability to quickly refoliate increases the chance of tree survival if high crown scorch occurs early in the season compared to the same level of injury occurring after the last flush of the year (Weise and others 1989).

Crown scorch is most easily determined several weeks to several months after the fire when the needles have turned brown but have not fallen (Ryan 1982). Immediately after the fire, scorched needles have a dull green appearance making it more difficult to determine scorch levels than when the needles are brown. Crown scorch cannot be reliably measured beyond 1 year post-fire because many scorched needles have already fallen and tree crowns may begin fading due to other factors, such as bark beetle attacks (Figure 3) or disease.

Figure 3. Fading ponderosa pine tree from bark beetle attacks 1 year after fire. No needles on this tree were scorched by the fire.

Bud kill is most easily measured soon after bud break, during the first spring following the fire, or after the next needle flush for southern pines. At this time, new needle emergence is highly visible and the majority of scorched needles still remain in the crown. Areas of the crown with both needle scorch and bud kill retain scorched needles longer than areas where buds and branches are alive because the dead limbs cannot actively shed the dead needles. These scorched needles on dead branches eventually weather off with wind and precipitation. Areas of the scorched crown with little bud kill can abscise the dead needles, making the crown appear thin because of the lost scorched needles (Figure 4) (Ryan 1982).

Cambium injury—Cambium kill occurs when lethal temperatures reach the cambium layer between the bark and wood. The tree is girdled if cambium is killed around the entire tree circumference. Bark thickness is the principal factor determining the amount of heat transferred to the cambium during a fire (Martin 1963). Bark insulates the cambium from heat and is not easily combustible; therefore, thicker bark provides more protection. The rate of thickening differs by species, individual genetic differences, and environmental factors, and it influences how quickly this insulating layer forms (Hare 1965; Hengst and Dawson 1994). Species that develop thick bark early in life become fire-resistant sooner and are adapted to survive frequent, low-intensity fire. Bark thickness generally increases linearly with tree diameter (Spalt and Reifsnyder 1962).

Figure 4. Tree crown in left foreground was scorched and buds were killed by fire. Center tree's needles were scorched, but the buds survived. These buds flushed 1 year after the fire and the majority of scorched needles have already fallen.

However, Myers (1963) found old ponderosa pines in the Southwest had thinner bark than the younger ponderosa pines of equal diameter.

Species differences in bark and cambium moisture content, physical and thermal properties, and chemical composition also influence a tree's resistance to cambium kill from fire (Jones and others 2004; Martin 1963; Spalt and Reifsnyder 1962). For example, Hare (1965) reported that for equal bark thickness, longleaf and slash pines (*Pinus elliottii* Engelm.) were nearly twice as resistant to cambium kill compared to sweetgum (*Liquidambar styraciflua* L.), American holly (*Ilex opaca* Aiton), and black cherry (*Prunus serotina* Ehrh.). However, Martin (1963) and Dickinson and Johnson (2004) conclude that differences in thermal tolerance among species and growing seasons were relatively small when compared to the effects of bark thickness. Peterson and Ryan (1986) estimated the length of time necessary to kill portions of the cambium based on tree diameter for several species in the northern Rockies (Figure 5).

Cambium is killed at approximately 140 °F (60 °C) (Dickinson and Johnson 2004). Lethal temperatures may be reached after a few seconds for species with very thin bark. However, this can take hours for species with thick bark. Long-term heating of this kind only occurs when there is a large amount of fuel burning near the tree, such as a stump, log, or deep duff. Basal cambium injury on tree species adapted to survive frequent, low-intensity fire is typically not a problem in low-intensity surface fires because these species have thick bark, and little litter and duff accumulates between fires. However, in long-unburned areas, duff depth typically increases dramatically near the base of a tree, forming a basal mound. The long-term smoldering combustion of this fuel accumulation can increase cambium injury even for species with thick bark (Ryan and Frandsen 1991). This type of low-intensity, high-severity fire often produces a ring of charred, blackened bark near the groundline indicating the amount of duff that was consumed during the fire (Figure 6).

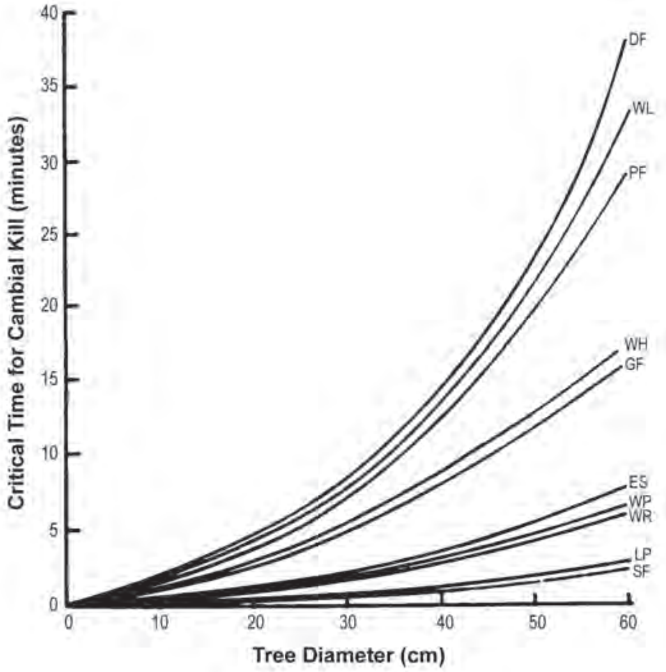

Figure 5. Critical time for predicted cambial kill as a function of tree diameter and species. Species are: Douglas-fir (DF), western larch (WL), ponderosa pine (PP), western hemlock (WH), grand fir (GF), Engelmann spruce (ES), western white pine (WP), western red cedar (WR), lodgepole pine (LP), and subalpine fir (SF). From Peterson and Ryan 1986.

Ryan and Frandsen (1991) developed a logistic regression model to predict the probability of ponderosa pine cambium death from prescribed burning. They measured duff consumption around old ponderosa pine trees during a prescribed burn in northwestern Montana. Cambium mortality was best predicted by the amount of duff consumed (Figure 7). This equation suggests that ponderosa pine duff depths deeper than 7 inches (18 cm) may cause substantial cambium mortality (>50 percent) if completely consumed. However, the results of this study are drawn from one research prescribed burn; additional research is needed to test this predictive model. Jones and others (2006) developed a physics-based stem heating model to predict cambium death during fire, but this model simulates stem heating and cambium death caused from flaming combustion and does not apply to long-term smoldering combustion.

A tree will likely die if the majority of its circumference is girdled by fire, or if additional injury to the crown also occurs. A girdled tree may take several years to die because the xylem is intact and can continue to transport water to support the crown, but photosynthate cannot be transported down to roots (Figure 8). The root system is eventually depleted of stored carbohydrate reserves

Figure 6. Using a drill to sample the base of a ponderosa pine for cambium kill after a prescribed burn. The charred, blackened area around the tree indicates the amount of litter and duff consumption. Arrows indicate the top of the duff pins radiating out from the tree base that were level with the surface litter prior to burning.

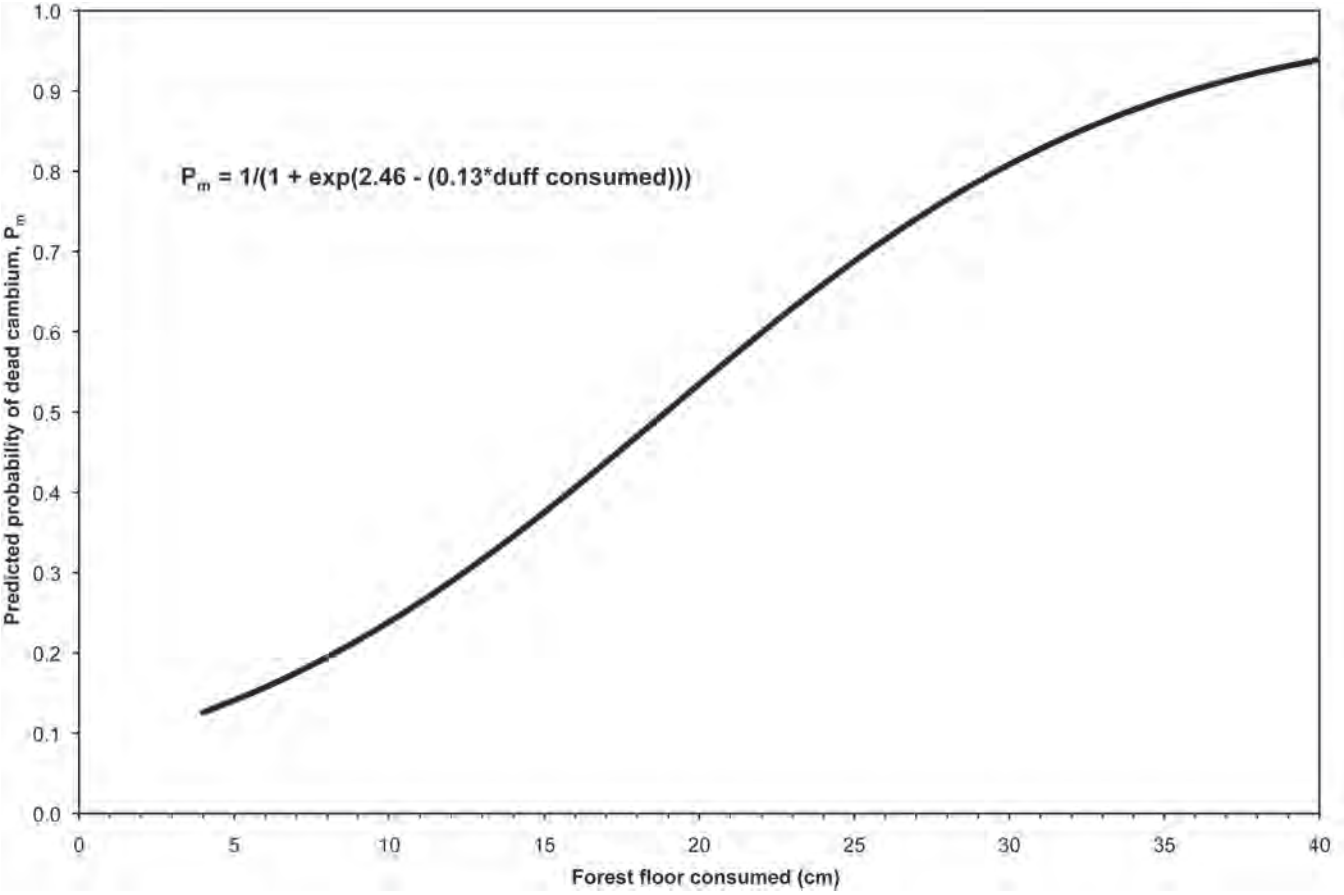

Figure 7. Logistic regression model for predicting the probability of cambium mortality in mature ponderosa pine resulting from duff consumption. Pm is the probability of cambium mortality (0 to 1) and duff consumed is the amount of duff depth reduction (cm). From Ryan and Frandsen 1991.

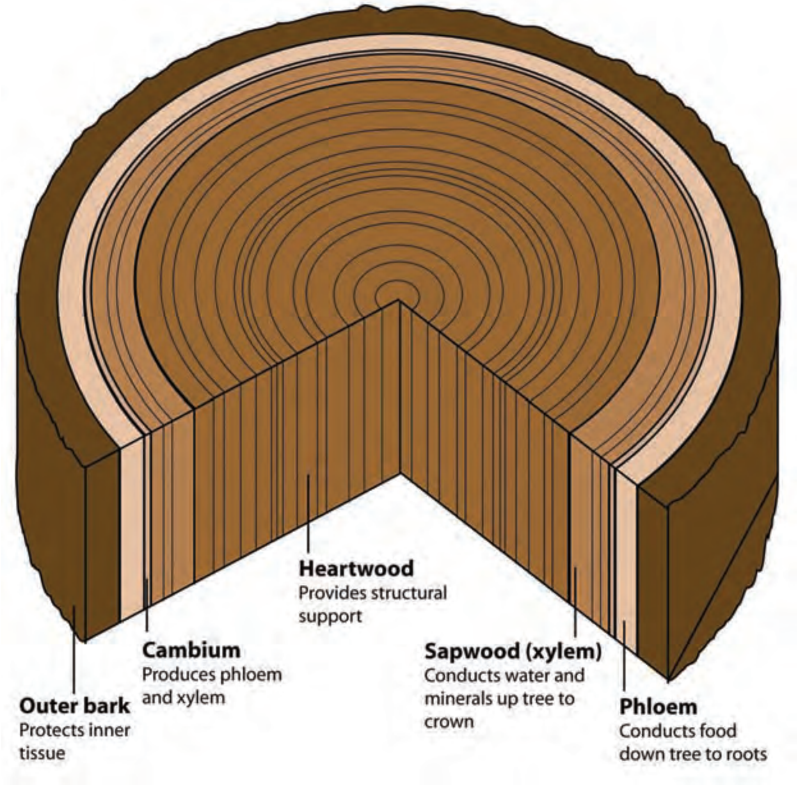

Figure 8. Cross section of tree showing functional parts of a tree stem.

and stops producing fine roots, which absorb soil water. Therefore, the tree dies from water stress (Greene and Shilling 1987; Michaletz and Johnson 2007).

Partial cambium kill produces a fire scar. Although trees can be scarred numerous times from reoccurring fires and survive, exposed fire scars are particularly susceptible to further injury in subsequent fires, especially if decayed wood is present. The leeward side of the tree, usually the uphill side in sloped areas, is most susceptible to cambium injury because of increased residence times, flame lengths, and temperatures as flames wrap around the backside of the tree and create vortices (Gill 1974; Gutsell and Johnson 1996). Guyette and Stambaugh (2004) found 90 percent of fire scars were located on the uphill side of the tree in mixed oak-shortleaf pine (*Quercus* spp. - *Pinus echinata* Mill.) forests in Arkansas.

Ryan (1982) developed bark char codes to help indicate stem injury after fire (Table 2). However, bark char on species with thick bark is not a definitive indicator of actual cambium kill (Breece and others 2008; Hood and others 2008). Hood and others (2008) evaluated these codes for many western conifer species and found that deep char usually indicated underlying dead cambium for species with thinner bark (Table 3). However, moderate char was not clearly associated with either live or dead cambium for species with thick bark. Breece (2006; Breece and others 2008) also reported an ambiguous relationship between bark char codes and cambium kill for ponderosa pine.

Cambium kill is most easily determined several months after a fire by removing a small portion of the bark at groundline (Figure 6 and 9). It is important to sample as close to the groundline as possible, as this is where heat injury to the cambium is most likely to occur (Hood and others 2007b). Samples are most easily obtained with a hatchet, or alternatively, a drill with a hole-saw attachment, an increment borer, or an increment hammer can also be used (Lentile and others 2005). Drills provide an exposed area of uniform size and go through thick bark quickly, but are heavy and cumbersome to use in most field situations. Increment borers and hammers are time consuming, reveal a very small portion of the cambium, and are easily damaged when used on charred, resinous bark (S. Hood, personal observation, 2002; Lentile and others 2005).

Once cambium is exposed, its status can be determined visually or tested using a vital stain (Ryan 1982). Live tissue will feel moist, soft, and spongy and will be a light pink or salmon color. Live cambium is pliable and is usually easily peeled away from the wood and bark. Dead cambium either will be hardened, with a dark, shiny appearance or will feel sticky, with a darker color

Table 2—Bark char codes and description of bark appearance (adapted from Ryan 1982).

Bark char code	Bark appearance
Unburned	No char
Light	Evidence of light scorching; can still identify species based on bark characteristics; bark is not completely blackened; edges of bark plates charred
Moderate	Bark is uniformly black except possibly in inner fissures; species bark characteristics still discernable
Deep	Bark has been burned into, but not necessarily to the wood; outer bark species characteristics are lost

Table 3—Recommended management guidelines for using Ryan's (1982) bark char codes as a surrogate for direct cambium sampling after fire. Species/code combinations not listed are not clearly associated with either live or dead cambium and should be sampled directly to determine injury.

Species	Bark char code	Probable cambium status
Lodgepole pine Whitebark pine Western white pine Western red cedar Engelmann spruce Subalpine fir	Light, moderate, or deep	Dead
White fir Incense cedar Ponderosa pine Douglas-fir Sugar pine	Light	Alive
White fir Incense cedar Ponderosa pine (wildfire) Douglas-fir (wildfire) Sugar pine	Deep	Dead
Ponderosa pine (prescribed fire)[a]	Moderate or deep	Alive
Douglas-fir (prescribed fire)[a]	Moderate	Alive
Western larch	Light, moderate, or deep	Alive

[a] If pre-fire duff mound depths are high and most duff is consumed in fire, then the probability of cambium mortality is higher.

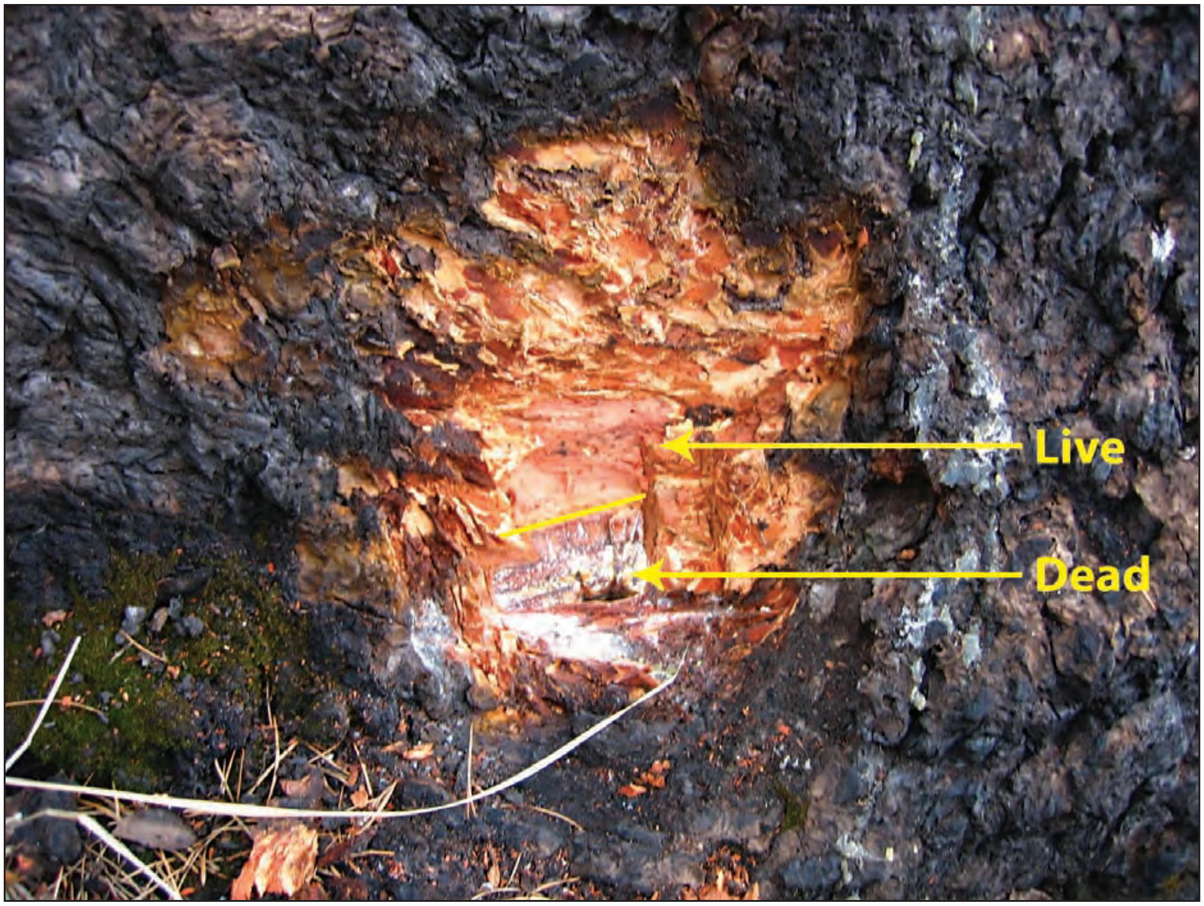

Figure 9. Douglas-fir cambium. The upper portion of exposed cambium is alive, and the lower portion is dead.

and a sour smell. Sometimes the resin may have dried and have a whitish cast (Figure 9). Dead cambium will not easily separate from the wood and bark (Hood and others 2007b; Ryan 1982).

Root injury—Root mortality is a function of temperature and duration of heat. Instantaneous tissue death occurs at approximately 140 °F (60 °C). However, the effect of long-term elevated temperatures below 140 °F (60 °C) on tissue is poorly understood. Smoldering ground fires can kill roots growing near the soil surface or in the duff either directly as duff is consumed or from heating the soil to lethal temperatures. Literature on root location, production, and turnover is sparse for most tree species, although it is commonly accepted that the majority of fine roots occur in the upper mineral soil horizon in most areas (Persson 2000). Soil is a poor conductor of heat, but studies have shown that deep, smoldering duff can heat soil to over 140 °F (60 °C) at least 8 inches (20 cm) deep in ponderosa pine (Sackett and Haase 1998) and longleaf pine (Varner and others 2009). In mixed-conifer forests of California, lethal temperatures were common to 4 inches (10 cm) deep in mineral soil during prescribed burns (Haase and Sackett 1998). In that study, forest floor depths beneath tree canopies where soil temperatures were measured ranged from 2.4 to 10.9 inches (6 to 28 cm) and duff consumption was complete. Increasing the time that soil was heated above 140 °F (60 °C) caused a steep decline in the amount of coarse root non-structural carbohydrates when burning a fire-excluded longleaf stand (Varner and others 2009). The authors hypothesized that fire-injured trees were using available carbohydrates stored in coarse roots to replenish heat-killed fine roots, thus compromising the trees and making them vulnerable to second order fire effects, such as bark beetles, diseases, or climatic stress. Another study in long-unburned longleaf pine found that trees were 20 times more likely to die when basal duff consumption exceeded 30 percent compared to trees with less basal duff consumption (J. O'Brien, personal communication). Tree mortality was also attributed to mortality of fine roots located in the accumulated duff layer that were consumed during the fire.

Studies of root location in the soil and in proximity to the bole are conflicting. Location likely varies by tree species, site productivity, tree age, duff depth, and drought conditions. Average fine root content and concentration was higher at the dripline than halfway between the dripline and tree bole for large Douglas-fir (>17 inches; >43 cm diameter at breast height (DBH)) and ponderosa pine (>19 inches; >48 cm DBH) in Idaho (Dumm 2003). However, the relationship was the opposite for small trees. The majority of their roots were located in mineral soil, rather than in the forest floor. Duff at this study site was relatively shallow, with a mean depth of 1.4 inches (3.5 cm), and differences in depth between sample locations were not reported. In contrast, there were no significant differences in fine root biomass by tree age or by distance from bole in ponderosa pines growing in central Oregon (Andersen and others 2008). This study compared root biomass among 15 to 20, 50 to 60, and greater than 250-year-old trees. Sampling occurred at 50, 100, and 150 percent of the distance between tree bole and dripline. Fine root lifespan was greater than 1 year. However, no roots were sampled from the forest floor layers, and duff depths or time since fire was not reported. Curtis (1964) excavated the root system of a 16.9-inch (42.9-cm) DBH, 60-year-old ponderosa pine growing on the Boise Basin Experimental Forest, ID. He found 24 percent of fine roots were located within 5 inches (12.7 cm) of the tree bole.

It is speculated that fire exclusion has allowed fine roots to grow up into accumulated duff on some sites where frequent fire would typically limit duff development and contain roots mostly to the mineral soil horizons (Jain and Graham 2004; Wade 1986). The presence of fine roots in the duff is an important observation when determining potential tree mortality from prescribed burning. Gordon and Varner (2002) found no significant differences in biomass of longleaf pine roots <0.08 inches (<2 mm) diameter in the forest floor and upper 9.8 inches (25 cm) of mineral soil at the base of old trees in a fire-excluded stand. Old ponderosa pine tree mortality has been attributed to fire-caused injury to fine roots located in the duff in Oregon (Swezy and Agee 1991) and in shallow volcanic soils in Arizona (Fulé and others 2002b). Duff consumption near the tree bole during a prescribed fire was significant in predicting white fir (*Abies concolor* (Gord. & Glend.) Lindl. ex Hildebr.), sugar pine (*Pinus lambertiana* Douglas), and ponderosa pine mortality (Stephens and Finney 2002). Pre-burn duff moisture averaged 15.8 percent, resulting in almost complete duff consumption.

Detecting root kill after a fire is much more difficult than detecting crown or cambium injury. Ground char codes exist to provide a general assessment of potential root damage (Table 4) (Ryan 1982; Ryan and Noste 1985), but they have not been tested to determine if there is a relationship between increasing ground char and root kill.

Table 4. Ground char codes and descriptions (Ryan 1982; Ryan and Noste 1985).

Ground char code	Ground appearance
Unburned	• Not burned
Light	• Litter charred to partially consumed • Upper duff layer may be charred but the duff is not altered over the entire depth • Surface appears black • Where litter is sparse, charring may extend slightly into soil surface, but soil is not visibly altered • Woody debris partially burned • Logs are scorched or blackened but not charred • Rotten wood is scorched to partially burned
Moderate	• Litter mostly to entirely consumed, leaving coarse, light colored ash (ash soon disappears, leaving mineral soil) • Duff deeply charred, but not visibly altered • Woody debris is mostly consumed • Logs are deeply charred and burned out stump holes are evident
Deep	• Litter and duff completely consumed, leaving fine white ash (ash soon disappears leaving mineral soil) • Mineral soil charred and/or visibly altered, often reddish • Sound logs are deeply charred, and rotten logs are completely consumed

Average ground char rating was significantly higher for dead ponderosa pine trees than live trees (McHugh and Kolb 2003; Thies and others 2006), but it was not significant in predicting either ponderosa pine or Douglas-fir tree mortality (Hood and Bentz 2007; McHugh and Kolb 2003; Thies and others 2006).

Delayed Tree Mortality From Bark Beetles

Many bark beetle species are attracted to burned areas and cause post-fire tree mortality beyond what is expected from fire injury alone (Breece and others 2008; Hood and Bentz 2007; Hood and others 2007c; Lombardero and others 2006; McHugh and others 2003; Perrakis and Agee 2006; Ryan and Amman 1996). The influence of this secondary interaction between fire and bark beetles on delayed tree mortality varies with beetle population levels and host availability, but the widespread influence of bark beetles on post-fire delayed tree mortality is evident from previous studies. Of the 41 studies that have examined the effects of fire on old or large-diameter tree mortality in historically fire-frequent forests in the United States, 22 reported bark beetles caused additional mortality post-fire (Table 5). This secondary interaction is further documented in other forest types and younger stands (Fowler and Sieg 2004; Negrón and others 2008).

Bark beetles can have a major influence on the timing and amount of post-fire delayed tree mortality. Many studies have reported little additional mortality beyond the second post-fire year (Fowler and Sieg 2004). However, others have observed considerable tree mortality occurring over much longer periods where bark beetles attacked fire-injured trees (Hood and Bentz 2007; Sackett and Haase 1998; Weatherby and others 2001). Differences in the influence of beetle attacks on fire-injured trees among studies may, in part, be a function of the length of time trees are monitored post-fire. Fifteen of the 41 existing studies on post-fire old or large-diameter mortality in fire-dependent U.S. forests monitored mortality and bark beetle attacks for 5 years or longer; the remaining studies only report post-fire mortality for 3 years or fewer (Table 5). Records of the long-term effects of bark beetles and fire on mortality are even scarcer, only three studies have reported results from 10 years or more post-fire (Table 5). There is clearly a need for longer-term monitoring in order to fully understand the effect of bark beetle attacks and other secondary interactions on post-fire tree mortality. This is discussed further in the *Monitoring the Effects of Fire on Overstory Tree Mortality* section of this publication.

Bradley and Tueller (2001) found significant correlations between prescribed burning and bark beetle attacks on Jeffrey pine in the Lake Tahoe Basin, CA. Beetles attacked 24 percent of trees in burned plots compared to less than 1 percent of unburned plots. A burned tree had a 24.81 times greater chance of being attacked than a similar unburned tree. The majority of attacks were from red turpentine beetles (*Dendroctonus valens* LeConte). Though it is not typically considered a tree-killing beetle, it seemed to be attracted to fire-injured trees and to predispose the burned trees to attacks by more aggressive *Dendroctonus* beetle species. All burned trees attacked by Jeffrey pine beetle (*Dendroctonus jeffreyi* Hopkins) were also attacked by red turpentine beetles. No red turpentine beetle attacks were observed in the control plots.

Prescribed burning an old-growth mixed-conifer forest in the Sierra Nevada, CA, increased bark beetle attacks and subsequent large-diameter sugar and Jeffrey pine mortality compared to unburned units (Maloney and others 2008). No crown kill was observed in the burned units, leading the authors to speculate that a combination of bark beetle attacks and basal injury killed the trees. However, another study in the Sierra Nevada found no difference in probability of sugar pine mortality after mountain pine beetle (*Dendroctonus ponderosae* Hopkins) attack between small and large trees after prescribed burning (Schwilk and others 2006).

Western pine beetles (*Dendroctonus brevicomis* LeConte), alone or in conjunction with fire injury, were the largest mortality agent after prescribed burns in old-growth ponderosa pine units in Crater Lake National Park, OR (Perrakis and Agee 2006). In a separate study in Crater Lake National Park, 2 percent of large ponderosa pine died from insects or pathogens over 5 years in the control units compared to 6 percent in spring burn units and 13 percent in fall burn units (Agee and Perrakis 2008). Thomas and Agee (1986) reported that the proportion of beetle-killed ponderosa and sugar pines greater than 27.6 inches (70 cm) DBH was higher in prescribed burned areas than in unburned areas in Crater Lake.

Douglas-fir beetles (*Dendroctonus pseudotsugae* Hopkins) are attracted to large-diameter, moderately fire-injured Douglas-fir trees (Furniss 1965; Hood and Bentz 2007; Rasmussen and others 1996). Large Douglas-fir trees that initially survive fire injuries are susceptible to Douglas-fir beetle attack, which can cause high levels of delayed tree mortality. In areas with nearby Douglas-fir beetle populations, Hood and Bentz (2007) estimated that the Douglas-fir beetle was responsible for an additional 25 percent of observed mortality of Douglas-fir trees greater than 9 inches (23 cm) DBH 4 years after wildfire in Montana and Wyoming. Ryan and Amman (1996) found beetle attacks increased with increasing Douglas-fir basal girdling after wildfires in Yellowstone National Park.

Table 5—Studies that have examined the effects of fire on old or large-diameter tree mortality in historically fire-frequent forests in the United States. Studies are listed in alphabetical order. Main reference is the most recent report of mortality. Additional references listed report older or other pertinent results from the same study.

Reference	Years monitored	Primary species[a]	Crown injury assessed	Basal injury assessed[b]	Root injury assessed	Basal duff depth assessed	Bark beetles influenced mortality	Additional references	Additional comments
Agee 2003	13	Ponderosa pine Douglas-fir White fir					Yes	Thomas and Agee 1986	Causal agent of mortality identified, but tree level fire injury not assessed
Agee and Perrakis 2008	5	Ponderosa pine					Yes	Perrakis and Agee 2006	Causal agent of mortality identified, but tree level fire injury not assessed
Breece and others 2008	3	Ponderosa pine	x	x			Yes		
Campbell and others 2008	1, 2	Longleaf pine					Yes		Causal agent of mortality identified, but tree level fire injury not assessed
Fettig and others 2008	2	Jeffrey pine Ponderosa pine White fir					Yes		Causal agent of mortality identified, but tree level fire injury not assessed
Fowler and others 2010	3	Ponderosa pine	x	x		x	No		
Fulé and others 2007	5	Ponderosa pine	x	x			No	Fulé and others 2002b; Roccaforte and others 2008; Waltz and others 2003	Duff around all presettlement trees was raked prior to burning
Fulé and others 2005	5	Ponderosa pine	x	x			No	Fulé and others 2002a	Duff around presettlement trees raked in some treatments
Ganz and others 2003	1	Jeffrey pine Ponderosa pine Incense cedar White fir	x	x		x	Yes		
Haase and Sackett 1998	9	Giant sequoia Sugar pine	x	x	x	x	No		Root injury inferred from soil temperature measurements
Hanula and others 2002	2	Longleaf pine Slash pine	x	x			Yes		
Henning and Dickmann 1996	2, 7	Red pine	x				No		
Hood and Bentz 2007	4	Douglas-fir	x	x			Yes		
Hood and others 2007b	2, 3, 4	Jeffrey pine Ponderosa pine Incense cedar White fir Red fir	x	x			Yes		
Hood and others 2007a	2, 3	Jeffrey pine Ponderosa pine	x	x		x	Yes		

Table 5 (CONTINUED)

Reference	Years monitored	Primary species[a]	Crown injury assessed	Basal injury assessed[b]	Root injury assessed	Basal duff depth assessed	Bark beetles influenced mortality	Additional references	Additional comments
Jerman and others 2004	2	Ponderosa pine	x	x		x	No		
Kaufmann and Covington 2001	3, 7	Ponderosa pine		x			No		
Kobziar and others 2006	1	Douglas-fir Ponderosa pine Incense cedar White fir Tan oak Black oak	x	x			No		
Kolb and others 2001	6	Ponderosa pine					No	Covington and others 1997; Feeney and others 1998; Stone and others 1999; Wallin and others 2004	Duff removed from site prior to burning
Lambert and Stohlgren 1988	2 to 8	Giant sequoia		x					
Laudenslayer and others 2008	6	Jeffrey pine Ponderosa pine Sugar pine				x	Yes		
Loomis 1973	Not reported	Black oak White oak Post oak Scarlet oak		x			No		
Maloney and others 2008	3	Jeffrey pine Sugar pine Incense cedar White fir Red fir	x				Yes		
McHugh and Kolb 2003	3	Ponderosa pine	x	x			Yes		
Menges and Deyrup 2001	7	South Florida slash pine	x	x		x	Yes		
Methven 1971	1	Red pine Eastern white pine	x				No		
Miller and Patterson 1927	3	Ponderosa pine	x	x			Yes		

Table 5 (CONTINUED)

Reference	Years monitored	Primary species[a]	Crown injury assessed	Basal injury assessed[b]	Root injury assessed	Basal duff depth assessed	Bark beetles influenced mortality	Additional references	Additional comments
Mutch and Parsons 1998	5	Giant sequoia Jeffrey pine Sugar pine Incense cedar White fir Red fir California black oak	x				Yes	van Mantgem and others 2003	
Outcalt and Foltz 2004	1	Longleaf pine Slash pine South Florida slash pine	x						
Regelbrugge and Conard 1993	2	Ponderosa pine Incense cedar California black oak Canyon live oak		x			No		
Rust 1933	5	Ponderosa pine	x	x			Yes		
Ryan and Frandsen 1991	1	Ponderosa pine	x	x		x	No		
Sackett and Haase 1998	19, 20	Ponderosa pine	x	x		x	No	Sackett and others 1996	
Santoro and others 2001	2	Red pine	x	x			Yes		
Schwilk and others 2006	2	Sugar pine White fir Incense cedar	x	x			Yes	Knapp and others 2005	
Sullivan and others 2003	3	Longleaf pine	x				Yes	Otrosina and others 2002	
Swezy and Agee 1991	4, 10	Ponderosa pine	x		x	x	Yes		
Varner and others 2007	2	Longleaf pine	x	x		x	Yes		
Willard and others 1994	4	Ponderosa pine	x				No		
Williams and others 2006	1	Longleaf pine	x	x			No		
Wright and others 2003	2, 3, 6, 7	Ponderosa pine				x	No		

[a] Tan oak (*Lithocarpus densiflorus* (Hook. & Arn.) Rehder); California black oak (*Quercus kelloggii* Newberry); Canyon live oak (*Q. chrysolepis* Liebm.); Black oak (*Q. velutina* Lam.); White oak (*Q. alba* L.); Post oak (*Q. stellata* Wangenh.); Scarlet oak (*Q. coccinea* Münchh.).

[b] Basal injury assessed directly or by noting bark char presence.

No differences in trap captures of southern pine beetles (*Dendroctonus frontalis* Zimmermann) or eastern five-spined ips (*Ips grandicollis* Eichhoff) were found between prescribed burn units and unburned, control units in 40-year-old longleaf pine stands in South Carolina. However, almost all dead trees in the burned units were attacked by the two bark beetles, suggesting that burned trees are more susceptible to attack than unburned trees (Sullivan and others 2003).

Bark beetles and pathogens can interact to cause extensive mortality after the first post-fire year. Most longleaf pine mortality after prescribed burns was not observed until 2 to 3 years post-fire (Otrosina and others 2002; Sullivan and others 2003). Fires that consumed more duff and killed fine roots resulted in the highest mortality. The authors hypothesized that root pathogenic fungi on the site may have opportunistically infected the trees through injured fine roots, predisposing the trees to subsequent bark beetle attacks (Sullivan and others 2003). The combination of root disease, root injury, and secondary bark beetle attacks could have resulted in the significant mortality observed after the low-intensity prescribed burns. The authors recommended dormant-season heading fires that consume litter but not duff to reduce longleaf pine mortality.

Concerns abound that bark beetle populations will increase after fire and attack neighboring unburned areas. Whether this phenomenon occurs regularly, however, is unclear. Miller and Patterson (1927) found western pine beetle attacks increased the first 2 years after fire, but dropped to pre-fire levels by year 3. Brood production decreased in the attacked, burned trees and no spillover effects were observed. Furniss (1965) expressed concern about Douglas-fir beetles spreading to adjacent unburned forests, but reported decreased brood production in attacked, burned trees. Douglas-fir beetles attacked adjacent unburned trees 2 years after wildfires in Yellowstone National Park (Amman and Ryan 1991). However, beetle populations were increasing before the fires occurred, making it difficult to conclude if fire further increased the populations. Beetles did not spread to adjacent unburned areas after wildfires or prescribed fires in south Florida slash pine (*Pinus elliottii* Engelm. var. densa Little & Dorman) (Menges and Deyrup 2001). According to Jenkins and others (2008), the likelihood of bark beetles attacking adjacent, unburned areas depends on: (1) susceptibility of stands in both burned and unburned areas before and after the fire, (2) extent and severity of fire damage, (3) local bark beetle populations before the fire, and (4) weather conditions before and after the fire.

Properties of Soil and Duff

The forest floor includes all litter and decomposing organic layers above the mineral soil surface (Pritchett and Fisher 1987). The forest floor typically consists of three layers: litter, fermentation, and humus (Figure 10), although some layers may not be found or may not be distinguishable on all forested soils. The fermentation and humus layers are often collectively called duff and may be bound by mycelium to form a mat-like structure. The following is a detailed description of the layers:

Litter layer (L) or O_i: consists of unaltered, recently cast organic matter, such as leaves, needles, twigs, bark flakes, cones, and animal scat. This is the uppermost layer of the forest floor. The origin of the material is easily identifiable.

Fermentation layer (F) or O_e: consists of fragmented, partially decomposed organic material. This layer is found immediately below the L layer. The material is discolored, but the origin is still identifiable. This is also referred to as the upper duff layer. It has a higher bulk density and mineral content than litter.

Humus layer (H) or O_a: consists of well-decomposed, amorphous organic matter and possibly some mineral soil. This layer is found between the F layer and mineral soil. This is also referred to as the lower duff layer. It has a higher bulk density and mineral content than the F layer.

Sackett and Haase (1996) described the forest floor in terms of fire behavior called the fire intensity (FI) and fire severity (FS) layers (Figure 11). The FI layer consists of the L layer and upper portions of the F layer. These surface fuels burn by flaming combustion. The FI layer is often highly combustible because of its surface position and low bulk density, and it is a major component in determining rates of spread. The FS layer consists of the lower, denser portion of the F layer and the entire H layer. This layer is ground fuel that burns as smoldering combustion after the main flaming front has passed.

Differences Between Duff Mounds and Typical Forest Floor Duff

In the absence of fire, litter and duff from bark and needle shedding accumulate rapidly around the bases of trees (first 3 to 4 ft (1 m) horizontally) to depths that can cause injury to the roots and stems when burned. This is especially evident in dry forest types that have slow decomposition rates. The forest floor is usually deepest at the bases of large, older trees that have higher crown masses (Figure 12). Depth then decreases rapidly from the bole to the dripline (Figure 13) (Gordon and Varner 2002; Ryan and Frandsen 1991; Swezy and Agee 1991).

Figure 10. Long-unburned longleaf pine forest floor profile. Photo by Morgan Varner.

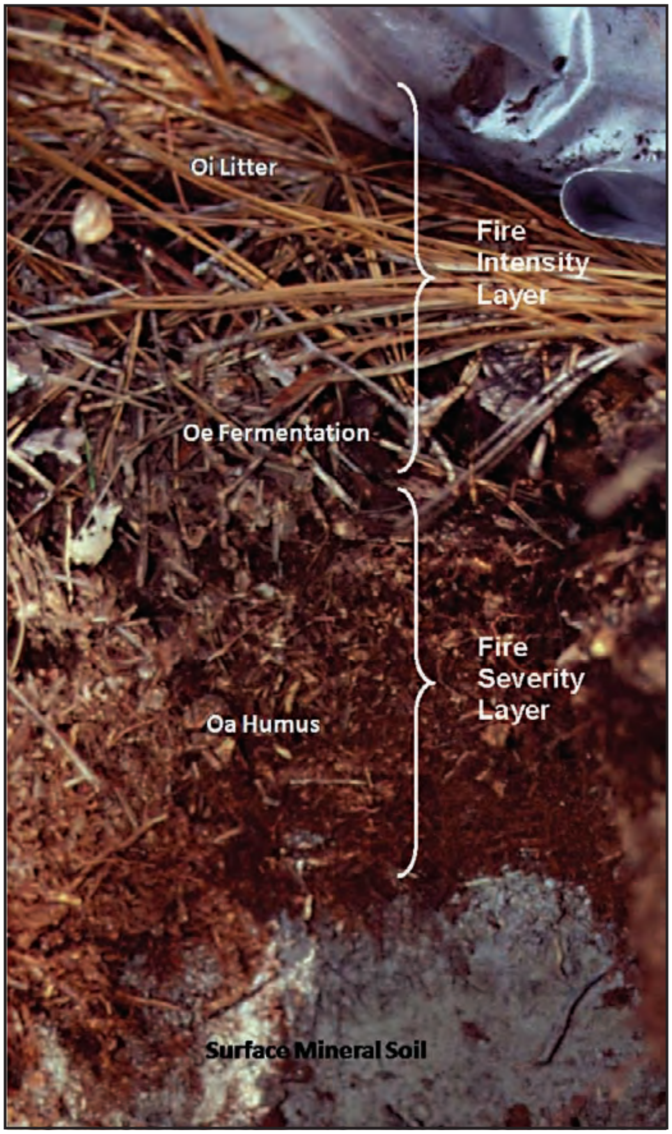

Figure 11. Forest floor profile showing fire intensity and fire severity layers. Photo by Morgan Varner.

Composition of duff also changes in proximity to the tree base. Duff at the base of trees typically has a much higher proportion of bark flakes than duff away from tree bases (Gordon and Varner 2002). As bark sloughs off trees, it is deposited directly at the tree base and is largely responsible for the mound of fuel accumulation often seen around large trees.

Duff is generally drier under tree crowns than between them due to crown interception of precipitation and radiation (Hille and den Ouden 2005; Miyanishi and Johnson 2002). Tree crowns intercept precipitation, reducing moisture input directly beneath the crowns. At night, tree crowns reduce terrestrial radiational cooling at the ground surface, which limits dew formation (Miyanishi and Johnson 2002). Litter moisture changes diurnally and is more variable than duff moisture because it wets and dries more quickly than the lower duff layers due to its surface exposure and lower bulk density. A study in longleaf pine found litter moisture content increased sharply after all rain events, but moisture in deep duff layers at the base of mature longleaf pine trees only increased after heavy and sustained rain events (>0.8 inches (>20mm) precipitation in 24 hours) (Ferguson and others 2002). The average time lag for ponderosa pine duff 3.4 inches (8.7 cm) deep was 50 hours (Fosberg 1977). See Appendix A for a description of methods used to measure duff moisture.

Figure 12. Deep duff mound at base of ponderosa pine after 100+ years of fire suppression. Large pine cones at base are vectors that increase the likelihood of duff ignition and consumption.

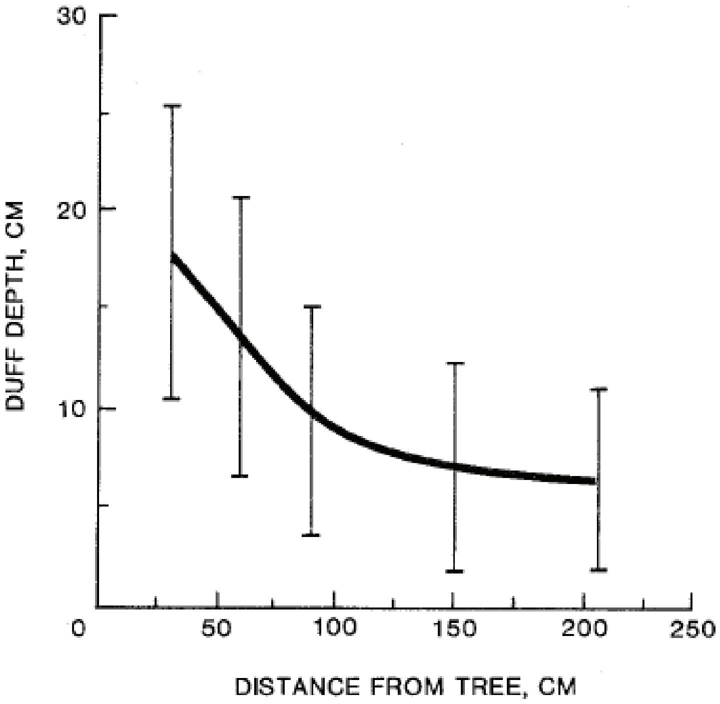

Figure 13. Mean and standard deviation of duff depth (cm) as a function of the distance (cm) from the base of the tree. From Ryan and Frandsen 1991.

Duff depth varies greatly throughout a stand, and temporal changes in duff are the hardest to predict of all fuel components (Hall and others 2006). Duff consumption is often reported and modeled as a unit average, assuming uniform consumption throughout the burned area. In reality, duff consumption can be patchy, ranging from completely burned areas to unburned or scarcely burned areas (Miyanishi and Johnson 2002). The percentage of duff consumption is often much higher in the duff mounds than in the ambient duff found away from tree bases (Hille and den Ouden 2005). This is likely because duff moisture varies throughout the stand and because deep duff can sustain smoldering at higher moisture contents (Miyanishi and Johnson 2002). In numerous prescribed burns in ponderosa pine in Arizona, almost all duff and litter was consumed to mineral soil around trees greater than 18 inches (45.7 cm) DBH to the dripline. In contrast, the forest floor was consumed to mineral soil for only a few inches around pole-size trees, 4 to 11 inches (10.2 to 27.9 cm) DBH. And in doghair thickets, only the litter layer was consumed and very little mineral soil was exposed (Sackett and Haase 1998). Prescribed burns in Montana reduced average stand-level duff depths from 17 to 30 percent, but 100 percent of duff was consumed around large tree bases (Kalabokidis 1992). Hille and Stephens (2005) found the probability of duff existence after a fire goes from near 0 percent at the tree base to over 60 percent in tree gaps in mixed-conifer forests of north-central Sierra Nevada, CA (Figure 14). This variability in duff depth highlights the importance of measuring forest floor depths at different locations throughout a stand before and after prescribed burning, as fire effects can differ significantly among points (Covington and Sackett 1992).

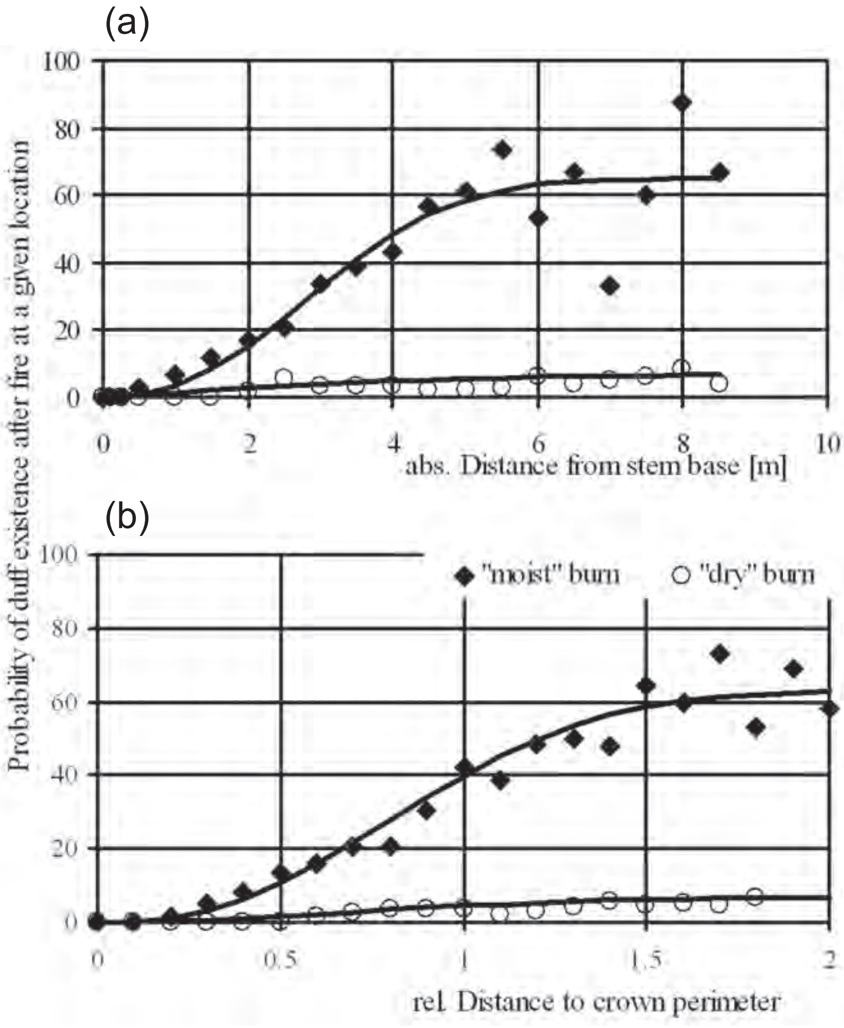

Figure 14. Spatial variation of duff remaining in the moist (♦) and the dry (O) prescribed fires, related to absolute (a) and relative (b) distance from dominant sugar and ponderosa pine trees. The probability of duff remaining (y-axis) is calculated from the percentage of data points where duff survived the fire. The relative distance from the stem base is expressed as ratio to the crown perimeter. A relative distance of “1” marks the edge of the crown (Hille and Stephens 2005). Copyright 2005 by Society of American Foresters. Reproduced with permission of Society of American Foresters in the format Journal via Copyright Clearance Center.

First-Entry Prescribed Burns

Long-unburned stands usually have greater duff to litter ratios than more frequently burned stands. Duff in old stands without recent disturbance is deeper and weighs more per unit area than younger stands (van Wagtendonk and others 1998), and duff bulk density generally increases with depth (Stephens and others 2004; van Wagtendonk and others 1998). Duff depth is deepest at the tree base and the high percentage of duff to total forest floor depth makes large trees more susceptible to fire injury during first-entry burns if the duff is consumed. Reducing basal duff consumption, either slowly through multiple burns under high duff moisture contents or by physical removal, is imperative to reduce cambium injury and possible tree mortality in areas with deep basal duff. Subsequent treatments normally do not require this intensive treatment because duff depths and, therefore, residence times are lower.

Factors Affecting Duff Consumption

There are two main questions concerning the probability of duff consumption during a fire:

(1) What factors influence duff ignition?
(2) What factors influence continued duff smoldering after ignition begins?

Initiation of smoldering is influenced by fuel moisture and surface fuel load. Surface fires spread over the forest floor and ignite woody fuels and cones as the fire burns through fine fuels. Burning large surface fuels increases residence times, dries out underlying duff, and increases the likelihood of duff ignition (Harrington 1987; Hille and den Ouden 2005; Sandberg 1980; Valette and others 1994). Therefore, areas with higher surface loads will likely lead to increased duff ignition. Large pine cones can also smolder for long periods, up to 74 minutes for Jeffrey pine and 49 minutes for longleaf pine (Fonda and Varner 2004). Long-duration heating from large cones or long-burning surface fuels act as duff ignition vectors and greatly increase the chance of igniting the underlying duff (Figure 12). The continued influence of surface fuels on duff consumption once smoldering begins is unclear. Some studies have shown that surface loading strongly influences duff consumption (Hille and den Ouden 2005; Norum 1977). Others have found little to no relationship between surface loading and consumption after duff moisture and depth are accounted for (Brown and others 1985; Reinhardt and others 1991b).

After duff is ignited, the fire may spread laterally and downward in the duff layer through smoldering combustion (Figure 15). As smoldering progresses, an insulating ash layer develops that traps heat and helps support combustion at high duff moisture contents (Frandsen 1987; McMahon and others 1980). Smoldering ground fires move up to three orders of magnitude slower than the slowest spreading surface fire (1.2 to 4.7 inches/hour; 3 to 12 cm/hour) (Frandsen 1987). Very little heat is transferred to the mineral soil during the passage of a surface fire because of the fast rate of spread through the litter layer and the insulating duff layer. However, smoldering fires that consume most of the duff layer can transfer large amounts of heat into the mineral soil because of the slow movement, long duration, and direct soil contact.

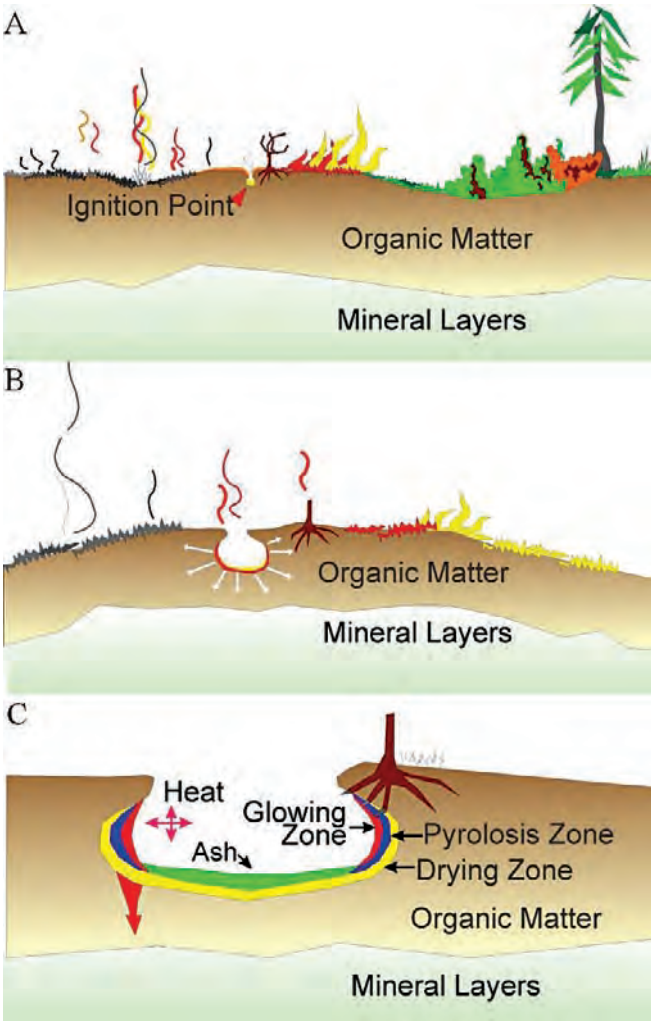

Figure 15. Diagram of the smoldering process. (A) Shows the ignition point where smoldering is initiated by a passing surface fire. (B) Shows the lateral and downward spread as duff is consumed from the initial point. (C) Shows the pyrolysis and drying zones ahead of the glowing zone. The ash cap helps to trap heat and sustain smoldering. From Hungerford and others 1995.

Propagation of smoldering combustion is influenced by duff moisture, mineral content, bulk density, and depth (Table 6). The likelihood of sustained smoldering decreases as duff moisture, mineral content, or bulk density increase (Hartford 1989). Duff depth influences smoldering propagation by trapping heat inside and conserving convective heat lost at the surface layer. Therefore, thicker duff layers can burn under higher moisture contents (Miyanishi and Johnson 2002).

Duff moisture is widely considered the most important factor controlling duff consumption (Brown and others 1985; Hille and Stephens 2005; Sandberg 1980). However, moisture of extinction limits vary widely and there is great variability in the data (Hungerford and others 1995; Reinhardt and others 1991a). The moisture of extinction is the fuel moisture content at which a fire will not spread, or will spread only sporadically and unpredictably (Jenkins 2005). Reinhardt and others (1991b) evaluated 24 duff consumption equations using data from 449 prescribed fires in short and long needle conifer forests in the western United States and Canada. The authors found that at average duff moistures above 175 percent, less than 15 percent of duff was consumed, and at duff moistures below 50 percent, more than half of duff was consumed. This finding did not support the rule-of-thumb suggested by Brown and others (1985) and Sandberg (1980) that most duff is consumed at moistures less than 30 percent and little is consumed above 120 percent (Figure 16) (Reinhardt and others 1991b). However, the 120 percent upper level was confirmed in laboratory experiments on Scots pine (*Pinus sylvestris* L.) duff (Hille and den Ouden 2005). In this study, duff consumption below 120 percent was best modeled as a parabolic curve; above 120 percent, consumption was negligible and was best modeled as a linear function (Figure 17). Van Wagner (1970, 1972) reported that red pine duff consumption is minimal above 60 percent moisture content and ceases to burn around 140 percent.

Lower duff moisture was the most important variable in predicting duff consumption when prescribed burning mixed-conifer forests in the northern Sierra Nevada of California (Kauffman and Martin 1989). In this study, experimental burns were conducted during early spring, late spring, early fall, and late fall on three sites to test the relationship between burning and consumption under a wide range of moistures. Average pre-burn forest floor depths at the sites ranged from 6.3 to 8.8 inches (15.9 to 22.3 cm). Burns conducted when lower duff moisture was less than 50 percent always consumed at least 70 percent of the duff. One burn consumed 70 percent of duff even with average duff moisture of 120 percent (Figure 18). However, regression models developed to predict duff consumption from duff moisture only explained 51 percent of the variability. Site specific equations were more accurate, leading the authors to conclude that general equations to predict duff consumption may not be useful. Reinhardt and others (1991b) reached the same conclusion after evaluating 24 duff consumption equations using independent data. Ferguson and others (2002) approximated the moisture of extinction for longleaf pine in the panhandle of Florida as 3 to 8 percent for litter and 16 to 19 percent for duff based on volumetric moisture content. Volumetric moisture values are generally lower than the more commonly reported gravimetric moisture values (see *Gravimetric versus volumetric moisture content* in Appendix A). The authors concluded that current forest floor moisture was almost completely explained by the previous day's moisture content and precipitation in longleaf pine forests.

Table 6—Factors influencing duff consumption by smoldering combustion. Compiled from Frandsen 1987; Hartford 1989; Miyanishi and Johnson 2002; Otway and others 2007.

Duff Variable	Influence	Impact on smoldering as variable increases
Moisture content	Heat sink	↓
Mineral content	Heat sink; increases space between burnable particles	↓
Bulk density	Increases packing ratio	↓
Depth	Traps heat more effectively; less heat is lost to surface convection	↑

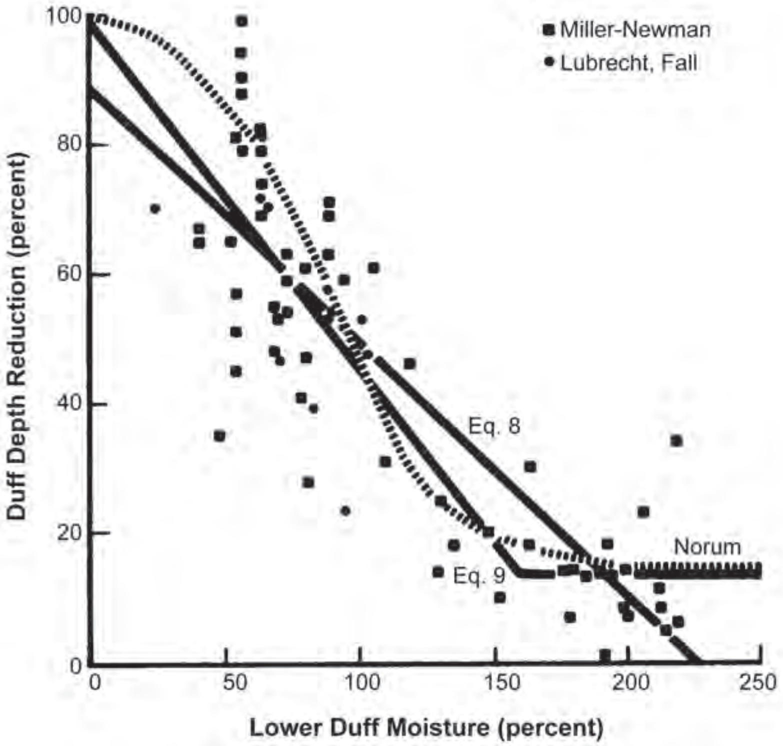

Figure 16. Percentage duff depth reduction versus lower duff moisture content. Equations 8 and 9 (solid lines) and Norum's (1977) curves (dashed line) are graphed. From Brown and others 1985.

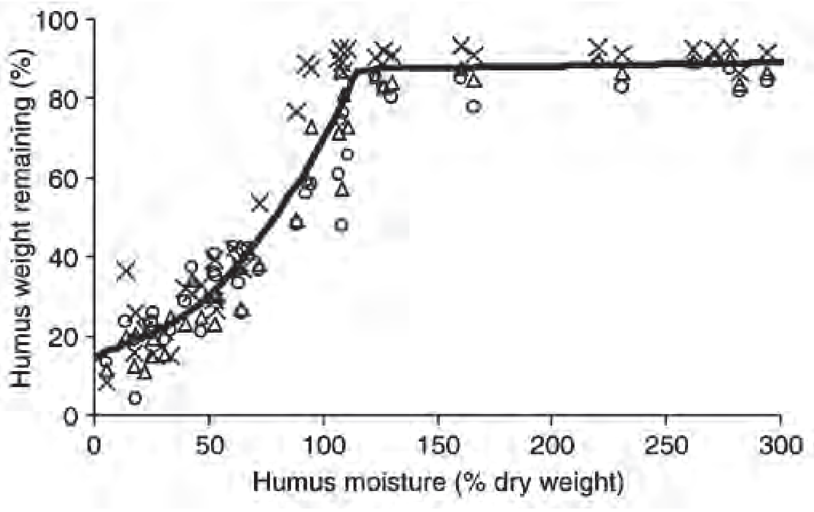

Figure 17. Humus consumption (weight percentage of humus remaining) at different humus moistures. Different fuel loads were simulated with one (×), two (Δ), or three (O) bars of charcoal lighter as an ignition source. The lines show the parabolic relation for humus moisture <120 percent and an almost constant humus consumption percentage for higher humus moisture. © International Association of Wildland Fire 2005. Reproduced with permission from the International Journal of Wildland Fire 14(2): 153-159 (Marco Hille and Jan den Ouden) http://www.publish.csiro.au/nid/114/paper/WF04026.htm. Published by CSIRO PUBLISHING, Melbourne Australia.

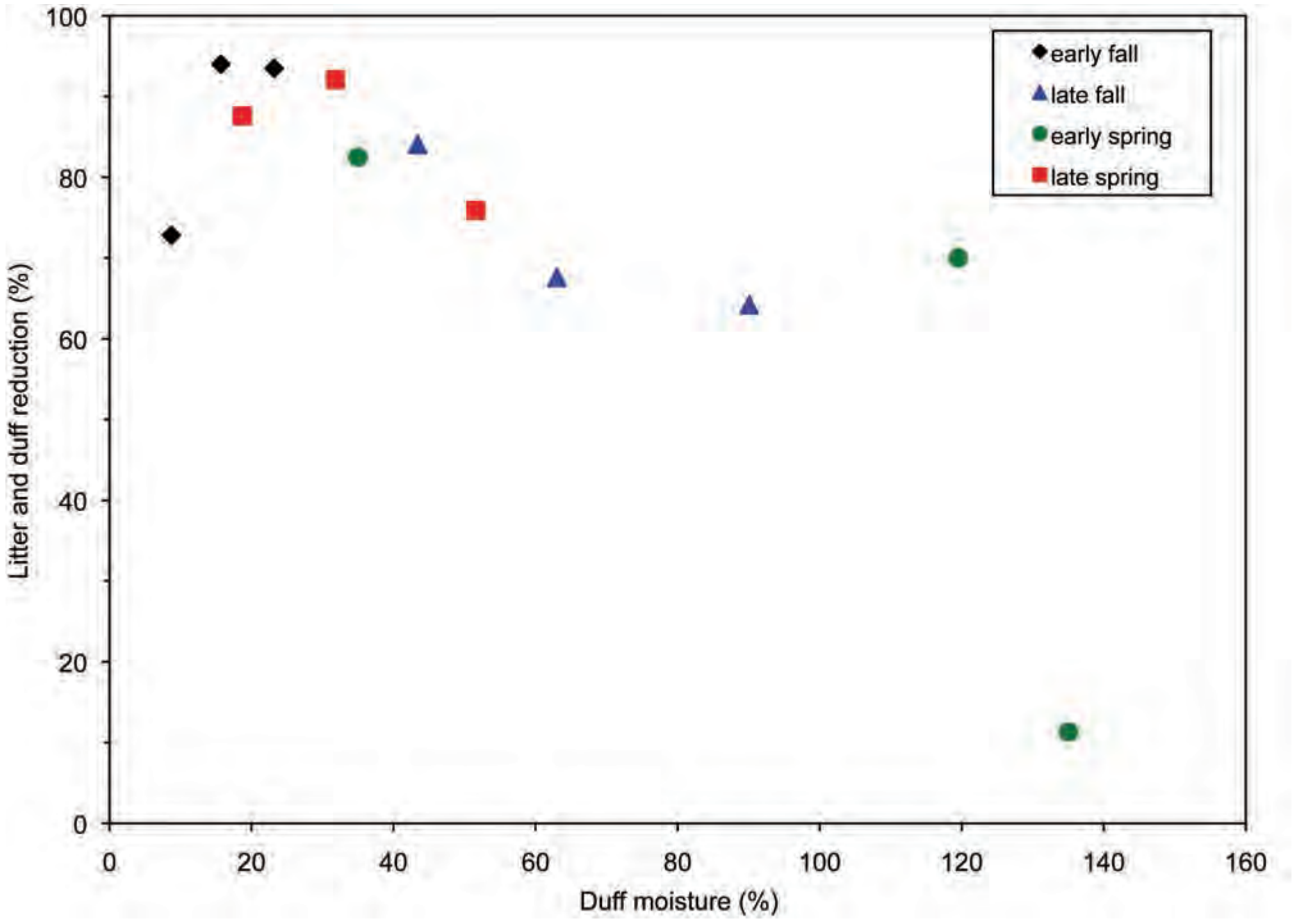

Figure 18. Percentage of forest floor fuel loading consumed and corresponding lower duff moisture for experimental prescribed burns in Sierra Nevada mixed-conifer forests. Adapted from Kauffman and Martin 1989.

Duff mineral content is another important factor in duff consumption (Frandsen 1987; Reardon and others 2007). Inorganic matter in duff absorbs heat, which causes a net loss to the propagation of smoldering. Frandsen (1987, 1997) estimated the limits of smoldering combustion in peat moss by varying the moisture and inorganic ratios during a series of laboratory burns (Figure 19). Samples stopped smoldering when the inorganic ratio increased while the moisture ratio was held constant. He attributed different field estimates of smoldering combustion limits to differences in duff mineral contents that were not accounted for in other studies. More recent work in thick organic soil horizons in North Carolina substantiated Frandsen's earlier work that found the limits of sustained combustion were a function of moisture and mineral content (Reardon and others 2007).

Another factor that influences duff consumption is duff bulk density. As bulk density increases, the surface-to-volume ratio decreases, which causes heat exchange to decline (Otway and others 2007). The authors questioned whether sustained smoldering is possible in shallow duff layers less than 2 inches (5 cm) deep if bulk density is high. Duff bulk density is strongly correlated with mineral content. Mineral soil weighs much more than duff given the same sample volume. This is likely a contributing factor to observations of increasing bulk density in lower duff layers that are closer to the mineral soil layer.

There are many equations to predict duff consumption during fire (Brown and others 1985; Harrington 1987; Reinhardt and others 1991b; Sandberg 1980). All of these models, however, were developed to predict average stand duff consumption using relatively shallow duff layers as samples. Hood and others (2007a) compared consumption of deep duff at the base of old Jeffrey and ponderosa pine trees to values predicted by the First Order Fire Effects Model (FOFEM) (Reinhardt and others 1997). FOFEM underpredicted duff consumption, and the authors concluded that the model was not appropriate for use in areas of deep duff.

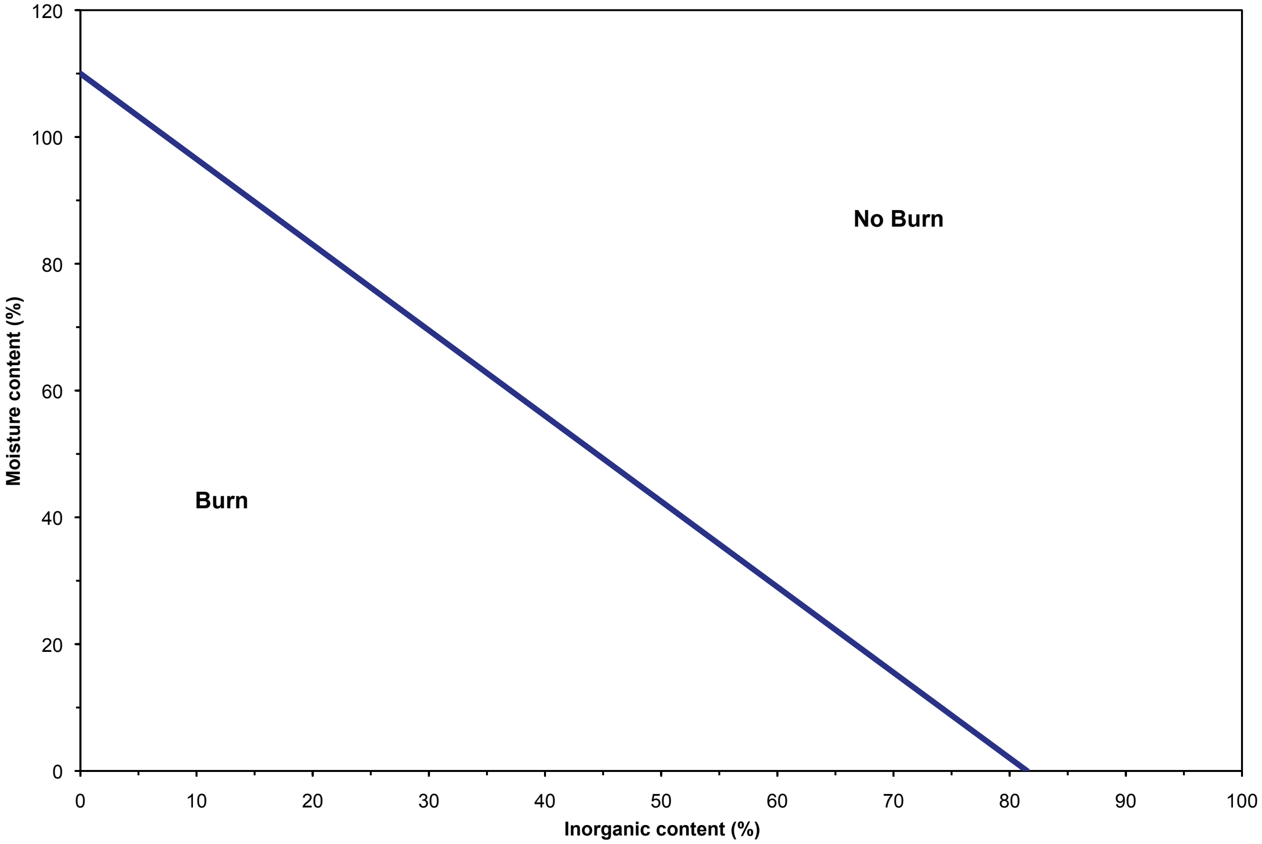

Figure 19. Ignition limit from Frandsen (1987, 1997). The line is the ignition limit based on moisture content and inorganic mineral soil content at an organic bulk density of 12.5 tons/acre/inch (110 kg/m3) from laboratory experiments burning peat moss. Successful ignitions are accomplished only when moisture content and inorganic content are within the triangle bounded by the axes and the ignition limit.

A general trend emerges from these studies of duff consumption. Complete duff consumption independent of adjacent burning fuels does not usually occur above 120 percent moisture content in relatively shallow duff. In areas of very deep duff, moisture contents greater than 150 percent are required to limit duff consumption. Duff consumption below these levels is extremely variable. These values reflect levels of reduced duff smoldering after ignition begins and do not pertain to the probability of duff igniting.

Impacts of Moisture on Soil Heating

Wet duff limits heat transport to the mineral soil (Frandsen and Ryan 1986). Burning duff under wet soil conditions reduces soil temperatures and heat duration (Busse and others 2005; Frandsen and Ryan 1986; Valette and others 1994) (Figure 20). In an experimental study, Frandsen and Ryan (1986) monitored soil heating and duration when burning under different combinations of wet and dry peat moss and wet and dry sand. Burning wet moss over dry sand greatly reduced sand temperatures 0.8 inches (2 cm) below the surface compared to burning dry moss over dry sand, even though all moss was consumed in both experiments. Burning wet moss over wet sand consumed 0.4 of the 0.8-inch (1 cm of 2-cm) moss layer and drastically reduced sand temperatures compared to the other moisture regimes (Figure 21). Burning dry moss over wet sand was not tested, and the burns were not replicated.

Historical and Current Fire Frequencies and Stand Characteristics

Reconstruction of historical fire regimes and stand characteristics provide insight to what forests may have looked liked before European settlement and to how disturbance shaped those characteristics. The historical record is best used to create a historical range of variation, not to recreate forest conditions from one point in time (Swetnam and others 1999).

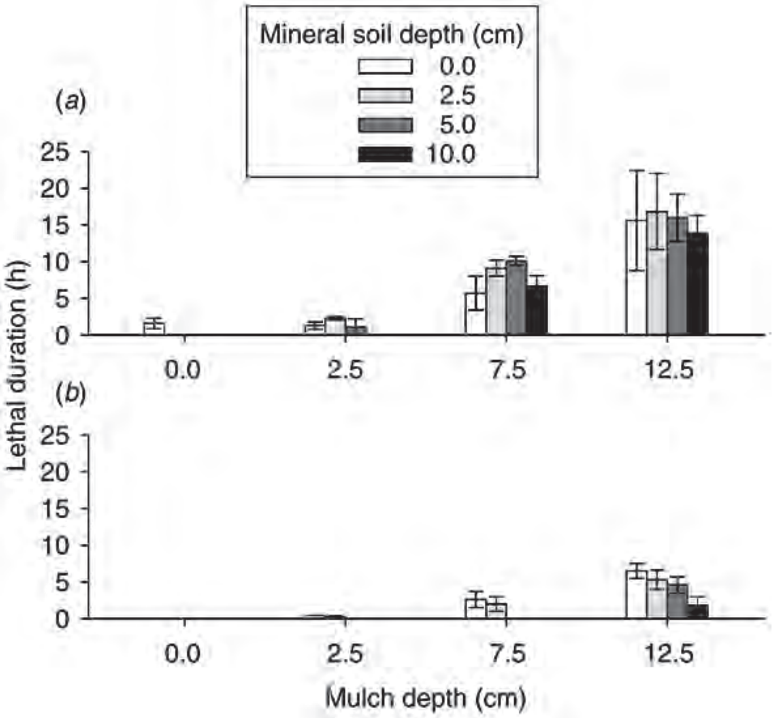

Figure 20. Heat duration exceeding the plant lethal temperature of 140 °F (60 °C) when burning different depths of wood mulch in (a) dry and (b) moist soil. Bars are means (n = 3) plus standard errors for four depths in the soil profile. From Busse and others 2005.

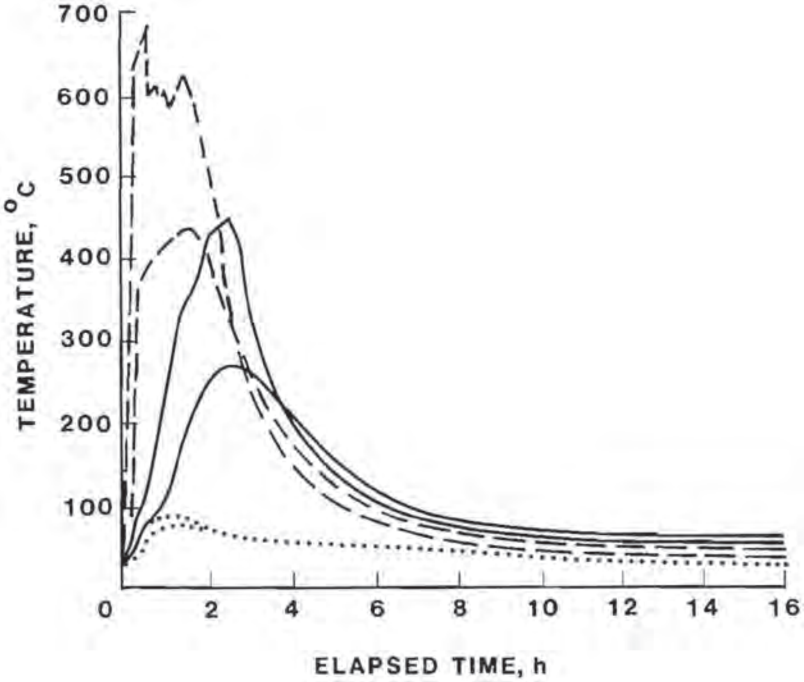

Figure 21. Temperature histories in uncovered dry sand (– – –), dry sand covered with wet peat moss (—), and wet sand covered with wet peat moss (····). Two curves are shown for each profile. The upper curve is the temperature at the sand surface; the lower curve is 0.8 inches (2 cm) below the surface. From Frandsen and Ryan 1986.

The species discussed in this synthesis are fire-climax communities. Frequent low-intensity surface fires perpetuated their existence. These fires perpetuated open conditions, created mineral seedbeds for seedlings, kept fuel loadings low, and reduced fire-intolerant species establishment. Implementation of a national fire suppression policy and removal of Native Americans significantly reduced the amount of land that burned, resulting in these forests succeeding to more shade-tolerant, fire-intolerant species.

Red Pine

Red pine occurs in a narrow zone about 1500 miles (2400 km) long and 500 miles (800 km) wide around the Great Lakes and the St. Lawrence River, most of it within or closely adjacent to the area glaciated during the late Pleistocene period. In the United States, red pine extends from Maine westward to southeastern Minnesota and eastward to Wisconsin, Michigan, northern Pennsylvania, northern New Jersey, Connecticut, and Massachusetts. It also grows locally in northern Illinois and eastern West Virginia (Burns and Honkala 1990). Prior to settlement, red pine/eastern white pine (*P. strobus* L.) forests comprised 97.7 million acres (39.5 million hectares). Today, red pine/eastern white pine forests cover approximately 20.5 million acres (8.3 million hectares), of which approximately 509,000 acres (206,000 hectares) are old-growth, late seral red pine/eastern white pine forests (Hauser 2008).

Red pine forests developed with both frequent low-intensity surface fires and infrequent, stand-replacement fires (Burgess and Methven 1977; Hauser 2008; Spurr 1954). A fire history study in a red pine dominated area in upper Michigan determined that the historic fire regime was characterized by frequent, low-severity, nonstand-replacing fires (Drobyshev and others 2008b). Fire return interval (FRI) was between 23 and 33 years, with a fire cycle (time required for all the study area to burn) of 150 years for sand ridges and 50 years for glacial outwash channels. More than half of fires were late-season (53 percent), and these fires burned a larger portion of the study area than the smaller, early-season fires. Two main cohort-initiation periods corresponded with large fire years and were likely due to higher-intensity, stand-replacement fires. Drobyshev and others (2008a) found duff depth and fine wood fuels were lower in stands that burned regularly. This frequent fire regime limited the establishment of other more fire-sensitive tree species, created multi-cohort stands, and maintained low fine fuel loadings and shallower duff depths (Burgess and Methven 1977; Drobyshev and others 2008a; Drobyshev and others 2008b).

Engstrom and Mann (1991) studied fire history of red pine in Vermont and also found evidence for a historically frequent, low-severity fire regime interspersed with small but high-intensity stand-replacing fires that allowed red pine regeneration to establish. The mean FRI was 37 years, but some stands had fires as frequent as every 3 to 5 years.

Seedling establishment is dependent on high-intensity surface or crown fire to create a mineral seedbed and full sun conditions. Red pine then develops thick bark by about 40 to 60 years of age that is resistant to bole injury (Henning and Dickmann 1996; Van Wagner 1970). Burgess and Methven (1977) reported that the majority of 30-year-old red pine survived a wildfire, even when over 50 percent of the cambium was killed. Trees can survive high levels of crown scorch. After prescribed burning two red pine stands on May 31 and June 15, Methven (1971) reported mortality of trees larger than 9 inches (22.9 cm) DBH began with 46 to 50 percent crown scorch, rose to 50 percent mortality with 81 to 85 percent scorch, and was 100 percent for trees with 96 to 100 percent scorch. In another study, trees survived much higher levels of crown scorch from an early season wildfire (April 12) due to little bud kill (Sucoff and Allison 1968). In that study, only 40 percent of trees with greater than 95 percent crown scorch and little to no bud kill were killed. Van Wagner (1970) found no tree mortality from basal cambium injury alone.

In the absence of fire, red pine declines dramatically (Spurr 1954; Van Wagner 1970). Today, most red pine in the Lake States are even-aged stands planted in the 1930s and 1940s after most of the native forests were clearcut (Palik and Zasada 2003). Without fire to create favorable seedling establishment conditions, red pine in the understory is now rare throughout much of its range (Burgess and Methven 1977; Engstrom and Mann 1991).

Longleaf Pine

Once the dominant tree species of the southeast, stretching from Virginia down the coast to Florida and westward to eastern Texas, the longleaf pine ecosystem is now one of the most endangered ecosystems in the United States (Noss and others 1995). Approximately 2.7 million acres (1.1 million hectares; 3 percent) remain of the estimated 91.4 million acres (37 million hectares) of pre-settlement longleaf pine forest (Frost 1993; Landers and others 1995). Old-growth longleaf pine is even more imperiled— only 12,600 acres (5,095 hectares) are estimated to exist (Varner and Kush 2004). Therefore, historical structure and fuel conditions are extremely limited to historical accounts, photographs, and a few remnant stands. Frost (1993) estimated that 80 percent of the pre-settlement longleaf pine forests were dominated by longleaf pine, while the remaining 20 percent were mixed species stands with a large longleaf pine component.

Dendrochronology is rarely used to reconstruct historical longleaf fire regimes because so few stands remain (Bhuta and others 2008), but historical accounts and reconstructions estimate the forests burned very frequently by low-intensity lightning-caused fires or fires deliberately set by Native Americans. Frequency depended on the area, but most accounts agree forests burned every 1 to 5 years (Christensen 1981; Frost 1993). This frequent fire regime created open forest conditions. Most stands were uneven-aged and were clustered into small, even-aged groups (Platt and others 1998). In the southern extent of longleaf pine's range, tree density was very low, with a savanna appearance.

Heyward and Barnette (1936) described frequently burned longleaf pine forest floors as having, at most, 3 years of pine needle accumulation and dead grasses and no duff layers. The authors described a compact 2- to 3.5-inch (5- to 8.9-cm) thick uppermost mineral soil layer (A_1) intermixed with organic matter that was more typical of grassland than forests. They described this A_1 layer as a "fire climax" layer because it was formed and maintained by frequent fires. Their research occurred when fire suppression was just becoming widespread in the region. After 10 years of fire suppression, they reported that the "luxuriant ground cover" was replaced by a developing traditional forest floor consisting of true L, F, and H layers (Heyward and Barnette 1936).

Longleaf pine is extremely tolerant of fire, except for a brief period of time between the grass and sapling stages. Adaptations to frequent fire include large buds, protective dense needle clusters around buds, and thick bark that develops at an early age (Chapman 1932). Chapman (1923) noted that longleaf saplings as young as 3 to 4 years survive complete crown scorch from winter and early spring fires. Longleaf and slash pine can tolerate high crown scorch with little to no mortality if bud kill is kept to a minimum (Wade 1986). Storey and Merkel (1960) reported no mature longleaf or slash pine mortality unless a portion of the crown was consumed, even with 100 percent crown scorch. Mortality was only high (87 percent) when more than 50 percent of the crown was consumed. They hypothesized that no mortality occurred among trees with high needle scorch and no crown consumption because low ambient air temperature at the time of the burn limited bud kill.

The majority of longleaf pine forests was harvested for timber, cleared for agriculture, or destroyed for naval stores production beginning in the 1800s. Many areas failed to regenerate after harvesting due to lack of fire and the introduction of open range hogs (*Sus scrofa* L.) that ate the roots of longleaf seedlings (Frost 1993). Slash pine and loblolly pine (*Pinus taeda* L.) naturally regenerated much of the cutover longleaf pine forests (Frost 1993; McCulley 1950). In the 1900s, much of the second-growth longleaf forests were converted to loblolly and slash pine plantations (Brockway and Lewis 1997).

Longleaf pine establishment quickly declines in the absence of fire, allowing a midstory layer of hardwoods, primarily oaks, to develop (Gilliam and Platt 1999). Deep forest floor layers develop and herbaceous diversity drastically declines (Varner and others 2005). Brockway and Lewis (1997) reported forest floor accumulations of 5.9 to 9.8 inches (15 to 25 cm) in a second-growth longleaf pine stand that had not burned in 40 years.

Southwestern Ponderosa Pine

Southwestern ponderosa pine forms almost a continuous belt for 400 miles (644 km) diagonally from northern Arizona southeastward across the Mogollon Rim to the Gila and Black Range Wildernesses in southwestern New Mexico (Kaufmann and others 2007). Historical stands were uneven-aged and had a clumpy or random distribution. A combination of good seed crop years once every 3 years, summer drought conditions, cone predation, and high fire frequency limited tree regeneration and maintained an open forested savanna (Bailey and Covington 2002; Schubert 1974; White 1985). Most reconstructed pre-settlement forests show low tree densities, averaging around 22.8 trees/acre (56.3 trees/hectare) (Covington and others 1997) to 24.9 trees/acre (61.5 trees/hectare) (Waltz and others 2003). However, densities as high as 74 trees/acre (183 trees/hectare) are also reported (Abella 2008). Basal area was concentrated in large ponderosa pine trees and averaged 17 to 57 ft^2/acre (4 to 13 m^2/hectare) (Waltz and others 2003).

Frequent surface fires typified the historical fire regime. No accounts of crown fires in Arizona exist before 1900, and surface fires rarely killed large trees (Cooper 1960). At Fort Valley Experimental Forest near Flagstaff, AZ, Dieterich (1980) determined that, prior to settlement, low-intensity surface fires occurred every 2 to 4 years.

Ponderosa pine is very tolerant of fire. Adaptations to survive surface fires include open crowns, self-pruning branches, thick bark, thick bud scales, high foliar moisture, a deep rooting habit, and tight needle bunches that enclose and protect meristems, then open into a loose arrangement that does not favor combustion or propagation of flames (Howard 2003). Ponderosa pine is able to survive high levels of crown scorch if little bud kill occurs (Dieterich 1979).

Today's southwestern ponderosa pine forests are much denser with heavier fuel loadings, largely due to fire suppression and grazing. Abundant research has been conducted and several syntheses have been written about restoration of southwestern ponderosa pine forests (Egan 2007; Friederici 2003; Kolb and others 2007). Covington and others (1997) found tree density increased from 22.8 trees/acre (56.3 trees/hectare) in 1876 to 1253.5 trees/acre (3096 trees/hectare) in 1992 in an unlogged ponderosa pine forest near Flagstaff, AZ. At the nearby repeated burn study site at Fort Valley Experimental Forest, tree density was also high before treatments in 1976, with 993 trees/acre (2454 trees/hectare) (Covington and Sackett 1984).

Considerable within-stand variation of density can exist and can be separated into five conditions dominated by different size classes (sub-stands): sapling (doghair thickets), pole stands, mature, old-growth groves, and open areas in the groves without crowns overhead (Sackett and Haase 1996). Fuel loadings can differ dramatically within a stand depending on where sampling occurs.

As early as 1960, Cooper identified that 40 years of fire exclusion in the southwest had increased the potential of destructive wildfires by allowing excessive fuel buildup on the forest floor, thereby lowering the average crown base height of the trees making crown fire more likely and permitting the formation of dense stands of saplings over wide areas. Continued fire suppression has only exacerbated the conditions observed by Cooper and has created conditions far different than pre-settlement ponderosa pine forests (Covington and Moore 1994).

Pacific Northwest and California

Giant sequoia-mixed-conifer forests—Giant sequoia-mixed-conifer forests are found at mid-elevation (4,920 to 7,545 ft (1,500 to 2,300 m)) on the west slope of the Sierra Nevada in California. These forests are dominated by giant sequoias in the upper canopy at heights of 147 to 246 ft (45 to 75 m), with a secondary canopy layer of giant sequoia, sugar pine, and white fir at 98 to 180 ft (30 to 55 m). On drier sites, incense cedar (*Calocedrus decurrens* (Torr.) Florin), ponderosa pine, or Jeffrey pine may be present. Red fir (*Abies magnifica* A. Murray) is likely on higher, cooler sites. Frequent, low-intensity surface fires were common, interspersed with some small, patchy crown fires likely occurring at longer intervals (Kaufmann and others 2007). Kilgore and Taylor (1979) reported a historic FRI of 3 to 35 years in sequoia-mixed-conifer forests, with a mean of 10 years on southwest aspects and 15 to 18 years on southeast aspects. These estimates are similar to the historic mean FRI of 2 to 3 years during drought periods and 10 to 25 years during cool periods that Kaufmann and others (2007) found.

Giant sequoia seedling and saplings are highly susceptible to fire. As giant sequoia age, they quickly become very fire-tolerant and exhibit the following adaptations to fire: rapid growth, thick bark, elevated canopies and self-pruned lower branches, latent buds, and serotinous cones (Habeck 1992). Frequent fire maintained relatively open conditions dominated by giant sequoia and ponderosa and Jeffrey pine and limited fuel accumulations (Kaufmann and others 2007). Periodic small crown fires created mineral seedbeds favorable to giant sequoia and pine establishment.

Sheep were introduced into the area in the 1860s. Heavy grazing reduced the fine fuel continuity and disrupted the frequent surface fires. Grazing and fire suppression have caused a significant increase in white fir tree density, with little giant sequoia regeneration (Kaufmann and others 2007). The increased density of shade-tolerant tree species creates more ladder fuels that increase the potential for crown fires (Stephenson 1999).

Mixed-conifer, ponderosa, and Jeffrey pine forests—Mixed-conifer and pine forests cover a broad area of California, Oregon, and Washington, occurring at elevations from 2,950 ft to 8,500 ft (900 to 2,600 m). Most precipitation occurs as snow during the winter months, with very little precipitation during the growing season (Kaufmann and others 2007).

Historically, the FRI was slightly longer and fires burned later in the season in the fire-frequent forests of the Sierra Nevada and Cascade Ranges, moving from south to north (Agee 1993; Beaty and Taylor 2008; McNeil and Zobel 1980). Prior to settlement, median fire occurrence was every 2.5 years, with a range of 1 to 13 years in a mixed-conifer forest in the San Jacinto Mountains of southern California (Everett 2008). The majority of these fires burned during mid to late summer. Mean historic FRI was 6.3 and 9.3 years for Jeffrey pine-dominated forests of Yosemite and Sequoia/Kings Canyon National Parks, respectively (Collins and Stephens 2007). Mixed-conifer forests on the west side of Lake Tahoe, CA, primarily burned during the dormant season, on average every 8 to 17 years (Beaty and Taylor 2008). Lower-elevation Jeffrey pine forests at Lassen Volcanic National Park, CA, burned an average of every 4 to 6 years (Taylor 2000). Fire history studies estimate the FRI in eastside Douglas-fir forests was 7 to 11 years in the Wenatchee Valley to 10 to 24 years in the Okanogan National Forest, WA. In the Blue Mountains of Oregon, the FRI averaged 10 years. Most fires were low intensity, although some higher-severity fires did occur (Agee 1993). Historic FRI in ponderosa pine-dominated forests in the Pacific Northwest averaged 7 to 20 years and likely burned frequently over small areas. In the ponderosa pine-white fir forests in Crater Lake National Park, mean FRI ranged from 9 to 42 years (McNeil and Zobel 1980).

Jeffrey pine/mixed-conifer forests in the Sierra San Pedro Martir, Mexico, have never been harvested or experienced widespread fire suppression. The vegetation is similar to forests of the southern Sierras and allows insight into historic forest structure, fire regime, and fuel loadings of the southern Sierra. Stephens (2004) reported an average surface fuel loading (1 to 1000 hour fuels) of 6.4 tons/acre (1.4 kg/m^2). Litter depth averaged 0.6 inches (1.6 cm) with an average loading of 3.5 tons/acre (0.8 kg/m^2); no duff was present. Fine fuel loading (1 to 100 hour fuels) was low at 0.87 tons/acre (0.2 kg/m^2). Snags averaged 2 trees/acre (5 trees/hectare), with 85 percent over 11.8 inches (30 cm) DBH. Snag distribution was patchy. Both snag distribution and fuel loadings were highly variable across the forest.

A reconstruction of forest structure of an old-growth mixed-conifer forest on the Teakettle Experimental Forest in California estimated tree density in 1865 was 27 stems/acre (67 stems/hectare) and a quadratic mean diameter of 19.5 inches (49.5 cm) (North and others 2007). The average historic FRI was 17 years, and the last widespread fire occurred in 1865. More than 140 years without fire had increased tree density to 190 stems/acre (469 stems/hectare), decreased quadratic mean diameter to 7.7 inches (19.6 cm), and altered species composition. Historically, shade-tolerant species comprised approximately 51 percent of the stems, mostly as white fir and incense cedar, and shade-intolerant Jeffrey and sugar pine comprised the remainder. Current forest structure revealed a dramatic decline in pine to only 14 percent of stems. White fir increased from an estimated 33.7 percent in 1865 to 67.2 percent of stems currently (North and others 2007).

Fire suppression has increased white fir density, created more homogeneous forests, and increased fuel loadings (Beaty and Taylor 2008; Knapp and others 2005; Stephens 2004). Frequent fire regulated tree density by killing seedlings and saplings still susceptible to fire because their bark was not yet thick enough to prevent cambium injury. Over 100 years of fire suppression has allowed many of these white firs to become resistant to low-to-moderate-intensity fires (Collins and Stephens 2007; Kilgore 1972; Thomas and Agee 1986). Youngblood and others (2004) suggested a tree density of 20 ± 1.5 trees/acre (50 ± 3.5 trees/hectare) and a mean diameter of 23.6 inches ± 0.6 inches (60.0 cm ± 1.55 cm) DBH as reference goals when restoring eastside ponderosa pine forests to mimic historic old-growth conditions in northern California and Oregon.

Interior West Ponderosa Pine, Douglas-Fir, and Western Larch

Ponderosa pine in the Interior West stretches from Montana to the Colorado Front Range. An estimated 21 percent of the ponderosa pine/Douglas-fir forests in the inland northwest historically consisted of large (11.8 to 23.6 inches (30 to 60 cm) DBH), widely spaced (approximately 101 trees/acre (250 trees/hectare)) ponderosa pine (Jain and Graham 2004). Currently, only 5 percent of the landscape consists of mature, open ponderosa pine forests (Hann and others 1997).

The low-severity ponderosa pine fire regime in the southwest was not as ubiquitous in the Interior West, where many ponderosa pine/Douglas-fir forests historically developed under a mixed-severity fire regime, although many areas did burn as low-severity (Kaufmann and others 2004). Ponderosa pine at lower-elevation, drier sites in Montana typically burned under a low-severity fire regime, with average fire-free intervals from 5 to 20 years. Maximum fire-free intervals ranged from 21 to 30 years, with minimum intervals of 3 to 4 years (Arno 1980). Lake sediment cores in northwestern Montana indicate a slightly longer historic FRI of 30 years for low-elevation ponderosa pine (Power and others 2006), but more fires may go undetected with this method than with dendrochronological methods. While these forests experienced frequent low-intensity surface fires, infrequent high-severity fires also occurred (Baker and others 2007; Pierce and Meyer 2008).

Above the drier ponderosa pine zone, in cooler and moister climates, forests were still dominated by ponderosa pine and western larch, mixed with Douglas-fir and lodgepole pine (*Pinus contorta* Douglas ex Louden). Historically, fire regimes were mixed-severity. Mean FRI ranged from 15 to 30 years with maximum fire-free intervals of approximately 35 to 60 years (Arno 1980). A study of 11 ponderosa pine and western larch stands in western Montana showed all stands had historically experienced frequent low-intensity fires, while three of the western larch stands also had occasional stand-replacing fires (Arno and others 1995; Arno and others 1997). In the absence of fire, forests in this zone are seral to Douglas-fir.

Sherriff and Veblen (2007) estimated approximately 20 percent of ponderosa pine forests along the Colorado Front Range burned as low-severity fires, with the remaining burning as mixed-severity fires. Sites below 6,900 ft (2,100 m) likely burned approximately every 10 to 30 years as low-intensity surface fires. At higher-elevation sites, the majority of ponderosa pine forests along the Colorado

Front Range had fire-free intervals of 30 to 100+ years. Fires here burned as mixed-severity, with large areas of stand-replacement fire, which helped create very patchy, open ponderosa pine forests. Kaufmann (2007) estimated that 90 percent of the historical landscape had a canopy cover of 30 percent or less.

Widespread harvesting of ponderosa pine in the late 1800s and early 1900s contributed to the decline in pine dominance in the Interior West. Fire suppression further contributed to changes by increasing fuel loadings, tree densities, and Douglas-fir dominance in these dry forests (Arno and others 1997). In the Selway-Bitterroot Wilderness, MT, these changes have resulted in a shift from equal proportions of surface and stand-replacement fires to 45 percent surface fires and 55 percent stand-replacement fires (Brown and others 1994). Large, stand-replacing fire frequency is also increasing in other areas of the Interior West (Kaufmann and others 2007).

Black Hills Ponderosa Pine

The Black Hills of southwestern South Dakota and northeast Wyoming support an isolated ponderosa pine forest covering almost 6000 miles^2 (15,540 km^2) that is surrounded by the Great Plains (Shepperd and Battaglia 2002). The majority of the Black Hills were logged within the past 100 years. While the extent of ponderosa pine forest remains relatively unchanged, Symstad and Bynum (2007) estimate that approximately only 5,130 acres (2,076 hectares) of old-growth ponderosa pine remain on public lands in the Black Hills.

Fire history studies and historical accounts show fire was a frequent disturbance agent in the area. Fire frequencies ranged from 10 to 13 years on the lower-elevation, warmer, and drier sites to 20 to 24 years at the higher-elevation sites (Shepperd and Battaglia 2002). The historical fire regime in the Black Hills was likely mixed-severity (Lentile and others 2005). Low-intensity surface fires that maintained ponderosa pine dominance, while controlling tree densities, were common. However, there is evidence of higher-intensity fires that killed large patches of trees and led to even-aged stand structures in areas (Shinneman and Baker 1997).

A century of fire suppression and livestock grazing has led to higher stand densities, fuel accumulations, and fuel continuity (Lentile and others 2005; Shepperd and Battaglia 2002). Favorable growing conditions and good seed crops often coincide, leading to abundant seedling establishment and dense stands in the absence of fire (Battaglia and others 2008; Shepperd and Battaglia 2002). These changes have led to several recent, large-scale fires in the Black Hills. Between 2000 and 2004, seven fires burned over 148,000 acres (60,000 hectares) (Keyser and others 2006). The 2000 Jasper Fire was approximately 25 percent larger than any recorded fire in Black Hills history (Lentile and others 2005).

Treatment Effects on Old Tree Resilience

Old trees generally grow slower than young trees (Yoder and others 1994). This reduction in rate of wood production is not fully understood, but it is often attributed to increased maintenance respiration costs as living biomass increases (Ryan and others 1997). However, other reasons may better account for reduced growth rates, such as reduced photosynthetic rates and increased energy investment in fine root production (Grier and others 1981; Kaufmann and Ryan 1986; Ryan and others 1997). Yoder and others (1994) found net photosynthesis averaged 14 to 30 percent lower in foliage from old ponderosa and lodgepole pine trees, while growth efficiency (wood growth and leaf area) of old trees averaged 41 percent less than younger trees. The authors hypothesized that reduced hydraulic conductance in old trees because of their greater height and longer branches cause stomata to close about 2 hours earlier in the day than younger trees, thus reducing photosynthetic rates and, in turn, growth efficiency. Kaufmann and Ryan (1986) also found growth efficiency declined with age for lodgepole pine, Engelmann spruce (*Picea engelmannii* Parry ex Engelm.), and subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.) trees.

Older trees in dense stands are often in competition with younger, more vigorously growing trees. Mortality of large-diameter (>39.4 inches (>100 cm) DBH) white fir, red fir, incense cedar, and sugar pine trees was significantly higher than expected in the Teakettle Experimental Forest, CA (Smith and others 2005). Mortality was also significantly higher in denser stands than in more open stands. Jeffrey pine was the only species for which mortality in the larger diameter classes was not higher, and these trees grew primarily in the more open, drier ridgetops. Teakettle Experimental Forest is a mixed-conifer, old-growth forest with a very limited logging history. The historic FRI was 17 years, but the last recorded widespread fire was in 1865. Fire suppression has resulted in significant increases in tree density on the forest. The authors hypothesize that this increase in density and competition is accelerating large-diameter, old tree mortality.

Silvicultural treatments to reduce stress may increase vigor of old trees and improve their resilience to fire, bark beetle attacks, and drought. Van Mantgem and others (2003) related pre-fire growth rates and crown injury to tree survival between burned and unburned stands. They determined that the majority of white fir with greater than 50 percent crown volume scorched and radial growth greater than 0.2 inches/year (5.0 mm/year) survive; the majority of those growing less than 0.2 inches/year (5.0 mm/year) died. Thinning understory Douglas-fir increased branch production of old ponderosa pine and western larch in Montana (Sala and Callaway 2004). Kolb and others (2007) provide a review of studies examining the effect of management treatments to stimulate old ponderosa pine vigor. They concluded that careful thinning can increase resource uptake and growth of old ponderosa pines by reducing water stress and can cause increases in constitutive resin defenses against bark beetle attacks.

Radial Growth

The few studies that have examined the effects of silvicultural treatments on old tree growth rates in fire-dependent forests primarily involve ponderosa pine. All but one study reported increased growth of old ponderosa pine trees after either thinning or thinning followed by burning. In Oregon, thinning stands dominated by old ponderosa pine significantly increased basal area increment (BAI) compared to old trees in unthinned stands for up to 15 years (McDowell and others 2003). Old trees in thinned units had decreased water stress and increased stomatal conductance, which improved carbon assimilation and growth. Treatment response time may take longer in old trees than in younger trees. In another Oregon study, lag time between thinning and increased growth varied by site and species for old trees, but growth rates for many of the trees did not increase until more than 5 years after treatment (Latham and Tappeiner 2002).

No differences in radial growth of pre-settlement ponderosa pine were observed compared to control trees 3 years after thinning from below and 1 year after burning an old-growth ponderosa pine stand near Flagstaff, AZ (Skov and others 2005). Measurements in this study may have been made too soon after treatment for the pre-settlement trees to respond. In contrast, pre-settlement trees on the Gus Pearson Natural Area, AZ, had increased BAI 3 years after thinning and thin/burn treatments (Feeney and others 1998). Prior to burning, litter (O_i) on the study plots was raked aside, and the duff layers (O_e and O_a) were removed. The litter and dried native grass foliage were then rescattered over the plots to mimic historical forest floor loadings and to reduce potential injury to tree bases and roots (Covington and others 1997). Zausen and others (2005) compared long-term changes in ponderosa pine tree physiology among unmanaged stands, stands thinned 8 to 16 years ago, and similarly thinned/burned stands in Arizona. Mean BAI was significantly greater in thinned/burned ponderosa pine stands than in unmanaged stands. BAI was intermediate in thinned-only stands, and was not significantly different from either the unmanaged or the thinned/burned stands.

Thinning increased BAI in old ponderosa pines in Montana (Fajardo and others 2007). BAI of the 10 years following treatment was significantly higher for pre-settlement trees in thinned treatments compared to controls. BAI of pre-settlement trees in the thinned and burned treatments was intermediate between the thinned-only and control treatments, but not significantly different from the other two treatments.

Moisture Stress

Thinning, both with and without burning, has been shown to reduce moisture stress in old ponderosa and Jeffrey pine trees. A second-growth Jeffrey pine stand (100+ years old) on the Tahoe National Forest, CA, was thinned to release dominant and codominant stems. Thinning reduced moisture stress over the 3-year study period, even though the treatment coincided with an extended drought (Walker and others 2006). Additionally, burning caused no detrimental effects on predawn water potential. Average flame length was 2.3 ft (0.7 m), although no descriptions of tree injury, such as crown scorch or cambium kill, were reported that could impact tree moisture stress. Thinning 90 percent of post-settlement trees on the Gus Pearson Natural Area, AZ, increased water uptake and foliar nitrogen concentration on old ponderosa pine trees the first year after thinning. Thinning also increased needle length and bud size of pre-settlement trees (Stone and others 1999), increased needle toughness (a measure of resistance to the defoliator pine sawfly (*Neodiprion* spp.)) and increased BAI compared to control pre-settlement trees (Feeney and others 1998; Wallin and others 2004) (see *Radial growth* for additional information). These positive treatment effects continued 3 to 7 years after thinning. Predawn water potential was significantly higher in ponderosa pine stands thinned 8 to 16 years ago, both with and without burning during the peak of the dry season (Zausen and others 2005). Thinning and thinning followed by prescribed burning caused a long-term decrease in water competition and improved growth rates across the northern Arizona study sites.

Resistance to Insect Attacks

Increased resin production is thought to be a measure of a tree's resistance to bark beetle attacks. Many studies have found increased resin production after burning.

Ponderosa pine resin flows were significantly higher than control trees after both spring and fall burns (Perrakis and Agee 2006). Burned, unattacked Virginia pine (*Pinus virginiana* Miller), table mountain pine (*P. pungens* Lambert), pitch pine (*P. rigida* Miller), and eastern white pine in North Carolina produced more resin than unburned, unattacked trees for up to 18 months after fire (Knebel and Wentworth 2007). Resin production was lower 5 months after prescribed fire in Arizona for ponderosa pine trees with greater than 51 percent crown scorch compared to trees with less crown scorch, and only trees with higher crown scorch were attacked by bark beetles (Wallin and others 2003). Red pine resin production initially decreased after prescribed burning, then returned to pretreatment levels within 7 to 10 days, and then increased to twice that of control trees 55 days post-fire (Lombardero and others 2006). Agee and Perrakis (2008) found this same trend of decreased resin production after fire, followed by increased production in the subsequent 4 years post-fire. These results suggest that fire-injured trees may increase constitutive and induced resin defenses to help deter successful bark beetle attacks.

The effect of thinning in combination with burning on bark beetle attack success is unclear. In an Arizona study, bark beetle attack rates and colonization success were lower in thinned and burned units than in the control unit (Wallin and others 2008). Every ponderosa pine tree baited with pheromone lures in the control was attacked, compared to 50 percent and 7 percent of baited trees in the full and partial restoration treatments, respectively. Of the attacked trees, beetle success rates were 100 percent in the control, 33.3 percent in the partial restoration, and 3 percent in the full restoration. The partial restoration treatment removed 35 percent of the basal area by thinning post-settlement trees. The full restoration treatment removed 58 percent of basal area. Beetle populations were low in the study area, and no unbaited trees were successfully attacked. However, study results support thinning ponderosa pine stands to reduce the potential for bark beetle attacks. Thinning likely aids in pheromone plume dispersal and burning increases resin production that may reduce successful beetle attacks.

Bark beetle attacks increased in thinned units following burning at the Blacks Mountain Experimental Forest in northeastern California (Fettig and others 2008). Two-year post-fire mortality was low at 5 percent, and the authors attributed 28.8 percent of mortality to bark beetle attacks. No differences in attack rates were found among diameter classes, and large-diameter (>23.5 inches (>59.7 cm) DBH) Jeffery and ponderosa pine mortality was not higher than smaller diameter classes.

Bark beetle attack success may be influenced by the timing of prescribed burns and beetle flight. Lombardero and others (2006) cautioned against burning during peak *Ips* beetle flight due to decreased resin production the first several days after prescribed burning. The authors hypothesized that red pine may be particularly susceptible to bark beetle attack during this short window. *Ips* abundance doubled in May following an April prescribed fire in an old-growth red pine forest and returned to control levels by late summer. *Ips* attack preference was not related to pre-burn tree growth rates, but seemed to prefer charred areas on the lower bole. Half of attacked trees died within one year (Santoro and others 2001).

Management Options

Management options relating to minimizing large-diameter and old tree injury and mortality when reintroducing fire into fire-dependent forests vary greatly depending on the scale of the treatment area. Landscape-level, stand-level, and individual tree-level treatments are all necessary to meet the multitude of resource management objectives for a given land area. Many small stand- or individual tree-level projects can be embedded within larger landscape-level projects. Regardless of scale, successful restoration of fire-dependent ecosystems typically includes reducing tree density and ladder fuels to reduce crown fire risk, protecting large trees from significant injury, restoring surface fires, and increasing native herbaceous ground cover and biodiversity levels (Allen and others 2002). Reducing tree density also reduces competition around large trees, which may improve vigor, and returns forest structure, and perhaps composition, closer to historical levels.

Our knowledge of appropriate treatment options in fire-dependent, old-growth ecosystems is limited by the relatively few existing studies on the subject (Table 5). Only a handful of these are long-term studies with prescribed fire treatments (Table 7).

General Management Issues

Treatment prioritizations—Reducing the risk of high-intensity fire, including crown fire, should be the first treatment priority when restoring forests that historically burned frequently. Other key considerations in fuels management are a forest's proximity to communities and important watersheds, protection of old-growth and areas with sensitive species, and strategic placement of treatments to break-up continuous fuels (Allen and others 2002).

Table 7—Long-term restoration ecology studies that include fire effects on old-growth trees in forests that historically burned frequently.

Study	Establishment year	Location	Dominant tree species	Treatments	Selected References
Gus Pearson Natural Area	1992	Arizona	Ponderosa pine	Control Thinning Thinning with area-wide forest floor removal, litter addition, and burning	Covington and others 1997; Feeney and others 1998; Stone and others 1999; Wallin and others 2004
Chimney Springs, Fort Valley Experimental Forest	1976	Arizona	Ponderosa pine	Control Burning every year Burning every 2 years Burning every 4 years Burning every 6 years Burning every 8 years Burning every 10 years	Sackett and others 1996; Sackett and Haase 1996, 1998
Limestone Flats, Long Valley Experimental Forest	1977	Arizona	Ponderosa pine	Control Burning every year Burning every 2 years Burning every 4 years Burning every 6 years Burning every 8 years Burning every 10 years	Sackett and others 1996; Sackett and Haase 1996, 1998
Mt. Trumbull	1997	Arizona	Ponderosa pine	Control Thinning, raking pre-settlement trees and snags, and burning	Fulé and others 2007; Waltz and others 2003
Blacks Mountain	1997	California	Ponderosa and Jeffrey pine, white fir, incense cedar	Control Burn only Low structural diversity (thinning from above) High structural diversity (thinning from below) Low structural diversity and burning High structural diversity and burning	Fettig and others 2008; Zhang and others 2008
Wade Tract	1982	Georgia	Longleaf pine	Annual summer burning	Noel and others 1998; Platt and others 1998
Tiger Corner	1958	South Carolina	Longleaf pine	Unburned control Annual burning Biennial burning Triennial burning Quadrennial burning	Glitzenstein and others 2003
Osceola	1958	Florida	Longleaf pine	Unburned control Annual burning Biennial burning Quadrennial burning	Glitzenstein and others 2003
Lick Creek	1991	Montana	Ponderosa pine	Control Thinning followed by spring burning Thinning followed by fall burning Thinning	Fajardo and others 2007; Sala and others 2005; Smith and Arno 1999

In the context of prioritizing treatments to perpetuate and develop areas of old-growth, Fiedler and others (2007) suggest classifying forests into one of three categories:

1. Forests that currently feature old-growth structural components,
2. Forests with developing old-growth structural components, or
3. Forests lacking old-growth structural components.

Managers commonly identify category (1) forests as most likely to benefit from restoration treatments. However, treatments that foster the development of old-growth structural and functional conditions in categories (2) and (3) are also necessary to perpetuate old-growth on the landscape over a longer time period.

No action alternative—Choosing the no action alternative and letting nature take its own course is an intentional management decision (Cole and others 2008). However, there is a conflict between the no action philosophy and continued attempted fire exclusion. Often, the no action alternative may be more of a threat to old and large trees than restoration activities (Noss and others 2006). Even in some protected areas such as National Parks and wilderness areas there is growing concern that human-perceived valuable ecosystem conditions cannot be maintained without natural disturbance or human-implemented treatments (Cole and others 2008). It is important to recognize that some large-tree mortality must be anticipated when implementing restoration treatments. This mortality creates structural diversity and important habitat by creating large snags and woody debris that are often scarce on the landscape (Allen and others 2002).

Choosing the no action alternative can leave forests more susceptible to high-intensity wildfire. In fire-dependent, low-elevation forests, the likelihood of fire is very high because of long, dry seasons and high potential for natural and human ignitions. We cannot predict when or where these wildfires will occur, but research studies and numerous anecdotal examples show that fuel reduction treatments in these forests can often reduce fire severity, thus reducing overstory tree mortality from wildfire. For example, mortality of trees greater than 11.8 inches (30 cm) DBH was nearly 100 percent after a wildfire in an untreated ponderosa pine stand on the Blacks Mountain Experimental Forest, CA, compared to almost no mortality within adjacent thinned and burned units. Mortality from wildfire in thinned-only units was less than 20 percent. Treatments were implemented within 6 years of the wildfire; prior to that, the areas had not burned in over 100 years (Ritchie and others 2007).

It is helpful to know typical background mortality in the absence of large-scale disturbance in order to set reasonable and attainable burn objectives when conserving large or old trees. Background mortality is the expected mortality if the no action alternative is chosen and no large-scale disturbance occurs. Ten-year mortality of ponderosa pine greater than 8.7 inches (22 cm) DBH was less than 10 percent in unburned areas of Crater Lake National Park, OR (Swezy and Agee 1991). This area was dominated by ponderosa pine and white fir, with scattered lodgepole pine, sugar pine, and other conifers, on well-drained soils derived from Mount Mazama deposits. In a separate study in Crater Lake National Park, 5-year mortality of ponderosa pine larger than 7.9 inches (20 cm) DBH from insects or pathogens was 2.3 percent in the control units (Agee and Perrakis 2008). Most mortality occurred in low vigor trees. Mortality rates were 2.1 and 8.6 percent, respectively, for trees rated C and D (low vigor) using Keen's vigor classes (Perrakis and Agee 2006). No trees in the A or B vigor classes (high vigor) died. Thirteen years after another prescribed burn at Crater Lake (Thomas and Agee 1986), mortality of trees greater than 7.9 inches (20 cm) DBH in unburned areas was 10 percent for sugar pine, 4 percent for white fir, and 14 percent for ponderosa pine (Agee 2003). Sugar pine and white fir mortality was significantly higher in the burned areas at 36 and 25 percent, respectively. This was not the case for ponderosa pine, which had 17 percent mortality.

When established in 1934, the Blacks Mountain Experimental Forest, CA, was unlogged and dominated by ponderosa and Jeffrey pine, white fir, and incense cedar. A comparison of forest structure between a 1933/1934 tree census and another conducted in the late 1990s showed large trees had declined by about half and small tree density increased more than four-fold (Ritchie and others 2008). Basal area of ponderosa and Jeffrey pine declined, and white fir and incense cedar concomitantly increased. Fifty-four to 61 percent of the remaining living, large trees in the untreated units were rated as high risk, compared to 15 percent in the thinned unit and 17 percent in the thinned and burned unit. Five-year periodic mortality rate of the large tree component was 6 to 19 percent in untreated areas (Ritchie and others 2008). The authors predicted that the control would experience similar declines in the large tree component over the next 15 years. In this area, a no action alternative is leading to the eventual loss of all large trees, with little opportunity to replace ponderosa and Jeffrey pine. Lutz and others (2009) also reported decreases in large-diameter Jeffrey, ponderosa, and sugar pine trees in unburned, low-elevation portions of Yosemite National Park, CA, whereas plots that had burned in the 20th century retained large-diameter ponderosa pine.

In another study of background mortality, the loss of old ponderosa pine in untreated areas increased from 0.2 trees/acre (0.5 trees/hectare) per decade in the 1920s to 2.4 trees/acre (5.9 trees/hectare) per decade in the 1970s at the Gus Pearson Natural Area, AZ (Mast and others 1999). This increased mortality rate was attributed to lack of fire that allowed numerous post-settlement ponderosa pine trees to establish and increase competition.

Defining prescribed burn and other management objectives—There are many appropriate objectives when planning prescribed burns and other fuel reduction treatments. Each objective should be measurable on a stated scale over a stated timeframe. Appropriate treatment options will vary by scale and forest type. For instance, small, remnant stands of old-growth can warrant intensive restoration efforts that are not economically or physically feasible on the landscape-scale. Objectives that pertain to maintaining large-diameter and old trees should first include descriptions of both the untreated forest structure and the desired post-treatment forest structure. This should include stand density, diameter distribution, age distribution, species composition, and spatial arrangement. These are all measurable objectives that will determine if immediate treatment goals were met (Fiedler and others 2007).

When using prescribed fire, both first order and second order fire effects should be included in the objectives. First order fire effects may include immediate mortality targets, duff and surface fuel consumption, acceptable crown scorch levels, or desired area burned under specified severity levels. These should be assessed within 1 year of the fire to determine if objectives were met. Second order fire effects and resource management objectives may include acceptable longer-term delayed tree mortality and changes in tree vigor, regeneration, or understory species diversity. Maintaining or reestablishing historical forest disturbance processes (for example, fire frequency, severity, intensity, season, and insect attack levels) may be other important objectives when prescribed burning (Agee 2003). Process and structural objectives should be considered together, as process goals can help create and perpetuate desired structural conditions. Monitoring programs that revisit treated areas are essential for determining if immediate and long-term treatment goals are being met. The only way to determine if goals are met is through the stated measurable objectives.

Identifying ecosystem components of interest is key to developing burn objectives and monitoring plans to assess fire effects beyond hazard reductions. Also, treatment results should be tied to the identified objectives. For example, if large-diameter tree retention is an objective for a prescribed burn, it is important to assess and report duff depth and moisture near the base of these large trees, in addition to the interspaces. Duff consumption is usually highly variable across a burned unit. This variability largely results from microsite changes in fuel moistures due to differences in canopy thickness and changes in surface fuel consumption. The tree crown shelters the forest floor immediately underneath it; therefore, fuels are deeper and drier there than in the areas between tree crowns. For example, an experimental prescribed burn in ponderosa pine at Chimney Spring, AZ, reduced forest floor fuel loadings by 63 percent. However, consumption was 100 percent from the bole to the dripline around all the large trees where the fuel loading was also the highest (Sackett and others 1996). In this case, reporting only the average stand fuel consumption would make it difficult to determine a possible cause of the later observed mortality in the larger-diameter trees.

Landscape-Scale Options

Landscape restoration—Noss and others (2006) provide several recommendations for successful widespread restoration of southwestern ponderosa pine ecosystems that pertain to retaining old trees when reintroducing prescribed fire into long-unburned areas. Many of these recommendations are also suitable for other ecosystems that evolved with frequent fire.

(1) Think big. Plan conservation and restoration projects on landscape and regional scales. Restoring a natural fire regime can result in a heterogeneous landscape with multiple stands conditions that are likely to provide suitable habitat for a wide range of species. Focusing on just a small project area can be contentious and may make it hard to justify potentially adverse treatment impacts on threatened or endangered species. Planning restoration treatments on a landscape-scale can restore a frequent fire regime, while allowing for areas of denser stands and differences in fire severity in order to provide diverse structural conditions.

(2) Recognize that protected areas may require active management. Protected areas should not be automatically excluded from consideration for restoration treatments in areas that historically burned frequently. Though treatments in high-elevation

protected areas are probably not suitable, treatments in lower-elevation areas that have experienced fire exclusion may foster the qualities for which they were originally protected.

(3) Restoration strategies should encompass both wildlands and the wildland-urban interface (WUI). Restoration treatments should include both the WUI and the extended landscape away from human development. Treatment prescriptions will likely differ based on location to nearby communities, but restoration efforts are necessary across the whole landscape.

Wildland fire use—In some areas, naturally ignited fires are allowed to burn with minimal to no suppression efforts to meet resource benefit objectives. Federal agencies have used various terms to describe this activity since the program was first implemented in the late 1960s, including "let burn," "prescribed natural fire," and "wildland fire use" (van Wagtendonk 2007). Beginning in 2009, fires are no longer categorized by the latest term "wildland fire use for resource benefit" (WFU). Fires are now designated as wildfires or prescribed fires based on whether the ignition was planned. Based on the existing land management plan, wildfires will be managed for a combination of protection and resource objectives (U.S. Department of Agriculture, U.S. Department of the Interior 2009). WFU is used in this document, though it is outdated, because it is the term used by the references discussed in this report.

Differences in ponderosa pine forest structure and fire occurrence were compared in the Gila Wilderness, NM, and Saguaro Wilderness, AZ (Holden and others 2007). Fires in the Saguaro Wilderness have been managed as WFU fires since 1971 and in the Gila since 1975 (van Wagtendonk 2007). In both wilderness study areas, tree density was significantly lower in areas that had burned one or more times than in unburned areas. Small tree density was significantly lower in burned areas versus unburned areas in the Saguaro Wilderness. In the Gila Wilderness, small tree densities were lower in areas that had burned two or more times compared to less frequently burned areas. Average DBH was also significantly higher in the burned areas compared to unburned areas in the Gila, but no differences were found in the Saguaro. No differences in basal area or large tree density were found between burned and unburned areas in either wilderness, except for areas in the Saguaro wilderness that had burned two or more times and also in a pre-WFU fire. In these areas, large tree density was significantly higher than less frequently burned areas. These results suggest that in areas where fire can safely be allowed to burn, forest structure may more closely mimic historical forests while maintaining large tree density. However, it may take multiple fires to achieve these results.

Fulé and Laughlin (2007) investigated the effects of WFU fires on the North Rim of the Grand Canyon, AZ. They were able to compare changes in forest structure and fuels between burned and unburned plots established prior to the WFU fires. The low-elevation sites dominated by ponderosa pine historically burned every 3.2 to 5.5 years before livestock introduction and fire suppression caused large fire cessation in 1879. Before the 2003 WFU fire, these sites had burned three times since 1879, in 1892, 1924, and 1987 (Fulé and others 2003). The mid- and high-elevation sites had not burned since 1879. The WFU fire decreased tree density by 36 percent on the low-elevation site, with small trees (≤7.9 inches (≤20 cm) DBH) comprising 95 percent of mortality 2 years after the fire. Across all sites, large (≥14.8 inches (≥37.5 cm) DBH) ponderosa pine tree mortality constituted 7 percent of the total mortality (Fulé and Laughlin 2007). This study suggests that the WFU fires on the North Rim of the Grand Canyon moved the sites closer to historical reference conditions and are a viable management alternative.

Keane and others (2006) investigated the effects of a 2003 WFU fire on old ponderosa pine in the Bob Marshall Wilderness, MT. Before 1930, the area burned every 20 to 30 years, but no fires had occurred since then. During this fire-free period, thick duff layers of 6 to 15 inches (15 to 38 cm) accumulated at the base of the pre-settlement ponderosa pine, and Douglas-fir and lodgepole pine trees became established. The WFU fire was primarily a low-intensity surface fire. One year after the fire, 16 percent of trees greater than 20 inches (51 cm) DBH had died, and an additional 18 percent were noted as dying. Some dead and dying trees had relatively high levels of crown scorch, but the authors attributed much of the mortality to basal girdling from complete duff consumption and mountain pine beetle attacks. Many trees in this area were peeled by Native Americans for food and are living cultural artifacts (Figure 22). The fire killed approximately half of the historic bark-peeled trees. This study suggests that high mortality may occur after WFU fires in old-growth ponderosa pine stands in the northern Rockies that have missed several fire cycles. However, using other treatments in wilderness areas is greatly restricted, and not allowing fire at all is worse for the long-term perpetuation of ponderosa pine.

Figure 22. Native American peeled ponderosa pine tree in the Bob Marshall Wilderness, MT. Photo by Robert Keane.

Stand-Level Options

Prescribed burning—It took decades of no fires to develop the thick basal duff layer that now exists in many stands. It will also likely take multiple treatments and broadcast burns to reduce fuel loadings in order to limit overstory tree mortality. This is especially true in the absence of other individual tree duff reduction treatments (for example, raking). Each consecutive prescribed broadcast burn should aim to remove only a portion of the accumulated duff around the bases of overstory trees.

Fire intensity, or fireline intensity, is the rate of energy or heat release per unit length of fire front and is mathematically related to flame length (Byram 1959). Fireline intensity or flame length is a good choice for predicting crown scorch; however, it is not a good indicator of the amount of heat transferred down into the soil (DeBano and others 1998; Wade 1986). Fire severity is the effect of the fire on an ecosystem (Ryan and Noste 1985). It relates to how the fire affects plant survival and consumption of forest floor material or surface fuels (in other words, the depth of burn). Therefore, fire severity is a better indicator of the amount of heat transferred into the soil (Wade 1986). It is possible to have a low-intensity, high-severity fire with little crown scorch but high duff and/or large surface fuel consumption. This type of fire may cause considerable stem and root injury through long-term smoldering combustion.

Manipulating fire intensity through ignition patterns is effective in achieving the desired above-ground fire effects. Heading fires have longer flame lengths, faster rates of spread, and higher fire intensities than backing fires. Backing fires have longer residence times than heading fires, which can increase the chance of duff ignition and lead to more smoldering (DeBano and others 1998). Backing fires consumed significantly more duff than heading fires in experimental prescribed burns in longleaf pine, but the amount of litter consumed was not affected by ignition pattern (Sullivan and others 2003).

Heading fires are effective at killing small-diameter, shorter trees by scorching most of their crowns. For thinning doghair thickets, lighting a spot fire in the center of the thicket, followed by a ring fire around the thicket is effective. Areas where flanking fires merge or heading and backing fires merge also increase fire intensity (Sackett and Haase 1998). Backing fires generally do not kill small-diameter trees, unless their bark is very thin.

Prescribed burning long-unburned longleaf pine forests—Introduction of growing season fires to long-unburned longleaf pine forests may cause delayed mortality of the older trees. Several dormant season prescribed burns should be applied when lower duff is very moist to gradually reduce duff layers before switching to growing season burns (Brockway and others 2004; Kush and others 2004). Burns conducted under lower ambient air temperatures help to reduce crown scorch because more heat is required to reach 140 °F (60 °C), the lethal level for living tissue (Wade and Johansen 1986). Removing midstory hardwoods either by mechanical thinning or by applying herbicides also reduces fire intensity, crown injury to overstory trees, and competition. Thinning followed by prescribed burning promotes understory grasses and forbs while reducing hardwood sprouts, which promotes future low-intensity prescribed fires (Brockway and others 2004; Kush and others 2004). In small restoration burns, generous amounts of water can be applied during and after prescribed burns at the bases of trees with heavy duff accumulations to stop smoldering (Kush and others 2004).

Mortality of large-diameter longleaf pines after prescribed burning old-growth stands in the Florida Panhandle was directly related to duff consumption and duff moisture (Varner and others 2007). In this study, burns were conducted under three different gravimetric duff moisture conditions: dry (55 percent), moist (85 percent), and wet (115 percent) (note that moistures are not volumetric as reported in Varner and others 2007; R. Ottmar, personal communication). Stands had not burned for approximately 30 years prior to treatment (M. Varner, personal communication). Duff consumption was highly related to lower duff moisture content (R^2 = 0.78). Duff consumption around mature tree stems greater than 5.6 inches (15 cm) DBH was significantly higher in the dry burns than in the moist and wet burns at 46.5, 14.5, and 5 percent, respectively. Overstory tree mortality averaged 20.5 percent in the dry burns, with no significant differences in mortality among the wet, moist, and control units. Mortality rates increased with increasing tree diameter in the dry burns (Figure 23). Crown scorch and stem char height were not significantly different across burn treatments. Mortality did not begin until 12 to 18 months after the burns, and all pines that died were attacked by black turpentine beetle (*Dendroctonus terebrans*) and ambrosia beetle (*Playypus flavicornis*). The moist prescription is now widely used at Eglin Air Force Base, FL, to achieve moderate basal duff consumption with little overstory longleaf mortality when burning fire-excluded stands (M. Varner, personal communication). This condition is achieved by burning within 2 days of a 1-inch (2.5-cm) rain event (K. Hiers, personal communication).

Dale Wade, retired USDA Forest Service scientist at the Southern Research Station, recommends the following prescription when reintroducing fire into long-unburned southern forests that have a dense midstory of hardwoods. Under most conditions, the midstory creates a humid, sheltered environment and prevents the litter layer from drying quickly after rain, yet the lower duff layers are moist enough to limit consumption. Therefore, the primary

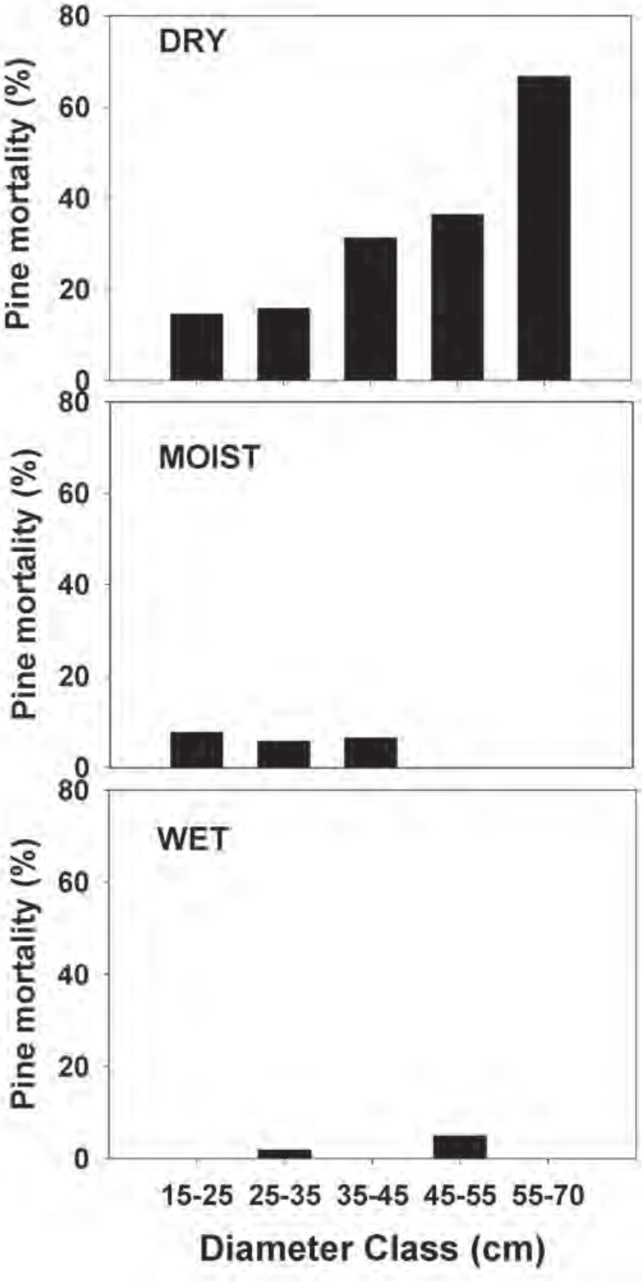

Figure 23. Diameter distribution of overstory longleaf pine trees (>6 inches (15 cm) DBH) killed following experimental prescribed fires of various duff moisture prescriptions in long-unburned longleaf pine forests in northern Florida. No overstory pines died in the unburned control treatment. From Varner and others 2007.

criterion for a successful first-entry prescribed burn is a very steep forest floor moisture gradient caused by the passage of two cold fronts in quick succession that wet the duff layer but bring wind to dry out fine surface fuels and push the fire quickly through the stand. The first cold front must bring precipitation and must be followed by a second, dry cold front. Ignition should occur within a few hours after the second front passes to utilize the high winds and to ensure the litter is wet enough to not carry a backing fire. Because of the sheltered conditions in the stand, the burn prescription is very narrow in level terrain and conditions may materialize only once or twice a year. The needles on the lower branches of the overstory pines may scorch, but residence times are short and little duff is consumed. This prescription topkills many small-diameter stems and widens the prescribed fire window for the next burn, which should occur in 1 to 2 years. The steep duff moisture gradient is necessary for ensuing prescribed burns until duff depths are greatly reduced. Brockway and others (2005) further describe this prescription and others appropriate for restoring longleaf pine ecosystems.

The chevron ignition technique proceeding down from the ridges is recommended in sloped areas. Igniters should never light from the bottom of the slope. The steep moisture gradient is the key to success, rather than season of the year. Hand removal of some understory and midstory fuels helps reduce fireline intensity and allows more wind into the stand, but cut material should not be left on site to burn. For the same reasons as thinning, herbicides also help to expand the prescribed fire burn window (D. Wade, personal communication).

Fire was successfully reintroduced into an old-growth longleaf pine forest in Flomaton, AL, using many of the techniques described above (Wade and others 1998). This 65-acre (26-hectare) tract had not burned in 45 years before the first prescribed burn was initiated in 1995. The area was burned when the duff layer was very moist and brisk, persistent winds were present to quickly push strip headfires through the stand. In this way, much of the hazardous midstory and understory layers were consumed, but not the duff layer. Two subsequent burns and thinning of the midstory have continued to slowly reduce fuel accumulations by 25 to 35 percent with limited overstory longleaf pine mortality (Kush and others 2004; Varner and others 2005; Varner and others 2000; Wade and others 1998).

Presence of fallen longleaf pine cones and mast years must be considered when scheduling burns in fire-excluded longleaf stands or duff consumption will be much higher than expected. At Eglin Air Force Base, FL, longleaf pine cones encountered along planar intercept fuel transects (Brown 1974) are recorded as 100-hour fuels because of their long burnout times (Fonda and Varner 2004; K. Hiers, personal communication). Longleaf pine typically produces heavy crops of cones every 8 to 10 years (Maki 1952). It is best to burn these areas before the heavy cone crop falls to the ground because cones take about 10 years to decompose. Mast years are known 1 year in advance, which gives the manager some leeway to complete the burn prior to cone fall (K. Hiers, personal communication).

Prescribed burning long-unburned red pine forests—A variety of mostly low-intensity surface fire with small patches of higher-intensity fire that causes some overstory mortality should both perpetuate overstory red pine and promote red pine seedling establishment. Van Wagner (1970) recommends the following when burning in red pine stands:

(1) a sparse but adequate stocking of mature red pines,
(2) a good red pine seed year,
(3) a considerable period of dry weather to promote mineral soil exposure,
(4) a summer surface fire of 200 to 500 Btu/ft/sec (690 to 1730 kW/m) and average flame lengths of 5 to 8 ft (1.6 to 2.4 m) to keep crown scorch of mature pine below 75 percent,
(5) satisfactory post-fire weather for germination and early growth, and
(6) no fire for several decades to allow red pine seedlings to become fire-resistant.

It should be noted that the stands Van Wagner studied likely did not have heavy basal duff accumulations caused from years of fire exclusion; therefore, these recommendations may be more suitable to promoting red pine seedling establishment than to limiting overstory red pine mortality. Henning and Dickmann (1996) support Van Wagner's recommendation to limit red pine crown scorch to less than 75 percent to minimize mortality, but suggest maximum flame lengths of 2 ft (60 cm).

Prescribed burning long-unburned ponderosa pine forests—Using prescribed fire to incrementally reduce basal duff depths in ponderosa pine forests seems more difficult and variable than in other forests types (M. Harrington, personal communication). This may be due to the generally dry summer conditions that rarely fully moisten lower duff layers.

Jain and Graham (2004) developed a method for incrementally reducing ponderosa pine basal duff depths in western Idaho by burning snow wells. They recommend burning when lower duff moisture is greater than 100 percent and temperatures are low (<28 °F; <-2 °C). This prescription consumes the litter and some upper duff, while leaving lower duff intact. These conditions occur in the early spring when snow is usually still present throughout the stand but the areas at the bases of trees are clear. The authors stressed the need for repeated prescribed burns to slowly reduce duff depths around tree bases and to force fine roots to grow back down into the mineral soil layers rather than in the lower duff.

With the exception of southwestern ponderosa pine, early season prescribed burning seems to be the best option when reintroducing fire to an area that has excessive fuel accumulations due to past suppression activities. Burning under higher moisture conditions, such as in spring after snow melt, often results in patchier burns and reduced fuel consumption compared to burning under drier conditions. Therefore, spring burning can moderately reduce fuel build-up while limiting injury to vegetation from long-term heating.

Perrakis and Agee (2006) found higher mortality after fall prescribed burns compared to spring burning. Mortality was highest in the lowest vigor classes, and low vigor was associated with lower growth rates (Agee and Perrakis 2008). All burns in this study were low-intensity and caused little crown scorch. Fall burns consumed 51.8 percent of total dead fuels versus 17.9 percent consumed in spring burns. Four years post-fire, mortality of old ponderosa pine was 2.3 percent in the control units, 6.1 percent in the spring burn units, and 16.4 percent in the fall burn units. Only 24 of the 139 dead trees were due to direct fire effects or windthrow. Bark beetle attacks were the largest cause of mortality (Agee and Perrakis 2008; Perrakis and Agee 2006), but the authors did not report differences in bark beetle activity between spring and fall burns. The higher mortality observed in the fall burns was attributed to "intense burning at the root collar" that caused stem injury and breakage and led to bark beetle attacks (Perrakis and Agee 2006).

In the southwest, Sackett and others (1996) recommend conducting initial prescribed burns in ponderosa pine stands in the fall due to the monsoons the area experiences. Historically, most fires occurred at the beginning of the monsoon season, just after spring. The first few storms are usually dry and accompanied by lightning. Therefore, burning dense stands with high fuel loadings in the spring when fuel moisture is low and the fire season is approaching is riskier than doing so in the fall. Weather and fuel moisture conditions are more moderate in the fall than in the spring, and high winds are not as likely. Spring burning is a good option after the first or second burn, after fuel loadings have been reduced (Sackett and others 1996).

Sackett and others (1996) established an experimental prescribed burn study on ponderosa pine in Arizona in 1976 to determine the optimal burn rotation to restore stands to near pre-settlement conditions, decrease wildfire intensities, and maintain low fuel loadings. Treatment plots were burned at 1-, 2-, 4-, 6-, 8-, or 10-year intervals. Conditions in the 1- and 2- year burn interval units had enough fuel to carry fire, but burning was often not possible due to marginal weather conditions. The most effective rotation was to burn every 4 years. At this timeframe, fuel loadings were kept to a minimum, making the prescribed burns easier to implement, and optimal weather conditions usually occurred. Heading fires ignited on the 4-year interval plots did not cause overly high crown scorch. The 6-, 8-, and 10-year rotations all allowed sufficient fuel accumulations to cause undesirable fire intensities and crown injury to overstory trees.

Prescribed burning long-unburned giant sequoia-mixed-conifer forests and mixed-conifer forests—Haase and Sackett (1998) found sugar pine was more susceptible to cambium and root injury than giant sequoia from prescribed fires in California. Eight research prescribed burns in Sequoia-Kings Canyon National Park recorded lethal cambium and soil temperatures around giant sequoia and sugar pine. Sixty-seven percent of sugar pine died after the prescribed burns compared to no giant sequoia mortality (Haase and Sackett 1998). In addition, park personnel had not observed giant sequoia mortality that could be attributed to the prescribed burn program during the previous 26 years. During the research prescribed burns, in which fire ignited and carried over the surface litter layer, complete duff consumption occurred with duff moisture contents ranging from 7 to greater than 200 percent. High duff moisture slowed the combustion rate but did not stop consumption. Average forest floor depths at the base of the sampled giant sequoia where cambium temperatures were measured ranged from 3.2 to 21.4 inches (8.1 to 54.4 cm) and 2.0 to 13.3 inches (5.1 to 33.8 cm) for sugar pine. Lethal temperatures varied around each tree. The authors noted that a substantial portion of the giant sequoia root system appears to be located directly under the tree base where it is protected from soil heating. Sugar pine also had proportionally more beetle attacks after fire than ponderosa pine or white fir in Crater Lake National Park, OR (Thomas and Agee 1986). In that study, mountain pine beetles killed 25 percent of sugar pines greater than 7.9 inches (20 cm) DBH 2 to 4 years after the fire. The authors recommended burning in late spring when soil and duff are wet but surface fuels are dry enough to carry a low- to moderate-intensity fire (<87 Btu/ft/sec

(<300 kW/m)) and flame lengths (<3.5 ft (<1 m)) with low duration in order to minimize large pine mortality.

Early season burns consumed significantly less fuel and were patchier than fall burns in a Sierra Nevada mixed-conifer forest. The authors concluded that the resulting tree mortality was related to fire intensity rather than tree phenology (Knapp and others 2005; Schwilk and others 2006).

Thinning and prescribed burning—Thinning can be an effective fuels treatment to reduce crown fire potential and to lower fire intensity by removing ladder fuels and creating gaps in the overstory canopy. Thinning is also commonly used to achieve restoration objectives by returning stands closer to historical stand structures. Under extreme weather conditions, such as in wildfires, thinning can reduce crown fire potential and, therefore, lower the probability of immediate tree death from crown scorch. However, thinning creates activity fuels and does not raise individual tree crown heights or control shrubs, seedlings, and small trees (O'Hara and Waring 2004). Thinning alone can also increase the intensity of a subsequent wildfire if activity fuels are not treated (Stephens and Moghaddas 2005). Thinning also does not solve the problem of accumulated fuel around the bases of old trees. These treatments are best used in conjunction with prescribed burning to meet restoration goals.

Mechanical thinning to reduce understory tree density is often much easier than using fire alone to thin smaller trees. In long-unburned areas, understory trees may also develop thick bark and become more fire-tolerant, making them difficult to kill with fire alone. After 18 years of prescribed burning to attempt to "manipulate fuels and tree density in an overstocked post-settlement ponderosa pine stand so that it would survive a wildfire that would otherwise be stand-replacing," Sackett and others (1996) concluded that achieving post-settlement conditions by prescribed fire only would be difficult. This and other research has led to the conclusion that a combination of thinning and prescribed burning to reduce stand densities and fuel loadings would better meet restoration goals in southwestern ponderosa pine forests (Covington and others 1997). In southern and eastern forests that historically burned frequently, fire suppression has also allowed many hardwood species that are easily killed by fire when young to become fire-resistant (Abrams 2006). Thinning this in-growth of now fire-tolerant trees is likely necessary before prescribed burning, as fire alone will not return the stands closer to historical forest structures (Harmon 1984; Hutchinson and others 2008). Modeling efforts also suggest that careful thinning of northern hardwood stands may shorten the time required to reach structures more typical of old-growth forests (Choi and others 2007).

Fulé and others (2002a; 2005) compared 1-year and 5-year post-treatment effects of two levels of thinning and burning (FULL, MIN), burning only (BURN), and a control on ponderosa pine stand structure near the Grand Canyon South Rim, AZ, where many of the larger, mature trees had been harvested earlier in the past 100 years. The FULL thinning and burning treatment removed the majority of post-settlement trees to restore the pre-settlement pattern of tree species and spatial arrangement. The MIN thinning and burning treatment removed post-settlement trees growing in the immediate vicinity of old trees to help protect them from wildfire. In both the FULL and MIN treatments, the forest floor was raked approximately 12 inches (30 cm) from all old trees. Old trees in the BURN and control treatments were not raked. No significant differences in crown scorch or bole char were found across the burned treatments. Large tree (>14.8 inches (>37.5 cm) DBH) mortality was low across all treatments. Five years post-treatment, 1 large ponderosa pine tree (3 percent) died in the control, 1 tree (9 percent) died in the FULL, no trees died in the MIN, and 2 trees (13 percent) died in the BURN.

Modeling scenarios predicted the FULL treatment would return the area most quickly to near pre-settlement forest structure conditions and would best mitigate against future wildfire. The FULL treatment was also predicted to remain effective against reducing fire intensity for at least 40 years post-treatment. Disadvantages to the FULL treatment are high costs and the necessity of roads for heavy equipment. Over larger areas or where road access is limited, the MIN and BURN treatments may be more feasible. In more remote areas with remaining old-growth, thinning treatments similar to the MIN treatment offer extra protection for these trees against future wildfire (Fulé and others 2002a).

Fire behavior was modeled under 80th, 90th, and 97.5th percentile weather conditions after fuel treatments in mixed-conifer forests in California (Stephens and Moghaddas 2005). Treatments included: (1) thinning from below followed by mastication (mechanical), (2) mastication followed by a prescribed fire (mechanical+fire), (3) prescribed fire only (fire), and (4) untreated control. Treatments did not affect predicted large tree (>20 inches (>51 cm) DBH) mortality under 80th percentile weather conditions. Under 90th percentile weather conditions, only the mechanical+fire treatment lowered the predicted mortality of trees 20 to 30 inches (51 to 76 cm) DBH, but not for trees larger than 30 inches (76 cm) DBH. Predicted large tree mortality was significantly lower for all fuel treatments compared to the control under 97.5th percentile weather conditions.

Thinning and a combination of thinning and burning stabilized the large (>23.6 inches (>60 cm) DBH) ponderosa and Jeffrey pine tree component at a study at the Blacks Mountain Experimental Forest, CA (Ritchie and others 2008). Five years after treatment, the mortality rate of the large tree component was 1.2 percent in the thinned units, 8.4 percent in the thinned and burned units, and 6 to 19 percent in the controls. The burn-only treatment did not reduce the risk of large tree mortality compared to the control units. Fifty-four to 70 percent of the large trees in the control and burn-only units had a high risk rating compared to 15 to 17 percent in the thinned units. The authors predicted that the 15-year change in tree density estimated similar declines in the large tree component for the control and burn-only units, whereas in the thinned and thinned and burned units, small increases in large tree density were forecasted. While more large trees died in the thinned and burned stand than in the thin only stand, prescribed burning lowered fuel loadings, which could increase resiliency to wildfire in the long-term. The authors predicted that in similar forests to the Blacks Mountain Experimental Forest study area, untreated stands will likely eventually lose most large ponderosa and Jeffrey pine trees if current mortality rates continue. In a separate study on the Blacks Mountain Experimental Forest, a high structural thinning treatment both with and without prescribed burning did not cause any mortality of old dominant trees (≥30 inches (≥76.2 cm) DBH) 5 years after treatment (Zhang and others 2008). However, a complete census of the experimental units in the study showed western pine beetle attacked and killed 6 percent of the large trees (>23.5 inches (>59.7 cm) DBH) in one thinned and burned unit (Fettig and others 2008). Fuel consumption and post-fire tree injury were not reported. Large trees continued to grow after treatment application, and the thinned treatments appeared to have enhanced late seral attributes compared to untreated stands without significantly increasing mortality rates.

Treating Individual Trees

Accumulated duff creates significantly greater potential for tree injury than deep litter when reintroducing fire. Deep litter layers will burn quickly during the flaming front without causing basal injury in thick-barked trees. Deep duff can smolder for many hours after the flaming front has passed. Smoldering basal duff, stumps, and logs near the tree bole typically result in basal and root injury; therefore, the decision to treat individual trees because of heavy fuel accumulations must focus on the duff layer around the base of trees.

Fire scars—Trees with exposed fire scars, or cat-faces, are especially vulnerable to prescribed fire. The scars are dry and often covered with pitch so they are easily ignited (Figure 24). Once ignited, the potential is high for the tree's heart wood to burn out, which usually kills the tree standing or burns it over (Figure 25). Duff adjacent to trees with fire scars should be mitigated before prescribed burning in order to minimize tree mortality. During snow well burning, filling cat-faces with snow before and during duff mound ignition reduces the potential of the scar igniting (Graham and Jain 2007; R. Taplin, personal communication). An alternative is to physically remove duff from the scar prior to burning using a rake or leaf blower.

Giant sequoias with fire scars seem to be the exception. Lambert and Stohlgren (1988) found giant sequoias with exposed fire scars did not have higher mortality rates than unscarred trees after prescribed burns in Sequoia and Kings Canyon National Parks. In that study, giant sequoia mortality rates in units prescribed burned between 1979 and 1984 were compared with unburned units. No

Figure 24. Exposed ponderosa pine fire scar burning.

Figure 25. Living ponderosa pine tree with exposed fire scar that ignited during a prescribed burn and fell over. Photo by Michael Harrington.

differences were found in mortality between trees with "extremely heavy ground fuels" removed around trees with large fire scars and those without fuel removal, as mortality was low for all treatments. Haase and Sackett (1998) also found low-intensity prescribed fire did not cause high rates of mortality in giant sequoia, even if fire scars were present.

Raking—Raking is a treatment to reduce the amount of litter and duff at the tree base in order to reduce potential bole and root injury from long-term smoldering (Figure 26). Researchers have reported mixed results, but treatment implementation and burn severity has differed greatly among studies, and only two studies (Fowler and others 2010; Hood and others 2007a) have specifically investigated the effectiveness of raking as a viable treatment to reduce old tree mortality.

In one of the first studies to examine raking, Swezy and Agee (1991) removed the litter layer around 3 trees before a prescribed burn in Crater Lake National Park, OR. The duff layer was left intact. These trees were compared to three unraked, burned trees and to three unraked, unburned trees. One high, moderate, and low vigor tree was chosen for each treatment. Four years post-fire, the low vigor raked and burned tree died after attack by western pine beetle. Duff moistures were not collected before the burn, but the authors hypothesized that raking only the litter layer dried the duff layer more quickly than duff around unraked trees. Perrakis and Agee (2006) also raked litter 3.3 to 6.5 ft (1 to 2 m) away from ponderosa pine trees greater than 7.9 inches (20 cm) DBH in a nearby area of Crater Lake National Park. Burn season and vigor were the only significant predictors of tree mortality; raking had no effect.

At Mt. Trumbull in northern Arizona, all pre-settlement ponderosa pine trees were raked after thinning and prior to burning to test the effectiveness of compressing slash prior to burning to reduce fire intensity (Jerman and others 2004). The majority of forest floor material was removed 1.6 to 3.3 ft (0.5 to 1 m) from the boles, but the areas were not raked to mineral soil. One unit was then broadcast burned with thinning slash intact. In a second

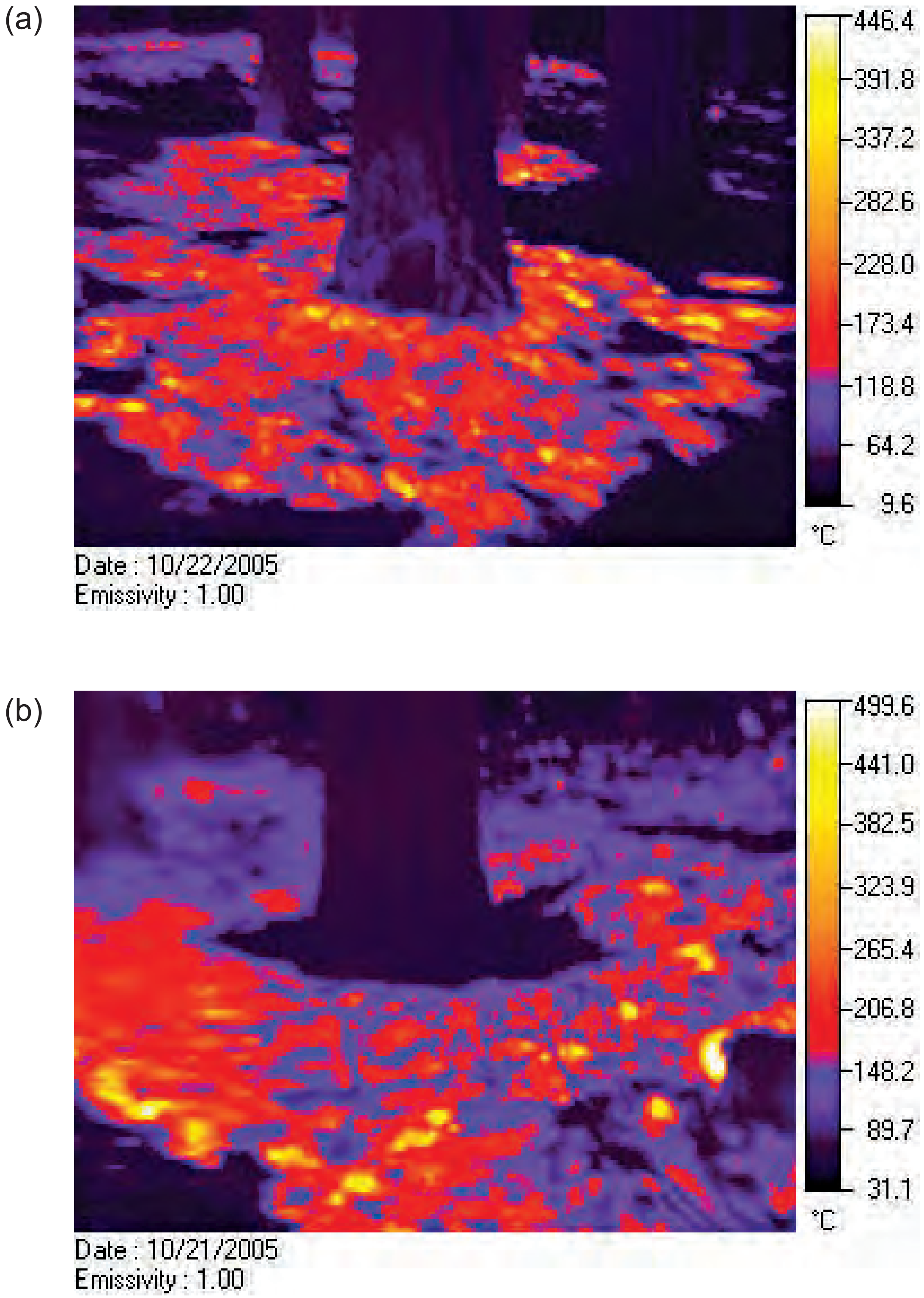

Figure 26. Infrared image of smoldering duff around an (a) unraked tree and (b) raked tree. Note the expanded black area around the base of the black tree indicating low temperatures.

treatment, a D-6 bulldozer compressed residual thinning slash throughout the unit before it was broadcast burned. No pre-settlement trees died within two growing seasons after burning in the slash compression treatment. In the burn-only treatment, raked pre-settlement tree mortality was 14 percent (3 of 22 trees) versus the 35 percent in post-settlement, unraked trees. Because raking was done as a precautionary measure around all pre-settlement trees instead of as a specific treatment, no comparison between raked and unraked pre-settlement trees was possible. Slash compression reduced fire intensity and crown scorch. The authors concluded that slash compression and raking treatments appear to reduce pre-settlement ponderosa pine mortality from broadcast prescribed burning in Arizona.

In a separate area of the Mt. Trumbull site, Fulé and others (2007, 2002b) observed high mortality of old ponderosa pine trees after burning. Accumulated duff and litter was raked 12 to 24 inches (30 to 60 cm) away from pre-settlement trees in the burned units prior to burning. This study was also not designed to test raking as a treatment; therefore, all trees in the burned units were raked. The high mortality only occurred in areas of shallow volcanic soils, leading the authors to hypothesize that the burns killed more fine roots that were growing near the soil surface and led to high rates of old-growth mortality (Fulé and others 2002b). Five years after treatment, an average of 4 large ponderosa pine trees/acre (>14.8 inches (>37.5 cm) DBH); 10 trees/hectare) had died in the thinned and burned units compared to 1.9 large ponderosa pine trees/acre (4.6 trees/hectare) in the control units. There was no difference in crown volume scorched between pre-settlement trees that died or survived (both were 30 percent) in the burned units (Fulé and others 2007). Prescribed burning on lava soils is currently suspended in Arizona due to concerns of excessive pre-settlement tree mortality, regardless of whether or not trees are raked (Waltz and others 2003).

Laudenslayer and others (2008) sampled 30 large (>24.0 inches (>61 cm) DBH) and 20 small (<24 inches (<61 cm) DBH) ponderosa, Jeffrey, and sugar pine trees in two units at Lassen Volcanic National Park in northern California. Half of the trees were raked around the first 3.3 ft (1 m) of the bole to mineral soil prior to prescribed burning. Trees were raked in September 1996 and prescribed burned in October 1996. Six years post-fire, 2 of the 10 large raked trees had died compared to 6 of 10 unraked trees in the Lake burn unit. In the Lost Creek burn unit, no raked trees (5 total) had died compared to 3 of 5 unraked trees. Pre-fire basal litter and duff depths, post-fire scorch heights, and bark beetle activity were greater in dead trees than in live trees, and the authors reported that most dead trees had heavy surface fuel loadings near the tree.

Fowler and others (2010, 2007) designed a study specifically to examine the effectiveness of raking treatments on ponderosa pine mortality in northern Arizona in 2004. Trees were assigned one of four treatments in both burned and unburned units: (1) no removal (unraked), (2) rake forest floor 9 inches (23 cm) away from bole, (3) rake forest floor 3.3 ft (1 m) away from bole, and (4) blow forest floor 9 inches (23 cm) (with leaf blower) from bole. All forest floor material was removed to mineral soil within 30 days of fall prescribed burns. Study trees were ≥ 18.1 inches (46 cm) DBH and had at least one measure of litter and duff ≥ 5 inches (13 cm) deep within 9 inches (23 cm) of bole before treatment. There were no woody fuels greater than 3 inches (8 cm) diameter around the first 3.3 ft (1 m) of the tree and trees showed no evidence of bark beetles, fire scars, dwarf mistletoe, or broken tops.

Forest floor removal by either raking or blowing around tree bases was effective at preventing cambium kill on the bole, and no differences were found among the removal treatments. Seventeen percent of the unraked, burned trees had areas of dead cambium, but there was no difference in mortality between raked and unraked trees 3 years post-fire, as only 3 trees had died. Two of these were struck by lightning and the third, an unraked burned tree, was mass attacked by western pine beetle. This study demonstrates that removing duff and litter as little as 9 inches (23 cm) away from the bole is as effective as greater removal distances at preventing cambium kill during fire. While duff removal was effective at reducing cambium kill, it had no effect on tree mortality within 3 years post-fire. The authors recommended that duff removal efforts in northern Arizona be limited to large trees (>18 inches (46 cm) DBH) to prevent cambial kill or to protect high fire-risk trees, such as those with rotten fire scars, pitch seams, or large nearby stumps, as well as those growing in droughty microsites.

Hood and others (2007a) also studied the effectiveness of raking treatments on old ponderosa and Jeffrey pine tree mortality. The authors chose sites dominated by ponderosa and Jeffrey pine sites in northern California that had not burned in over 100 years (Taylor 2000). Three units (two burned and one unburned) were located on the Lassen National Forest (LNF) and two units (one burned and one unburned) were on Lassen Volcanic National Park (LVNP). Ponderosa and Jeffrey pine trees greater than 25 inches (63.5 cm) DBH with no sign of insect attack were chosen randomly throughout the units. One tree in each pair was then randomly selected for raking to mineral soil in the first approximate 2 ft (60 cm) around the tree base unless a fire scar was present. In this case, the tree with the fire scar was designated for raking. Raked material was spread out away and around the tree so as not to form a mound (Figure 27). Trees were raked in the late summer/fall of 2003 on the LNF units and in the late summer/fall of 2004 on the LVNP unit. The LVNP burn unit was prescribed burned in June 2005. Both LNF burn units were prescribed burned in October 2005. Raked areas were cleared of any newly fallen material since the first raking just prior to burning.

Average time to rake the duff away from the tree bole was 16 minutes/person. A crew of two or three people could clear duff and shrubs in approximately 6 minutes/tree. The time required was dependent on the depth of litter and duff at the tree base ($p<0.0001$) and the amount of shrubs in the duff removal area ($p = 0.0001$) (Figure 28). The presence of shrubs increased the amount of time necessary to clear the area to mineral soil by up to 10 minutes/tree.

Figure 27. Crews raking ponderosa pine basal litter and duff prior to prescribed burning.

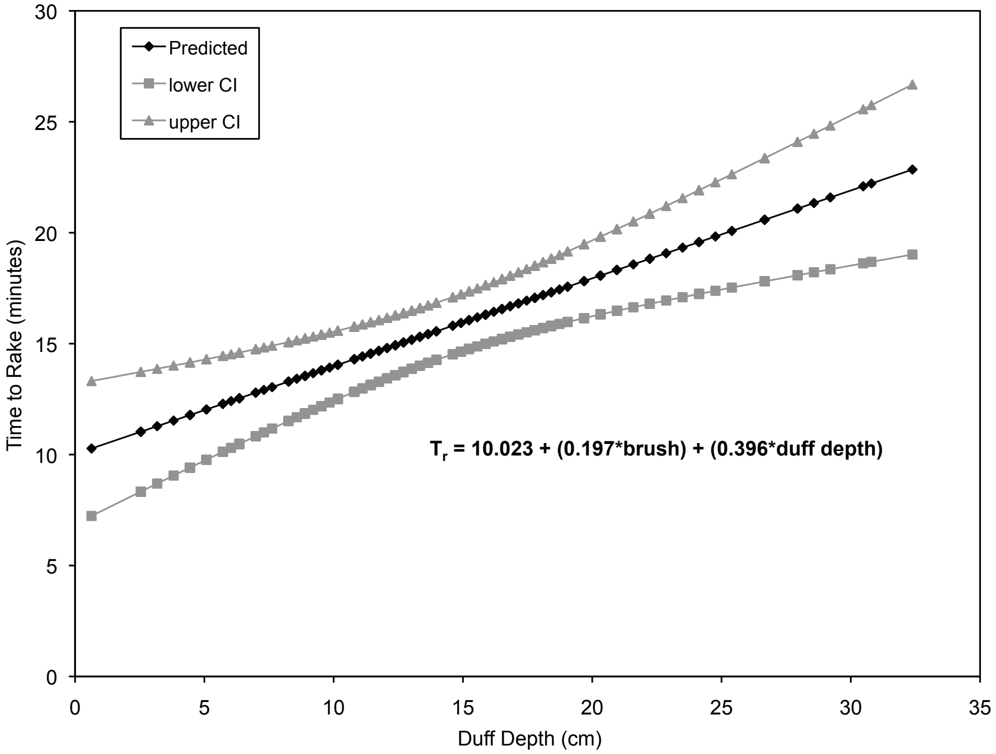

Figure 28. Predicted time and upper and lower confidence intervals (CI) for one person to rake duff and litter to mineral soil 2 ft (60 cm) away from ponderosa and Jeffrey pine tree boles when no shrubs are present in the removal area. T_r is raking time; brush is percent circumference of the raked area occupied by shrubs; duff depth is average duff depth (cm) immediately adjacent to tree base. From Hood and others 2007a.

Duff mound consumption was almost 100 percent in both LNF burned units (Figure 29). On the LVNP burned unit, duff consumption around the sample trees was lower and much more variable, with a median of 45 to 70 percent consumed around the first 4 ft (1.2 m) of the tree bole (Figure 29). Average duff mound moisture at burn time for the LNF units was 24 percent compared to 101 percent for the LVNP unit.

Raking reduced the probability of red turpentine beetle attacks in the burned units. Though the number of trees attacked by western pine beetle or Jeffrey pine beetle was low, most of the attacked trees in the burned units had previously been heavily attacked by red turpentine beetle. This seems to indicate that burned trees with numerous red turpentine beetle attacks were susceptible to attacks by primary bark beetles. This finding was also reported by Bradley and Tueller (2001). It is unclear if the red turpentine beetles were attracted to the charring of the tree bole, the cambium injury, or both.

Raking decreased cambium injury by limiting heating at the base of the trees in the burned units. However, tree mortality was very low (13 of 380 trees; <4 percent) and there was no difference in tree mortality among the treatments 3 years post-fire (LNF units) and 4 years post-fire (LVNP units). Raking did not appear to significantly reduce tree mortality in the study, but the authors cautioned that additional mortality could still occur and that trees need to be assessed for a longer period. They concluded that the decision to rake should be based on the management objectives for large trees in the prescribed fire area, current bark beetle activity, amount of duff around the large trees, and duff moisture prior to burning.

Five-year post-raking tree growth as determined by basal area increment (BAI) was compared between raked, unburned trees and unraked, unburned trees on the LNF unburned site (Noonan-Wright and others, in review). No differences in 5-year BAI (1.32 inches^2 unraked, 1.30 inches^2 raked (8.5 cm^2 unraked, 8.4 cm^2 raked); p = 0.871) or tree age (265 years for unraked, 267 years for raked; p = 0.525) were found between treatments. This suggests that raking alone does not stress the trees enough to influence growth or mortality.

Injury to raked and unraked old western larch trees was compared after a low-intensity fall prescribed burn in western Montana (Michael Harrington, unpublished data). Basal duff was very deep on unraked trees, and

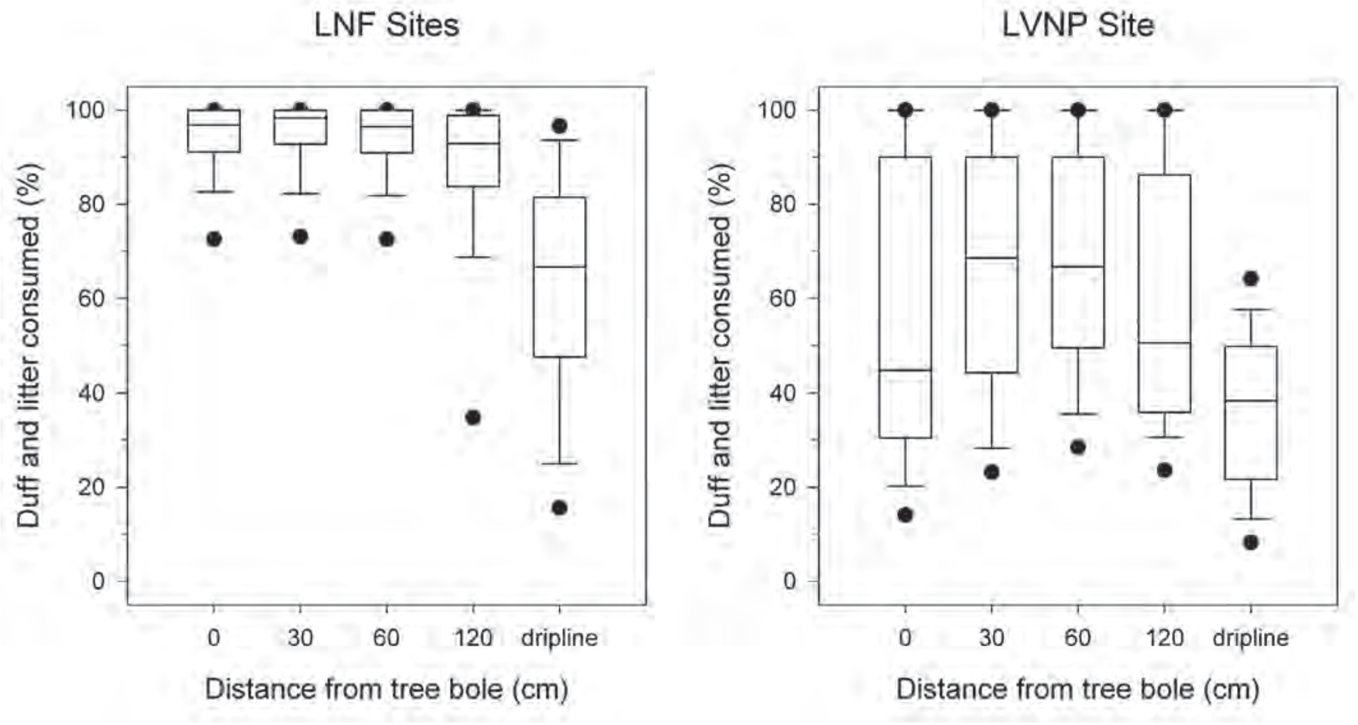

Figure 29. Average litter and duff consumption for unraked trees by study site. The Lassen National Forest (LNF) burned sites were combined for simplicity due to very similar results. LVNP= Lassen Volcanic National Park. Solid bars in boxes are median values and dots are 5th and 95th percentile outliers.

the fire consumed 100 percent of basal duff at 35 percent duff moisture content on all but one tree, with virtually no crown scorch. All unraked trees had some cambium kill, while raked trees had none. No tree mortality occurred within 5 years of burning. Large western larch have extremely thick bark, and cambium was killed primarily in bark fissures even though a significant portion of the bark was consumed. Also, western larch is not susceptible to any primary *Dendroctonus* beetles. These features, in addition to being deciduous, make western larch highly fire-resistant. This study suggests that removing deep basal duff around western larch trees may not be necessary prior to fall prescribed burning.

Longleaf pine trees with red-cockaded woodpecker (*Picoides borealis* (Vieillot)) cavities were raked to test the effectiveness of reducing tree mortality from fire at Eglin Air Force Base, FL (Williams and others 2006). Red-cockaded woodpecker colonies are typically in stands where fire has not been excluded, so basal duff accumulation is usually not a concern (K. Hiers, personal communication). Cavity trees have copious amounts of sap streaming down the bole, and the goal when burning is to not ignite the sap, which increases the probability of tree death. Therefore, treatments were designed to reduce fire intensity around cavity trees, not necessarily to reduce duff loadings. Trees received one of six treatments:

(1) clearing with hand tools and light raking,
(2) mechanical clearing only (performed with a DR® mower),
(3) mechanical clearing and light raking,
(4) mechanical clearing and raking to mineral soil,
(5) burning out from the tree base prior to the actual burn, and
(6) control (burn-only).

Light raking consisted of removing all vegetation and the litter layer with fire rakes while leaving the organic duff layer intact. Deep raking removed all vegetation, litter, and the duff layer down to mineral soil. Protection treatments were applied from the bole to the dripline, an average of 10 ft (3 m) from the base of the tree. Mortality was significantly lower for treated trees (2.70 percent) compared to the burn-only treatment (6.18 percent) 1 year after burning. Among the protection treatments, mortality was lowest (0.86 percent) for trees receiving treatment (1), hand clearing and light raking, and highest (4.46 percent) for those receiving treatment (3), mechanical treatment and light raking. However, there was no significant difference in mortality among the protection treatments (Figure 30). Treatment implementation times varied from a minimum of 30 minutes/tree on average for mechanical clearing only to a maximum of 65 minutes/tree for burning around the tree prior to the broadcast burn (Figure 30).

Light and deep raking around longleaf pine were compared at the Ordway Biological Station, FL (M. Varner, personal communication). Light raking consisted of only removing litter approximately 3.3 ft (1 m) out from the tree base 1 to 2 weeks prior to prescribed burning. Deep raking removed all material to mineral soil from the bole out to the dripline. Mortality was low for both treatments; however, the light rake was much easier and quicker to implement. The prescribed fire only singed the remaining duff around the lightly raked trees and caused very little bark char (Figure 31).

Kolb and others (2007) and Perrakis and Agee (2006) recommend raking 1 or 2 years before burning if fine roots are growing in the duff. This may offset the immediate loss of fine roots by raking before any further loss occurs from prescribed burning, and it may encourage new roots to grow in mineral soil rather than in the lower duff. Ponderosa and Jeffrey pine stands were burned 1 and 3 years after raking with little tree mortality within 3 years post-fire (Hood and others 2007a). However, Fowler and others (2010) and Laudenslayer and others (2008) raked duff within approximately 1 month of prescribed burning and very little mortality occurred. More research about the timing of raking to burning treatments is needed to determine if waiting to burn is necessary after raking.

Raking around old ponderosa pine trees is becoming a common practice in some areas of the Blue Mountains, OR. Managers there are advised to rake orange, smooth-barked, ponderosa pine greater than 21 inches (53 cm) DBH and duff greater than 5 to 6 inches (13 to 15 cm) deep (D. Scott, personal communication). Large-diameter, young trees do not produce the exfoliating bark scales like old trees and typically do not have deep duff accumulations at the base, thus raking these is not usually a concern. Recommendations include raking trees to mineral soil, about 3 ft (1 m) out from the boles, using care to not create a berm of raked material around the trees. More recent recommendations state that leaving a couple of inches of duff at the tree base is satisfactory if the majority of the material is removed. A resting period of 1 to 2 years between raking and burning is also advised (Scott 2002, 2005).

Leaf blowers are an alternative to removing duff accumulations around tree bases. Raking and blowing both clear litter and duff to mineral soil and produce no differences in treatment effects (Fowler and others 2010). Leaf blowers ease the task of material removal, disperse it more effectively, and often require less time to clear away the accumulated forest floor than raking, but shrubs in the duff mound area can reduce the leaf blower effectiveness

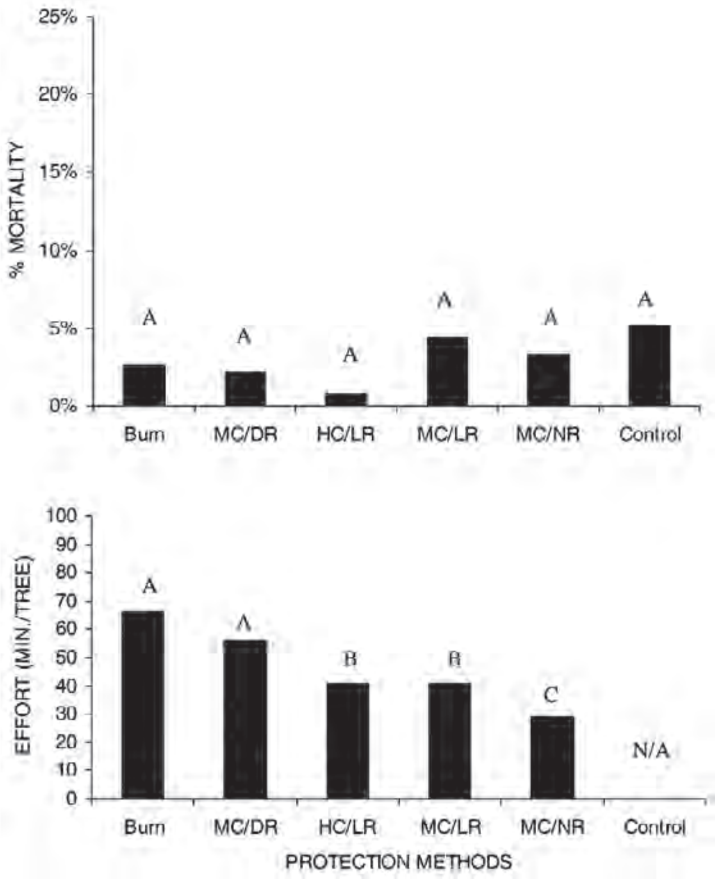

Figure 30. Comparison of protection effort requirement and percent mortality (for all trees) among five red-cockaded woodpecker cavity tree fire protection methods on Eglin Air Force Base, FL, 1 year post-fire. MC/DR = mechanical clearing/deep raking, HC/LR = hand clearing/light raking, MC/LR = mechanical clearing/light raking, MC/NR = mechanical clearing/no raking. Different letters above treatment bars indicate significant differences at the alpha ≤0.05 level. From Williams and others 2006.

Figure 31. Longleaf pine with light raking treatment (litter removed approximately 3.3 ft (1 m) away from bole) after a prescribed burn on the Ordway Biological Station, FL. The fire barely carried over the raked surface and consumed no duff. Photo by Morgan Varner.

(M. Harrington, personal communication). Two people are necessary to effectively use a leaf blower in areas of very deep duff. One person should first loosen the duff with a pitch fork, while a second person follows operating the blower (Figure 32).

Time required to rake duff away from trees increases with forest floor depth, heavy fuels, and shrubs (Figure 28). Though raking is intensive and potentially costly to implement, it is a one-time cost. Raking pre-settlement trees is not necessary in subsequent burns. Scott and Spiegel (2007) reported an average raking cost of $16 to $20/tree for ponderosa pines in the Blue Mountains of Oregon. Basal duff depth and time to walk between trees will also impact treatment costs.

Duff removal around large-diameter and/or old trees allows managers to burn under a wider range of duff moisture scenarios without concern that the duff removal treatment alone will cause tree death. This is important because of the difficulty in predicting duff consumption in duff mounds based on pre-fire duff moistures.

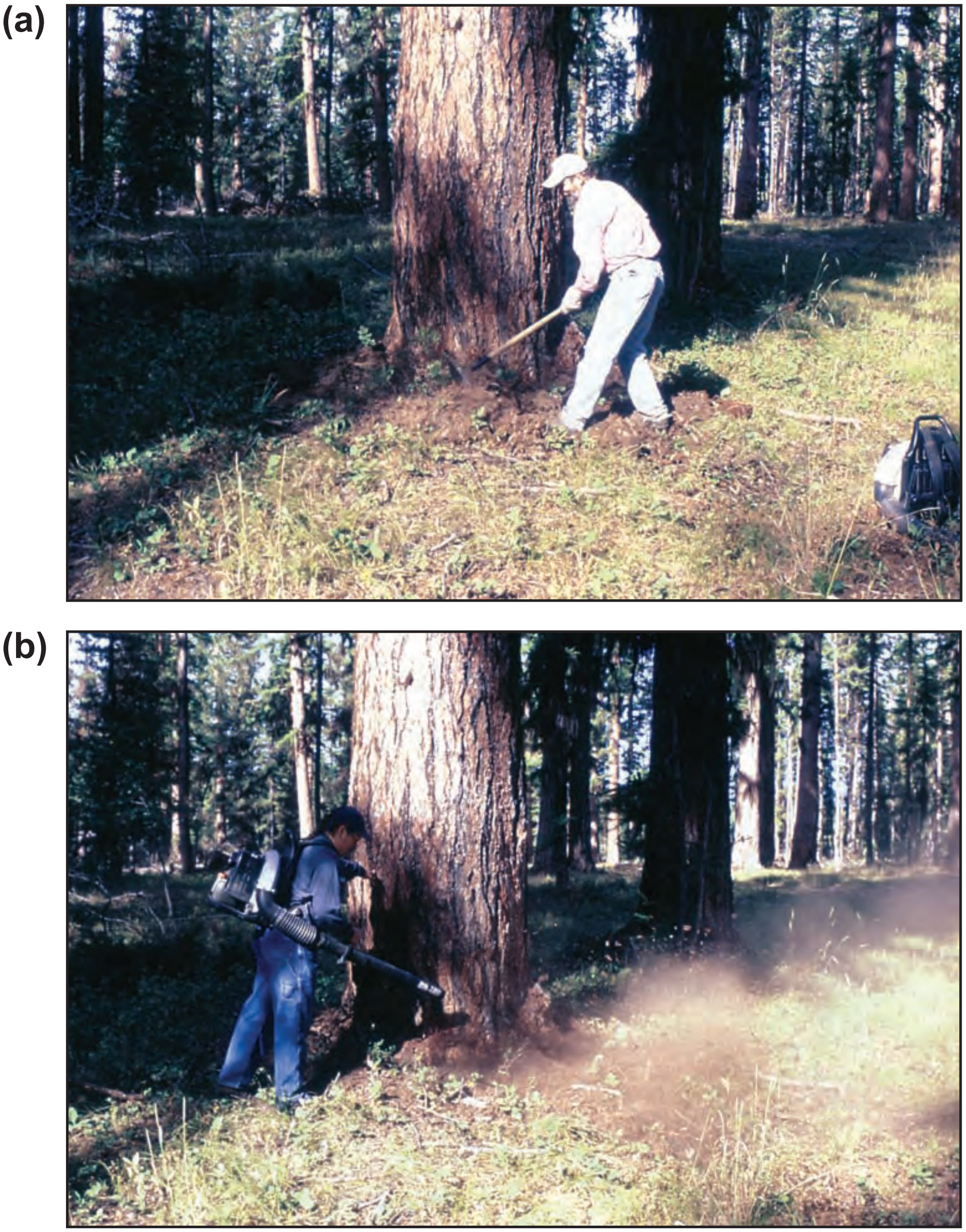

Figure 32. (a) Loosening basal duff with a pitchfork and (b) using a leaf blower to clear loosened litter and duff away from the tree base and to spread material out before a prescribed burn. Photos by Michael Harrington.

In areas of deep duff, where the potential for basal cambium injury is high, raking minimizes injury to the tree bole near groundline from long-term duff smoldering (Fowler and others 2010; Hood and others 2007a). By reducing the residence time of the fire, the chance of cambium injury is reduced. Most studies examined duff mounds raked to mineral soil; however, this degree of removal may not be necessary. Raking the majority of the duff, but not to mineral soil, will prevent long residence times, reduce potential injury to roots in the mineral soil, and reduce the time required to rake. However, the exception is where fire scars exist on large-diameter or old trees. These scarred trees typically ignite with any flame contact, so duff removal to mineral soil adjacent to the scar is important. Raking is a viable option when there is concern that burning will cause large-diameter, old ponderosa, Jeffrey, and longleaf pine mortality. The effect of season on raking is not known. Most researchers have raked basal litter and duff in the fall when fine root growth is less active to minimize injury to roots growing in the lower duff layers.

The following raking techniques are recommended to remove forest floor accumulations from the bases of trees based on the available literature and expert knowledge:

- Rake the majority of litter and duff away from the tree base. Raking litter only is not advisable in areas with low summer precipitation because the duff will dry significantly and ignite without litter. In the southeastern United States, raking only litter prior to burning will reduce potential for fire spread around raked trees, thereby reducing basal injury; however, it will not ameliorate duff accumulation. Raking to mineral soil is not necessary except around fire scars. For trees without fire scars, leaving 2 to 3 inches (5 to 8 cm) of duff is acceptable in the West, and leaving 1 to 2 inches (3 to 5 cm) of duff is acceptable in the South.
- Remove litter and duff at least 9 inches (23 cm) away from the tree base. Expand raking to 3 ft (1 m) if shallow supporting roots are present. It is not necessary to remove material all the way to the dripline.
- Take care to spread raked material away from the tree in order to not create a new fuel mound around the tree.
- Rake during the fall or winter when fine root growth is minimal.
- If possible, allow at least one growing season between raking and burning to encourage new fine root development in the mineral soil on sites with numerous fine roots growing in the lower duff.

Snow well burning—Snow wells are areas immediately adjacent to trees that are free of snow, while snow is still present farther away from the tree base. Snow wells are usually about the size of the width of the tree crown (sometimes larger on steeper slopes and south and west aspects) compared to areas outside the tree wells that usually have a foot or more of snow. Snow well burning in the early spring when temperatures are below 40 °F (4 °C) and lower duff moistures are greater than 100 percent can consume litter and upper duff layers while leaving the lower duff intact. This treatment has been tested in ponderosa pine stands in Idaho (Graham and Jain 2007). The required burning conditions in Idaho usually occur when snow is still present throughout the stand but when the forest floor around the tree bases is clear. However, duff moistures and temperatures during the burn are the key factors, not the presence of snow (T. Jain, personal communication). Snow well burning around old ponderosa pine has been successful at Ponderosa State Park, ID, since 1995 (R. Taplin, personal communication).

The primary objective of snow well burning is to gradually reduce duff depths in order to force fine roots growing in the lower duff layer to migrate back down into the mineral soil. The area can be broadcast burned once the amount of fine roots in the duff layer is reduced—usually 1 to 2 years after the snow well burn. To burn the well, ring the tree with fire (Figure 33). Flame lengths are typically 6 inches and burn for approximately 2 to 3 minutes before going out, depending on upper duff moisture (T. Jain, personal communication).

Figure 33. Snow well burning around ponderosa pine trees on the Boise Basin Experimental Forest, ID. Photo by Theresa Jain.

Old ponderosa pine trees in the Boise Basin Experimental Forest, ID, were burned using the snow well technique followed by broadcast burning. This area had not burned in 100+ years. An unpublished fire history study of the area estimated a historic FRI of 8 to 30 years (T. Jain, personal communication). The snow wells around selected trees were first burned in 2002, and half of these were burned a second time in 2004. Snow well burning reduced root concentrations in the duff layer compared to unburned control trees. The unit was then broadcast burned in the spring of 2005 (Graham and Jain 2007). To date, approximately 11 old trees in the 90-acre unit have died (approximately 3 percent) (T. Jain, personal communication). In these cases, tree death was due to bark beetles and ignited fire scars that burned out the center of the tree (Graham and Jain 2007). A comparison was not made between snow well treated trees and broadcast-burn-only trees.

At Ponderosa State Park, burns are conducted when the duff is very moist, so little duff is consumed beyond the first 6 inches (R. Taplin, personal communication). Trees with fire scars are either packed with snow or are raked to remove duff from the scar area but not from the whole tree base. Snow well burning in the park reduces duff around trees by approximately 3 to 6 inches (7.5 to 15 cm). More consumption occurs on trees with larger snow wells, trees on south and west aspects, and during spring seasons with longer drying periods. Fire scars on unraked trees often ignite but can be extinguished by packing available snow in the scar area. Duff around the trees continues to break down or decompose over the summer, possibly due to warmer temperature from the blackened surface, nutrient release, or some combination of the two. Sometimes another 6 or more inches (15 cm) of duff decomposes after the initial fire treatment. Multiple snow well burns have reduced duff accumulations around some large ponderosa pine trees in the state park from over 20 inches (51 cm) down to mineral soil. Old ponderosa pine trees with very deep basal duff accumulations usually require two snow well burning treatments before conducting a broadcast prescribed burn, during which the remaining duff is expected to be consumed. Snow well burning in Ponderosa State Park is also used as a precautionary treatment to increase the probability of old tree survival in the event of a wildfire.

Benefits of snow well burning are: (1) only a few people are needed to conduct the burn, (2) firelines and suppression activities are not necessary, and (3) fire fighter safety concerns are minimal. The main drawbacks are the short window of adequate environmental conditions and uncertainty about the level of duff consumption. At Ponderosa State Park, adequate conditions occur every spring for about 4 to 7 days (R. Taplin, personal communication). Burning snow wells to gradually reduce duff layers should be tested in other areas to determine the treatment's applicability outside of Idaho. For example, Haase and Sackett (1998) reported that for prescribed burns in giant sequoia-mixed-conifer forests, 100 percent of duff consumption usually occurs if fire can carry through surface litter, even if duff moisture exceeds 200 percent. The prescribed burns described by Haase and Sackett (1998) were not conducted to test snow well burning prescriptions. However, many of the burns were conducted under the high duff moisture conditions recommended for snow well burning, and high duff moisture slowed the combustion process, but did not stop it.

Mixing—Mixing the litter and duff layers around tree bases may increase decomposition rates by allowing moisture and heat to penetrate through the forest floor (Graham and Jain 2007). The goal of mixing is to speed decomposition and to train fine roots to grow into the mineral soil, while broadening the prescribed burning window. Once the presence of fine roots in the duff layer is reduced, usually 1 to 2 years after mixing, the area can be broadcast burned. To mix, a hoe is used to break up and aerate the forest floor layers around a tree base, but material is left in place (Figure 34). This treatment was tested in ponderosa pine stands in the Boise Basin Experimental Forest, ID, in conjunction with the snow well treatments previously described. Mixing was applied to selected trees in 2002. Half of those were mixed a second time in 2004, followed by a broadcast burn in spring 2005 (Graham and Jain 2007). Mixing required approximately

Figure 34. Mixing duff mounds around a ponderosa pine tree on the Boise Basin Experimental Forest, ID. Photo by Theresa Jain.

3 to 5 minutes/tree at the study site (T. Jain, personal communication) and reduced root concentrations in the duff layer compared to unburned control trees. Eleven old trees in the 90-acre unit have died (approximately 3 percent) in four growing seasons post-fire, due to fire scars igniting and bark beetles (Graham and Jain 2007; T. Jain, personal communication). A comparison between mixed trees and broadcast-burn-only trees was not made.

Hand lining—Digging a fireline, or lining, is commonly used around snags or large jackpots of fuel to prevent them from burning. However, lining around trees to prevent the forest floor from burning does not solve the problem of deep duff accumulations. Therefore, it is not recommended as a way to reduce large tree injury and mortality from prescribed burning.

Foam—Spraying fire-retardant foam is sometimes cited as a technique to reduce old tree mortality during prescribed fire (Arno and others 2008). It has more typically been applied to create temporary fire breaks during prescribed burns. The only known study to examine the effectiveness of this treatment in reducing cambium mortality was conducted by Ryan and Steele (1989) on leave trees during prescribed burns in mixed-conifer shelterwood harvests on the Priest River Experimental Forest, ID. Though foam statistically reduced cambium mortality, the difference in mortality rates between foam-treated, burned trees and untreated, burned trees was less than 6 percent. A key deficiency is that foam is only effective for a relatively short time after application, usually less than one hour depending on weather conditions (Schlobohm 1995). Therefore, timing between application and ignition is critical and may be logistically difficult (Ryan and Steele 1989). If spraying, foam should be applied on the duff mound around the tree, not on the bole. The problem of heavy duff accumulations is not abated by spraying foam around individual trees. It may only prevent fire from burning surface fuels around selected trees during the broadcast prescribed fire. Therefore, it is not recommended as a way to reduce large tree injury and mortality from prescribed burning.

Water—Water has been successfully used to extinguish smoldering duff at the base of trees in small stands of longleaf pine (Kush and others 2004). Copious amounts are required to stop smoldering—enough to thoroughly saturate the area surrounding the tree base, because once duff begins to smolder it can be extremely difficult to stop. Duff can still smolder, even when no smoke is visible. Therefore, this method requires intense monitoring after the burn to make sure enough water is applied and smoldering is extinguished. Another concern is that fire fighters must be within the burn perimeter shortly after ignition, which exposes them to heavy smoke and the potential of falling snags.

This treatment is extremely labor-intensive and is probably only applicable to small areas or around unique trees with good accessibility. For example, hundreds of gallons of water were applied around the Nation's largest western larch tree in Montana (http://www.americanforests.org/resources/bigtrees/index.php) prior to burning the stand in order to limit forest floor consumption (S. Hood, personal observation, 2003). Another example is old-growth longleaf pine stands. These are very rare, and efforts to increase tree survivorship during fire can be justified that are not feasible in other areas.

Fire shelter wrap—Fire shelters wrapped around the bases of old trees is another technique that has been proposed to reduce old tree mortality during prescribed fire (Arno and others 2008). However, no studies exist regarding the effectiveness of this treatment, and it is not recommended as an option for reducing old tree mortality. Fire shelter material is expensive and wrapping tree bases is time-intensive. This treatment could prevent bole heating during passage of surface flames, but that is not normally an issue for fire-adapted thick barked trees. Fire shelters would do nothing to prevent lower stem heating from smoldering ground fires unless all duff was cleared to ground level during shelter placement. Unless the shelter material was placed in contact with mineral soil, deep duff accumulations could still girdle the tree directly at the ground line. In deeply fissured trees, shelters can create air currents between the tree and shelter that cause fire columns to funnel up through the shelter. This may actually increase stem heating (M. Varner, personal communication).

Mechanized equipment—Mowers were tested around red-cockaded woodpecker cavity trees prior to burning as a protection treatment in Florida (Williams and others 2006; see *Raking* for additional detail). Red-cockaded woodpeckers typically are not found in long-unburned longleaf pine forests, and the trees in this study did not have much duff accumulation at the bases (K. Hiers, personal communication). The mowing treatment was intended to reduce fire intensity by reducing midstory oaks and other hardwoods around a specific cavity tree so that the sap on the tree bole would not ignite. Mowing alone does not mediate basal duff accumulations. Trees were mowed either using a DR® mower alone or in conjunction with a raking treatment. One year after burning, burn-only trees had higher mortality rates than those receiving a protection treatment. However, no difference in mortality was found among the different protection treatments (Figure 30).

The authors concluded that mowing alone was the most cost effective treatment. It took 30 minutes/tree on average, required fewer personnel, and was faster than other protection treatments; all of which reduced costs and allowed more trees to be treated prior to burning. Mowing in late autumn remained effective for 6 months. When mowing, it is important to avoid damage to the bole of trees with the mower head or to fine roots by setting the blade too low. Mowers are not appropriate for use in wetland areas or in areas inhabited by the flatwood salamander (*Ambystoma cingulatum* Cope) (Williams and others 2006). Mowing around cavity trees is now the preferred preparation treatment at Eglin Air Force Base, FL. Managers there prepare approximately 2000 red-cockaded woodpecker trees a year on the largest tract of longleaf pine in existence. Mowing to reduce fire intensity is an appropriate option in long-unburned stands if used in conjunction with other duff abatement treatments (for example, burning under high duff moisture, raking, or blowing).

Using dozers to remove fuels around tree bases is not recommended. This treatment is hard to apply without causing injury to roots growing near the soil surface and duff interface from the dozer blade. Dozers have caused extensive mortality around longleaf pine red-cockaded woodpecker cavity trees (D. Wade, personal communication).

Management Implications

Management options included in this section provide background information, guidance, and precautions for prescribed burning areas with deep basal duff. Basal duff less than 2 inches (5 cm) deep in the southeastern United States (K. Hiers, personal communication) and less than 5 inches (13 cm) deep in the western United States at the base of mature trees are generally not considered hazardous. In these cases, prescribed burns can be conducted in accordance with locally accepted methods, objectives, and prescriptions.

Management options exist for areas with deep duff, but are limited. The provided decision key (Figure 35) highlights the best available treatment options based on project scale. Options are: (1) burning when the basal duff layer is very moist during the dormant season and (2) reducing basal duff around individual trees by physical removal. The available burning window is narrow for prescribed burning when basal duff is very moist. It is also much more difficult to predict actual duff consumption, making it harder to achieve burn objectives. More overstory tree mortality should be expected if no individual tree treatments are implemented before broadcast burning. All individual tree treatments are labor-intensive and require extra time to implement before broadcast burning. However, individual tree treatments widen the broadcast burn prescription window and can be completed years before broadcast burning. They should be considered additional tools in the manager's toolbox when concerns exist that standard prescribed burning techniques will not meet objectives.

Thinning from below, followed by activity fuel treatments, will also reduce competition and increase water and nutrient resources available to old trees. Mechanical thinning can quickly manipulate stand structures to more closely resemble historical stand conditions and to be more resilient to future disturbances.

These efforts must be couched in the larger perspective of the importance of maintaining and perpetuating old trees on the landscape and with the realization that no action will likely result in significant tree mortality in forests that historically burned frequently. Acceptable levels of old tree mortality will vary by location and species. Places where little mortality is acceptable will warrant more intensive treatments. The high value of old trees on certain landscapes, especially at historically significant and high-use recreation sites, and the length of time required to produce large and old trees merit strong consideration of using the unconventional burning and individual tree treatments previously described. Some may hesitate to use a novel strategy to reduce overstory tree mortality when reintroducing fire to long-unburned areas because of the increased treatment costs or logistical difficulties. But remember that an individual tree treatment need only occur once to initially reduce the deep duff layer, and then regularly scheduled maintenance burning can be conducted without supplemental treatment.

Monitoring the Effects of Fire on Overstory Tree Mortality

Monitoring is fundamental to successful land management programs. Without monitoring and treatment documentation, it is extremely difficult to understand the relationship between treatments and subsequent effects. This understanding leads to adaptive management, under which treatments are continually refined to better achieve management objectives (Mayfield and Smith 2008). It is important to distinguish between a record of post-burn observations and a true monitoring program. Monitoring requires pre-fire and during-fire measurements in order to relate the pre-fire conditions and silvicultural treatment to post-fire outcomes. When the primary objective is to reduce overstory tree mortality, long-term monitoring is key, as mortality may not occur until several years post-fire.

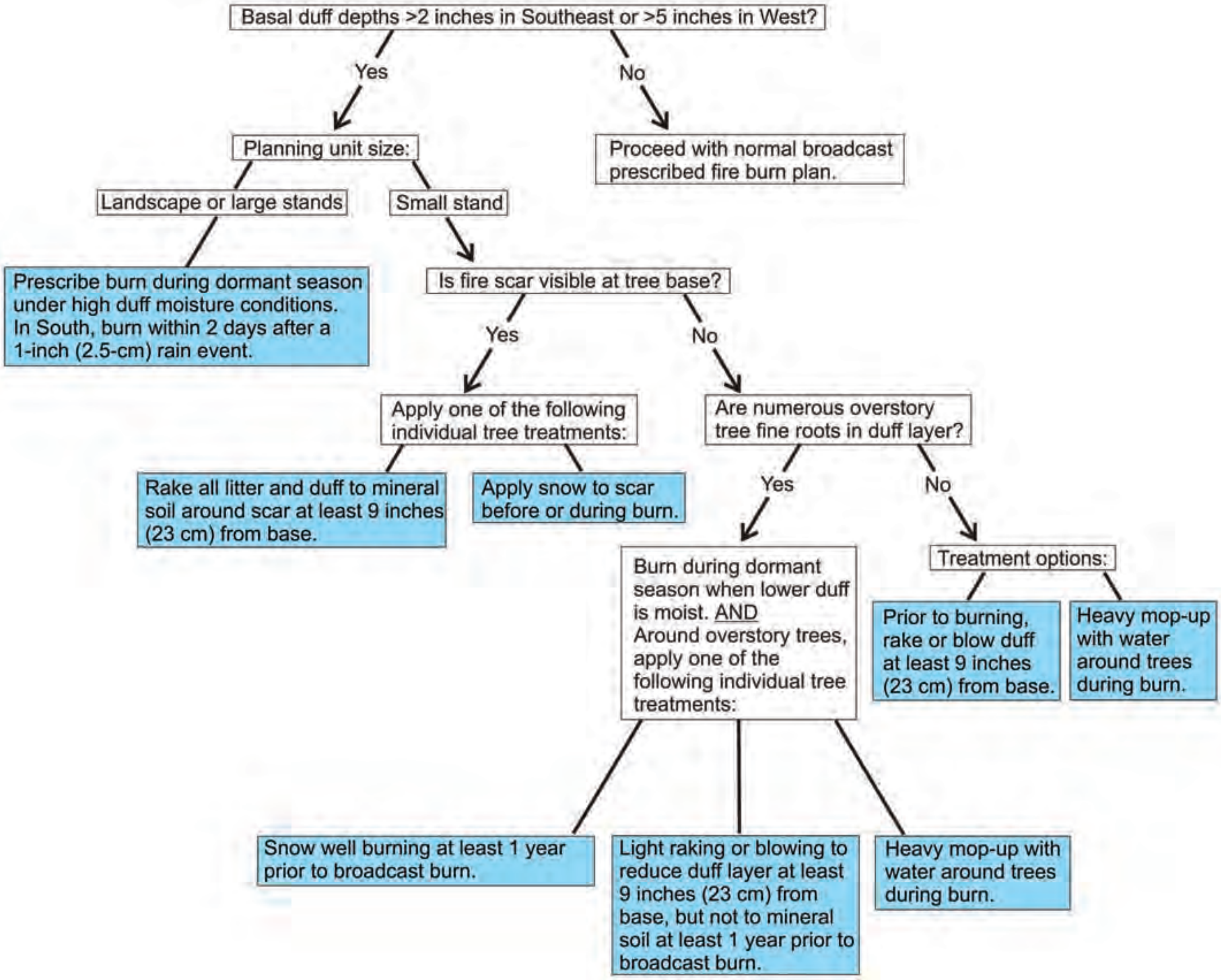

Figure 35. Decision key of treatment options when reintroducing fire to long-unburned forests to reduce overstory tree mortality. Treatment options apply to forests that historically burned frequently. See text for detailed treatment descriptions.

This section is not a how-to guide to build and implement a monitoring program, and it does not describe the different sampling methods. Many such guides are available (Elzinga and others 1998; Lutes and others 2009; Lutes and others 2006; U.S. Department of the Interior, Fish and Wildlife Service 1999; U.S. Department of the Interior, National Park Service 2001). This section provides general information about appropriate monitoring timeframes and sampling techniques pertinent to the objective of limiting overstory tree mortality from prescribed burning in historically fire-frequent forest types.

What to Monitor?

Pre-burn and post-burn fuel loadings, weather and moisture conditions at the time of burn, fire behavior, tree characteristics, post-burn tree injury, resident insect populations and post-burn attack densities, and tree status should be evaluated during monitoring sessions to determine if tree mortality related objectives are met. Without one of these pieces, the burn and subsequent fire effects on tree mortality cannot be accurately connected. The following variables should be documented to determine tree mortality from first-entry prescribed burns:

- Fuel loadings: pre- and post-fire duff depth at base of trees desired for retention
- Weather: temperature, relative humidity, windspeed, time since last precipitation
- Fuel moisture: percent litter, duff, and fine fuel moisture at base of trees desired for retention

- Fire behavior: flame length, rate of spread
- Tree characteristics: DBH, species, condition
- Tree injury: percent crown volume or length killed. Basal injury is also helpful if feasible to assess.
- Post-fire insect attacks: species, intensity of attacks (mass or stripped)
- Tree status: alive or dead

How to Monitor?

Monitoring overstory mortality from fire where heavy duff accumulations exist calls for slightly different strategies than standard monitoring techniques. The specific trees of interest must be evaluated and monitored over time in order to know if objectives are being met. Fixed area tree plots are best, but often include few large or old trees because of generally wide spacing between these trees. Three options to resolve this issue in order to most efficiently collect data on the trees of interest are: (1) install more plots, (2) install larger area plots, and (3) monitor individual trees.

Installing more or larger plots will increase the likelihood of capturing a greater number of larger and/or older trees. Fixed area plots will most accurately describe forest stand conditions, as tree density and basal area of all size classes are assessed. To save time, apply appropriate break-point diameters and plot sizes to most effectively sample the trees of interest. For example, if an objective is to limit mortality of trees >20 inches (>50 cm) DBH to 10 percent, set a break-point diameter of 20 inches (50 cm) DBH and only sample trees larger than this in the largest plot. The plot size should include at least one tree of interest per plot. If this criterion is not met, the plot size should be increased. Data on smaller trees can be collected on a smaller plot nested inside the larger plot. This way data on all size classes are collected, but less time is spent collecting data on the smaller trees.

Alternatively, individual trees can be monitored. Tagging and tracking individual trees ensures that information on the trees of most interest is collected, and it is a good way to increase sample size of these trees. However, it does not provide data on forest structural conditions. A mix of fixed area plots supplemented with individual tree monitoring may often be the most efficient way to collect the most pertinent data related to the identified prescribed burn objectives.

Fuels data are most commonly collected using the planar intercept method (Brown 1974). Though appropriate for describing stand-level fuels, site-level fuel transects will not provide information about fuels near large or old trees. Measure duff depths and collect moisture samples near the base of the sample trees (identified during plot establishment) to best describe conditions affecting individual trees. Document where data was collected to help clarify stand-level versus individual tree-level effects.

How Long to Monitor?

Mortality from low-intensity, high-severity prescribed burns may not occur until several years after the burn and is often from the secondary effect of bark beetle attacks (Swezy and Agee 1991). Most studies of post-fire mortality have reported less than 5 years of results (Table 5), but long-term studies show that significant mortality may go unreported if not monitored for longer periods. For example, after prescribed burning old ponderosa pine in Oregon, 75 percent of the trees died 2 to 4 years post-fire (J. Agee, personal communication) and 35 percent died 3 to 4 years post-fire (Agee and Perrakis 2008). Mortality in the spring burns had returned to the control unit levels 4 years post-fire. Mortality in the fall burns was still slightly elevated, but was steeply declining. In another study in Crater Lake National Park, most small-diameter and younger trees died within the first year after a prescribed fire, while the majority of larger and older ponderosa and sugar pine died between 4 and 8 years post-fire. Larger, older white fir died mostly 8 to 13 years after the fire (Agee 2003; Thomas and Agee 1986). Drought and bark beetles were thought to significantly influence long-term post-fire tree mortality; however, it was not possible to know the exact impact of these second order fire effects and fire-caused tree injury. Mortality of old ponderosa pines at the Chimney Spring study site in Arizona began approximately 1.5 years after an initial prescribed burn in a stand that was long-unburned. Twenty years after the initial burn and other subsequent burns, 39 percent of the old trees had died compared to 16 percent in the control (Sackett and others 1996). The researchers attributed the higher mortality to the heavy fuel consumption at the base of the trees during the initial burn.

The above examples highlight the importance of long-term monitoring to determine prescribed fire effects on overstory tree mortality. In these cases, the fact that the prescribed burn tree mortality exceeded objectives would have gone undetected had monitoring been conducted for only a few post-burn years.

So, how long should prescribed burns be monitored? The first evaluation should occur within 1 year of the prescribed fire to capture first order fire effects. The timing of subsequent evaluations to capture bark beetle attacks, delayed tree mortality, and other second order fire effects will vary by location and forest type. In general, 3-year and 5-year post-burn monitoring is recommended. Filip and others (2007) recommended monitoring for at least

5 years to determine post-fire delayed tree mortality. If mortality has not stabilized between the 3- and 5-year assessments, then monitoring should continue. Developing an appropriate monitoring schedule should be an adaptive management process, whereby monitoring programs are continually evaluated to determine if they are capturing the treatment effects of interest.

It was only by repeated monitoring and adaptive management that delayed tree mortality was observed in some burn units after prescribed burning at Grand Canyon National Park, AZ. One of the park management's prescribed burning objectives is to limit overstory tree mortality to 20 percent as measured 5 years post-fire (Kaufmann and Covington 2001). Selected prescribed burns in the park appeared to meet this objective, but Kaufmann and Covington (2001) advised longer-term monitoring due to sustained higher levels of pre-settlement tree mortality in burned areas compared to unburned areas.

Knowledge Gaps

This synthesis reports the current state-of-knowledge for reintroducing fire into long-unburned forests while limiting overstory tree mortality. However, there are still many unknown answers to the multitude of managerial questions on this topic. A literature search for research on old or large-diameter tree mortality in fire-dependent U.S. forests yielded 41 studies on the topic (Table 5). A cursory review of the table shows how limited the research is on relating post-fire tree mortality to first order fire injuries, pre-fire fuel loading, and bark beetle attacks. Many of these studies had primary objectives other than overstory tree mortality; however, Table 5 makes clear the need for long-term studies that document pre-fire forest and fuel conditions, fire and silvicultural treatments, and post-fire effects.

Research provides managers with statistically tested, peer-reviewed results. In the absence of applicable research, the expertise of experienced managers is often the best resource for deciding what treatments work on the local level. As these managers retire or change positions, local monitoring programs become even more important for determining appropriate treatment actions. Monitoring programs help bridge the gap between scientific research, local experience, and operational land management programs, especially where little to no applicable research exists for a given topic or region.

Abundant room exists for more research on limiting overstory tree mortality from prescribed fire in long-unburned forests. Research topics include but are not limited to the following:

- Define the relationship of time-temperature profiles of soil heating to actual root mortality.
- Characterize deep duff moisture-of-extinction limits for all fire-dependent forests.
- Determine the feasibility and parameters of reducing only a portion of deep basal duff layers during prescribed burns in the western United States.
- Determine critical microsite characteristics and parameters that affect basal duff consumption and potential cambium injury for fire-dependent species and overstory size classes.
- Determine if season of raking or timing of raking to prescribed burning affects tree mortality.
- Correlate level of cambium injury to insect attack level.
- Determine the horizontal and vertical distribution and abundance of fine roots adjacent to the tree bole for a variety of sites and species.
- Conduct long-term studies on the effects of fire on old trees and other ecosystem components.

Climate Change

Restoring fire to fire-adapted ecosystems is important even in the face of climate change. Expert consensus suggests that fire frequency will increase as temperatures rise. Therefore, improving ecosystem resilience to fire makes sense. Restoration efforts that increase forests' resistance to wildfire, insects, pathogens, and invasive species will also increase resilience to these stresses under a changing climate (Fulé 2008).

The future effects of climate change on fire-adapted forests are certainly open to conjecture. Tree mortality across the western United States has increased over the past 50 years, likely due to increased temperatures and subsequent drought stress associated with climate change (van Mantgem and others 2009). However, fire and other disturbances have shaped these forests for millennia. Forests that more closely resemble historical reference conditions seem most likely to survive increased fire intensities and frequencies (Fulé 2008). Therefore, carefully restoring fire to long-unburned forests that historically burned frequently will reduce accumulated fuel and duff, retain old trees, and perpetuate these fire-dependent forests.

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Appendix A: Determining Duff Moisture

Duff moisture is probably the most important predictor of duff consumption; therefore, knowing duff moisture before prescribed burning helps determine if conditions are right to meet objectives. Tracking duff moisture levels prior to burning and then monitoring duff consumption after the burn allows for better prediction of future burn outcomes. Unfortunately, obtaining duff moisture is not nearly as straightforward as measuring other fuel components. Duff moisture meters for estimating volumetric duff moisture exist; however, currently there is no accurate way to immediately estimate gravimetric duff moisture in the field.

Gravimetric Versus Volumetric Moisture Content

Gravimetric moisture content is the mass of water per unit mass of dry soil. This is most frequently used by the fire management community because it is the easiest, most direct measurement of moisture content. Woody fuel moistures are always reported as gravimetric moisture content. The calculation is as follows:

$$duff\ moisture\ content_{gravimetric} = \frac{weight_{wet\ sample} - weight_{dry\ sample}}{weight_{dry\ sample}} \times 100 \qquad \text{(eq. 1)}$$

Volumetric moisture content is the volume of water per unit volume of soil. Bulk density of the sample must be calculated to determine volumetric water content. Bulk density of the duff sample is calculated as follows:

$$bulk\ density = \frac{weight_{dry\ sample}}{volume_{sample}} \qquad \text{(eq. 2)}$$

Moisture probes and meters calculate only volumetric moisture content. Gravimetric moisture content can be calculated from volumetric moisture content and bulk density using the following equation:

$$duff\ moisture\ content_{gravimetric} = \frac{duff\ moisture\ content_{volumetric}}{bulk\ density_{sample}} \qquad \text{(eq. 3)}$$

Sampling location and collection

It is important to sample duff near the base of large trees where heavy fuel has accumulated and tree mortality is a concern. In deep duff, collect the sample from the lower portion of the profile, being careful to not include mineral soil. A large handful of material is sufficient. For oven-drying, place the sample into an airtight container for transport to drying and weighing facilities. Duff samples taken to determine bulk density should also be collected at the base of large trees. For bulk density samples, measure duff depth around a sampling frame and then collect all duff within the frame. Volume is calculated from the dimensions of the frame and duff depth.

Duff moisture meter

The duff moisture meter (DMM600) is a portable, battery-powered device that gives an immediate reading of volumetric duff moisture content (Robichaud and others 2004). The DMM600 consists of a cylinder that houses the electronics, sample chamber with a compression knob, and LCD readout (Figure 36). To measure duff water content, place the sample in the sample chamber and turn the compression knob until an audible indicator signals the sample is properly

Figure 36. Duff moisture meter (DMM600).

compressed and the measurement is complete. Total time for measurement is about 30 seconds. Readings are displayed in real-time only; measurements are not stored. The included sieve fits in the opening of the sample chamber and helps to break up large fragments and improve measurement accuracy in duff materials with a large range of fragment sizes. The meter's standard calibration converts the output of the measurement circuit to volumetric water content. This factory-supplied calibration is derived from laboratory measurements of duff moisture content from four forest cover types: Douglas-fir, western larch, lodgepole pine, and Engelmann spruce/subalpine fir. User-derived calibrations are possible using the included PCDMM software. If gravimetric moisture content is desired, the bulk density of several duff samples should be calculated first (eq. 2). Using the average bulk density, gravimetric moisture content can easily be calculated in the field from the duff moisture meter readings (eq. 3) (Robichaud and others 2004). A duff moisture meter costs $1,950.

Advantages: quick; easy; determines moisture in field

Disadvantages: gives volumetric moisture content; more expensive than oven-drying; requires calculation of bulk density to determine gravimetric moisture content

Oven-drying

Oven-drying duff samples provides the most accurate measurement of gravimetric moisture content. Weigh sampled duff before drying to determine the weight of the wet sample. Place duff samples in paper bags or in other permeable, oven-safe containers and dry samples for at least 24 hours, or until weight stabilizes in a 212 ^{o}F (100 ^{o}C) oven. Weigh oven-dried sample and calculate gravimetric moisture content using equation 1. Norum and Miller (1984) provide more detailed instructions for collecting, drying, and weighing fuel to determine moisture content. Basic drying ovens cost around $400 and balances are around $200. Ovens stuffed full will not completely dry in 24 hours.

Advantages: most accurate measurement; gives gravimetric moisture content

Disadvantages: slow—requires 1 to 2 days to calculate; sample is invalid if any precipitation has occurred between sampling and the prescribed burn

Moisture probes

Time domain reflectometry (TDR) moisture probes give an immediate reading of volumetric moisture content. There are several different designs based on either two or three probes that are inserted into the duff to provide a moisture reading. These probes were originally designed to estimate soil moisture. They do not work well in non-homogenous, low bulk density materials such as duff (Ferguson and others 2002; Robichaud and others 2004). Ferguson and others (2002) used moisture probes to generate a moisture index of prescribed burn units prior to burning. They cautioned that moisture probes should be inserted with minor disturbance, remain in place, and be calibrated once installed when determining moisture in organic soils. Calibration requires repeated sampling of a known volume of duff, then drying and weighing the samples to calculate volumetric moisture content. This setup is more appropriate for research burns when detailed moisture trends and values are needed. Miyanishi and Johnson (2002) used a simpler setup of a three-pronged moisture probe connected to a portable, battery-powered meter (Delta-T Devices, Ltd. Cambridge, U.K.) to determine multiple duff moisture readings in a unit prior to burning. However, no calibrations using oven-dried samples were made to determine accuracy of this sampling method. Moisture probes are not recommended to estimate duff moisture for typical field use because they are extremely dependent on contact along probe length and it is hard to achieve consistent readings.

Large scale indices

The National Fire Danger Rating System (NFDRS) (Deeming and others 1977) and the Keetch-Byram Drought Index (KBDI) (Keetch and Byram 1968) are tools to predict fire intensity and fuel availability on a large scale. The NFDRS is a risk rating of fire potential throughout the United States. NFDRS areas are typically greater than 100,000 acres (40,468 hectares) using weather observations from one time during the day at one location. The system was designed for low-resolution, medium-to-large scale applications (Bradshaw and others 1984). KBDI uses measures of evapotranspiration and precipitation to estimate cumulative moisture deficiency in deep duff or upper soil layers that relates to the flammability of organic material in the ground. The purpose of the drought index is to provide managers with a continuous scale of reference for estimating deep-drying conditions in areas where such information may be useful in fire planning and preparedness levels (Keetch and Byram 1968). Some duff consumption studies have related the NFDRS 1000-hour fuel moisture estimate to duff consumption (Brown and others 1985; Sandberg 1980). While these rating systems provide valuable information about fire potential, general trends, and long-term drought, they are not appropriate to predict localized duff mound moisture and consumption.

Appendix B: Survey respondents

John K. Agar	Wenatchee National Forest, WA
James K. Agee	University of Washington, WA
Andy Aldrich	Stanislaus National Forest, CA
James Bennington	Camp Grafton Training Center-Army, ND
Bernie Bornong	Bighorn National Forest, WY
Tim Brickell	Gallatin National Forest, MT
Beth Buchanan	National Forests in North Carolina, NC
Larry Burd	Sequoia National Forest, CA
Jason Butler	Boise National Forest, ID
Kelly Cagle	Uwharrie National Forest, NC
Carol Carlock	Humboldt-Toiyabe National Forest, NV
Jonathan L. Casebeer	Department of Military Affairs, IL
Gerald Chonka	Gunnison National Forest, CO
Chris Church	Boise National Forest, ID
J. Allison Cochran	National Forests in Alabama, AL
Blaine Cook	Black Hills National Forest, SD
Diane Cote	Manti-La Sal National Forest, UT
Scott Dailey	Tahoe National Forest, CA
Dennis Divoky	Glacier National Park, MT
Gabe Dumm	Umpqua National Forest, OR
Rich Fairbanks	California Nevada Region, The Wilderness Society, CA
Calvin Farris	National Park Service, Klamath Network, OR
Roger D. Fryar	Ozark-St. Francis National Forest, AR
Peter Fulé	Northern Arizona University, AZ
Bill Gabbert	Sagacity Wildfire Services LLC, SD
Allen Gallamore	Colorado State Forest Service, CO
Sarah Gallup	Colorado State University, CO
Todd Gardiner	San Juan National Forest, CO
Bruce Greco	Coconino National Forest, AZ
Steve Hanna	Sequoia and Sierra National Forest, CA
Joseph Harris	Red Lake Department of Natural Resources, Forestry, MN
Hylton Haynes	MTC - Fort Pickett, VA
Reed Heckly	Umatilla National Forest, OR
Jennifer Hensel	Lassen National Forest, CA
Dan Huisjen	BLM, Montrose Interagency Fire, CO
Theresa Jain	U.S Forest Service, Rocky Mountain Research Station, ID
Jason Jerman	Idaho Panhandle National Forest, ID
Dale Johnson	BLM and Inyo National Forest, CA
Kim M. Johnson	Bitterroot National Forest, MT
Mike Johnson	Wallowa-Whitman National Forest, OR
Jeffrey Kane	Humboldt State University, CA
Tobin Kelley	U.S Forest Service, Rocky Mountain Research Station, MT
Alan Kelso	Cibola National Forest, NM
Eric E. Knapp	U.S. Forest Service, Pacific Southwest Research Station, CA
Thomas E. Kolb	Northern Arizona University, AZ
Mike Landram	U.S. Forest Service, Region 5, CA
George M. Libercajt	Fremont-Winema National Forest, OR
W. Scott MacDonald	Mt. Hood National Forest, OR
Steve Martin	Lewis and Clark National Forest, MT
Rob Martinez	Helena National Forest, MT

Bob Means	Wyoming BLM, WY
Anne Mileck	Modoc National Forest, CA
Lauren B. Miller	Wasatch-Cache and Uinta National Forests, UT
Dave Mills	Kaibab National Forest, AZ
Paul S. Minow	Rio Grande National Forest, CO
Steve Mooney	Fremont-Winema National Forest, OR
Caroline Noble	National Park Service, Southeast Region, GA
Shilow T. Norton	Apache-Sitgreaves National Forest, AZ
Tonja Opperman	Bitterroot National Forest, MT
Kara Paintner	Fire Management Program Center and Natural Resource Program Center, National Park Service, CO
Ed Paul	Prescott National Forest, AZ
Todd Pechota	Black Hills National Forest, SD
Stephen Pietroburgo	Little Pend Oreille National Wildlife Refuge, WA
Alicia Reiner	U.S. Forest Service, Enterprise team, CA
Michele Richards	Fort Custer Training Center, MI
Peter R. Robichaud	U.S Forest Service, Rocky Mountain Research Station, ID
Kevin Ryan	U.S Forest Service, Rocky Mountain Research Station, MT
Kristen Sanders	BLM, ID
Richard Taplin	Ponderosa State Park, ID
B. Walker Thornton	Coconino National Forest, AZ
Meg Trebon	Okanogan and Wenatchee National Forests, WA
Eric Trimble	Colville National Forest, WA
Jamie Tripp-Kahler	Flathead National Forest, MT
Russ Truman	Kaibab National Forest, AZ
Phillip van Mantgem	U.S. Geological Survey, Sequoia and Kings Canyon Field Station, CA
Morgan Varner	Humboldt State University, CA
Scott Wagner	San Juan National Forest, CO
Jon Warder	Bighorn National Forest, WY
Gary A. Weber	U.S Forest Service, Coeur d'Alene Dispatch Center, ID
Scott Weyenberg	Mississippi National River and Recreation Area, MN
Andrew White	San Isabel National Forest, CO

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