# Fire Ecology of Ponderosa Pine and the Rebuilding of Fire-Resilient Ponderosa Pine Ecosystems [1]

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## Abstract

The ponderosa pine ecosystems of the West have change dramatically since Euro-American settlement 140 years ago due to past land uses and the curtailment of natural fire. Today, ponderosa pine forests contain over abundance of fuel, and stand densities have increased from a range of 49-124 trees $ha^{-1}$ (20-50 trees $acre^{-1}$) to a range of 1235-2470 trees $ha^{-1}$ (500 to 1000 stems $acre^{-1}$). As a result, long-term tree, stand, and landscape health has been compromised and stand and landscape conditions now promote large, uncharacteristic wildfires. Reversing this trend is paramount. Improving the fire-resiliency of ponderosa pine forests requires understanding the connection between fire behavior and severity and forest structure and fuels. Restoration treatments (thinning, prescribed fire, mowing and other mechanical treatments) that reduce surface, ladder, and crown fuels can reduce fire severity and the potential for high-intensity crown fires. Understanding the historical role of fire in shaping ponderosa pine ecosystems is important for designing restoration treatments. Without intelligent, ecosystem-based restoration treatments in the near term, forest health and wildfire conditions will continue to deteriorate in the long term and the situation is not likely to rectify itself.

## Introduction

Historically, ponderosa pine ecosystems have had an intimate and inseparable relationship with fire. No other disturbance has had such a re-occurring influence on the development and maintenance of ponderosa pine ecosystems. Historically this relationship with fire varied somewhat across the range of ponderosa pine, and it varied temporally in concert with changes in climate.

Over the last century this relationship has undergone an increasing amount of strain. Although wildfires continue to burn in ponderosa pine ecosystems, recent wildfires tend to be more intense and lethal, and consume large expanses of ponderosa pine forests. There is an impending need to better understand the role of fire and techniques land managers can use to emulate fire to restore fire-resiliency. I define fire-resiliency simply as the ability of ponderosa pine forests to survive wildfires relatively intact, as typically occurred during presettlement times.

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This paper discusses the ecological role of fire in ponderosa pine ecosystems, changes in forest structure and fire behavior over the past century, and strategies for rebuilding fire-resilience in ponderosa pine ecosystems in western North America.

## Adaptations and Morphological Characteristics Affecting Fire Resistance and Survival

Various adaptations allow vegetation to survive fire. Adaptations can either facilitate survival of species (e.g., fire-stimulated flowering, refractory seed buried in soils, etc) or individuals (e.g. thick bark, basal sprouting, etc) (Kauffman 1990). Ponderosa pine is considered one the most fire resistant conifers in the west, and fire resistance increases as the tree matures (Miller 2000). Ponderosa pine is well suited to survive low-intensity surface fires primarily due to its bark characteristics. Ponderosa pine develops a protective outer corky bark (0.3-0.6 cm) early in life when saplings reach a basal diameter of 5 cm allowing some young trees to survive very light-intensity surface fires (Figure 1a) (Hall 1980). Mature ponderosa pine trees possess thick, exfoliating bark (Figure 1b), which slough off when the bark is on fire. Presumably, this helps “take away” heat as flaming bark flecks flake off, thus reducing or preventing heat transfer and minimizing injury to cambial cells; however, this mechanism has not been well researched. Ponderosa pine bark on mature trees continues to flake off with or without fire, and over long time periods without fire a thick mulch layer of bark develops at the base of trees. When ignited, this mulch smolders for days, conveying heat directly to and through the bark to the cambial layer, often killing or severely stressing the tree. Bark beetles may then attack and kill weakened trees. Historically, frequent low-intensity surface fires prevented this bark mulch layer from accumulating around mature trees.

Ponderosa pine also has a deep rooting habit compared to other western conifer species (e.g., true firs, Engelmann spruce, and lodgepole pine). Although a surface fire may heat the soil and kill some surface roots, deeper roots remain intact and allow for continued uptake of water and nutrients. The amount and moisture content of surface fuels (needles and branches, saplings and herbaceous plant material) along with larger woody debris (downed logs) beneath or in contact with the tree affects the degree of injury to surface roots.

Ponderosa pine crown structure, branching pattern, and needle and bud characteristics also affect survival during fire. The open crown structure and branching pattern of ponderosa pine allows for better mixing of air and dissipation of heat within stands during a fire, thus reducing the potential for crown scorch. The open crown structure may also dampen fire-spread through tree crowns in less extreme fire conditions (Flint 1925, Agee 1993). Ponderosa pine has long needles with high moisture content that surround terminal buds. Although needles may be scorched and killed by heat, they help protect meristematic tissue within the bud, allowing branch tips to refoliate. Buds of ponderosa pine have thick outer scales that also help protect meristematic tissue from heat (Miller 2000).

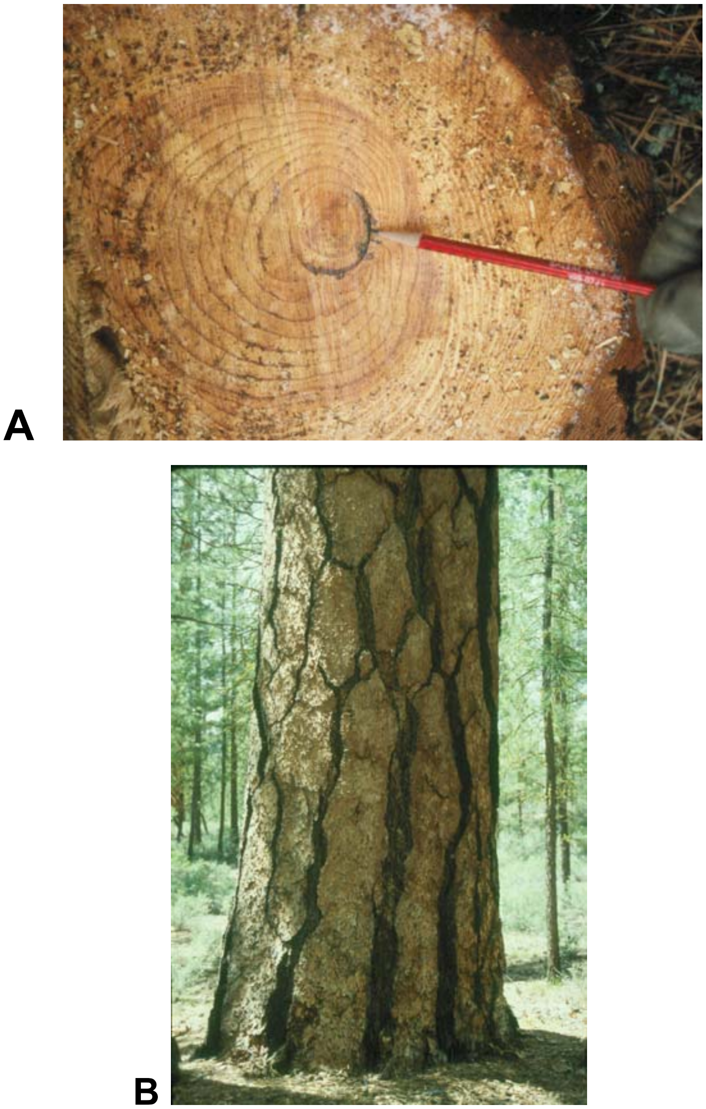

**Figure 1**—(A) This young ponderosa pine survived a light-intensity surface fire when the basal diameter was about 3-4 cm. Note that the cambium on approximately half the circumference was killed. The sapling recovered and greatly accelerated its diameter growth probably as a result of less competition and a flush of nutrients following the fire. (B)Typical fire-resistant bark of an old-growth ponderosa pine showing the platy bark surface.

Another factor reportedly affecting fire resistance is ponderosa pine's ability to self-prune (gradual shedding of lower branches) (Flint 1925, Starker 1934, Miller 2000), resulting in the clear bole that often characterizes large-diameter old-growth ponderosa pine. Presumably, this mechanism lifts the lower crown over time and prevents surface fires from moving up into the tree's canopy. However, there is no evidence that ponderosa pine self-prunes on its own. The clear boles are a result of either repeated surface fires, which scorch and kill lower branches when trees are young and lower branches have small diameters, and/or death of lower branches from competition (shading) from neighboring trees. In both cases, dead branches are shed and remaining stubs are grown over after decades or centuries of tree growth. Evidence that counters the notion of self-pruning is demonstrated by open-grown ponderosa pine in areas where fires were naturally excluded, such as in rocky areas where fuels are too scarce to carry fire. Often these trees have branches that are large, heavy, and located on the lower portions of the bole showing no propensity for self-pruning.

## Fire Regimes in Ponderosa Pine Ecosystems

Fire regimes are influenced greatly by climate, vegetation types and by topographic and geologic features that either facilitate or restrict fire spread (Agee 1993, Camp and others1997, Taylor and Skinner 1998). Fire regimes are characterized by their frequency, intensity, severity, extent, and seasonality and have a great influence on vegetative recovery, plant succession, and forest and ecosystem structure (Agee 1993).

### *Frequency*

Fire frequency, or the mean fire return interval, is a measure of how often fire returns, on average, to an area. There may be a wide range around this mean, which has important ecological implications for stand development and forest structure (Baker and Ehle 2001). The median fire return interval is also used to characterize fire return intervals in forest ecosystems.

Within ponderosa pine ecosystems, fire returned approximately every 2-47 years. This estimate of fire frequency is based on several studies that date fire scars on individual trees (point sample) or from several fire-scarred trees in an area (composite fire interval) (Table 1). The wide range in fire frequency is a reflection of current and past regional climate, plant association, aspect and slope, elevation, aboriginal burning and other factors. In the Front Range of Colorado, for example, ponderosa pine forests were subject to frequent surface fires at lower elevations, much like other ponderosa pine forests in the west. At higher elevations (2400 m), where ponderosa pine is mixed with Douglas-fir and lodgepole pine (more moist conditions), fires were less frequent and were a combination of both surface and stand-replacing fire (Veblen and others 2000). In western Montana, Arno and others (1997) observed the same change in fire frequency from pure ponderosa pine stands to more mesic mixed stands of ponderosa pine and western larch. Other studies have shown a link between regional climate patterns, such as periods of wet and dry (drought) conditions and fire occurrence (Swetnam 1988, Touchman and others 1996, Veblen and others 2000, Grissino-Mayer and others 2004, Wright and Agee 2004).

Lightning is thought to have been the primary source of presettlement fire ignitions. Some geographic areas are more prone to lightning than others due to prevailing summer weather patterns and topography. The zone that extends from northwest California up through Oregon, northern Idaho and northwest Montana, known as "lightning alley," is a prime example of the relationship between lightning ignitions and fire frequency in ponderosa pine forests (Figure 2).

Aboriginal burning also affected fire occurrence in localized areas. Barrett and Arno (1982) compared presettlement fire intervals in forests known to have had heavy use by Native Americans and compared that to fire intervals on similar sites but in more remote areas. Fire intervals were twice as frequent in heavy use areas (MFI of approximately 5-6 years in heavy-use areas versus 12.5 years in remote areas for two sites). However, Indian-caused burning may have been much more wide spread, as documented by early explorer and pioneer writings, particularly after Native Americans acquired horses in the early 1700s (Barrett 1980, Barrett and Arno 1982).

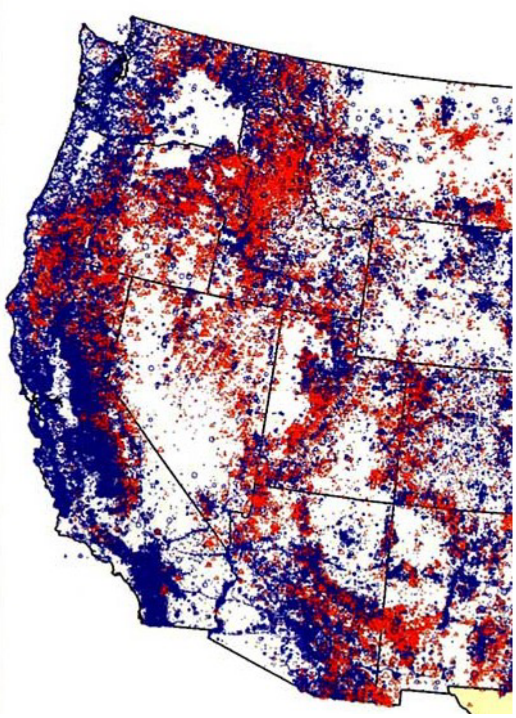

**Figure 2** — Lightning occurrence in the western United States (from Schmidt and others 2002). Note the concentration of lightning from northern California extending northeast through Oregon, Idaho, and northwest Montana.

## *Intensity and Severity*

Fire intensity and severity are often used interchangeably, but fire scientist distinguish between them. Fire intensity is a measure of heat or energy released (kW) per unit length (m) along the fireline, and can be estimated by measuring flame length as the flaming front passes a known point (Rothermal and Deeming 1980). Fire severity is determined by either a visual estimate or measured assessment of fire effects on soils and vegetation. High intensity fires (e.g., long flame lengths), for example, result in more consumption and charring of surface fuel, increased exposure of soil and alteration of soil properties, and more damage and mortality of trees and other vegetation.

Historically, ponderosa pine ecosystems were predominantly subjected to frequent, low-intensity fire (Agee 1993). These periodic fires would consume accumulated fuels, thin young seedlings and saplings, and consume shrubs and herbaceous plant material, leaving the large, fire-resistant trees intact. Some individual large trees or small groups of large trees may have been directly killed or stressed by fire and later attacked and kill by bark beetles (Munger 1917).

On more moist sites where ponderosa pine is seral (on Douglas-fir, dry and wet Grand fir series), fire intensity was often greater and resulted in a more mixed-severity fire regime composed of a combination of underburning (light intensity) and patch stand-replacement (high intensity) fire (Agee 1993, Arno and others 1995, Arno and others 1997, Veblen and others 2000, Baker and Ehle 2001, Wright and Agee 2004). In the ponderosa pine forests of the Black Hills of South Dakota, fires were of higher intensity and more of mixed-severity (Brown and Sieg 1996, Shinneman and Baker 1997), most likely because of longer fire intervals and abundant regeneration that establishes between successive fires.

## *Extent*

The perimeter and extent of presettlement fires is often difficult to ascertain because fires of very low intensity may not scar trees, or subsequent fires may destroy fire scars in catfaces or kill and consume fire-scarred trees (Agee 1993). The extent of presettlement fires was highly variable and often associated with changes in inter-annual weather patterns (Norman and Taylor 2003). In central Washington, Wright and Agee (2004) found that most fires were small (< 1000 ha (2470 ac)) and that large fires (> 4000 ha (9880ac)) occurred every 27 years and were associated with annual periods of drought (Palmer Drought Severity Index and winter Southern Oscillation Index (El Nino)). In northern California, Taylor and Skinner (1998) found that average burn area was 350 ha, but documented 16 fires between 1627 and 1992 that were larger than 500 ha. In southwest Colorado, Grissino-Mayer and others (2004) found that historic fires in the lower elevation ponderosa pine stands were small and quite localized but at higher elevations, where ponderosa pine is mixed with other species, fires were less common but larger in size. In central Colorado and in the Southwest there is an association between large fires and periods of wet years that increase dry matter production (fuel), followed by dry spring and summer months (Swetnam and Baisan 1996, Touchan and others 1996, Veblen and others 2000, Donnegan and others 2001, Norman and Taylor 2003, Grissino-Mayer and others 2004). Norman and Taylor (2003) found that extensive burning of 1000s of hectare took place approximately every 20 years in northeastern California.

***Table 1*** – Fire return intervals by region and plant series for climax and seral ponderosa pine (adapted from Agee (1994) and Baker and Ehle (2001)).

| Geographic Region | Mean Fire Return Interval | Median Fire Return Interval | Composite (C) or Point (P) Sample | Plant Series | Study |
|---|---|---|---|---|---|
| Central Washington (E. Cascades) | 18.8 | 15.5 | C | Douglas-fir | Wright and Agee (2004) |
| | 20.6 | 17.4 | C | Grand fir (dry) | Wright and Agee (2004) |
| | 7 | 6.7 | C | Douglas-fir | Everett and others (2000) |
| | 7-11 | -- | C | Douglas-fir | Wischonfske and Anderson (1983) |
| | 23.9 | 20.6 | C | Grand fir (wet) | Wright and Agee (2004) |
| Northeast Washington | 10-24 | -- | P | Douglas-fir | Finch (1984) |
| Northern Rocky Mountains: | | | | | |
| Western Montana | 6-11 | -- | P | Ponderosa pine | Arno (1976) |
| | 7-19 | -- | P | Douglas-fir | Arno (1976) |
| South Dakota (Black Hills) | 20-23 | -- | C | Ponderosa pine | Brown and Sieg (1996) |
| | 10-12 | -- | C | Ponderosa pine | Brown and Sieg (1999) |
| Central Oregon (E. Cascades) | 16-38 | -- | C | Ponderosa pine (dry) | Bork (1985) |
| | 7-20 | -- | C | Ponderosa pine (mesic) | Bork (1985) |
| | 9-25 | -- | C | White fir | Bork (1985) |
| North-central Oregon (E. Cascades) | 11-16 | -- | P | Ponderosa pine | Weaver (1959) |
| | 3-36 | -- | P | Ponderosa pine | Soeriaatmadja (1966) |
| Northeast Oregon (Blue Mts.) | 10-43 | 20 | C | Ponderosa pine | Heyerdahl and others (2001) |
| | 10 | | P | Douglas-fir | Hall (1976) |
| | 12-53 | 5-15 | C | Douglas-fir | Heyerdahl and others (2001) |
| | 47 | -- | P | White fir | Weaver (1959) |
| | 13-71 | 15 | C | White fir | Heyerdahl and others (2001) |
| South-central Oregon (Cascades) | 9-42 | -- | C | White fir | McNeil and Zobel (1980) |

***Table 1*** -- continued

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Northern California (S. Klamath Mts.) | 11.5 | | -- | | C | Ponderosa & limber pine | Taylor and Skinner (2003) |
| | 13.0 | | -- | | | Douglas-fir | Taylor and Skinner (2003) |
| | 13.0 | | | | | Douglas-fir/white fir | Taylor and Skinner (2003) |
| | 12.5 | | -- | | | Douglas-fir/ponderosa pine/incense-cedar | Taylor and Skinner (2003) |
| | | | | C | | | |
| | 13.5 | -- | | C | | Douglas-fir &limber pine | Taylor and Skinner (2003) |
| Northern California (N. Klamath Mts.) | 12.0-15.5 | | -- | C | C | Douglas-fir | Taylor and Skinner (1998) |
| Northern California (S.Cascades Mts.) | 21.4 | -- | 12.0 | C | C | Ponderosa pine | Norman and Taylor (2003) |
| Central California (Westside Sierras) | 9-18 | | -- | | | White fir | Kilgore and Taylor (1979) |
| | | | | C | | | |
| Central Rocky Mountains: | | | | | | | |
| San Juan Mts. | 6-13 | | 5-9 | | | Ponderosa pine | Grissino-Mayer and others (2004) |
| | 19-30 | | 19-29 | | C | Mixed conifer | Grissino-Mayer and others (2004) |
| Northern Front Range | 8.3-22.4 | | 6.4-11.6[1] | C | C | Ponderosa pine | Veblen and others (2000) |
| | 17.2-18.6 | | 8.1-10.4[1] | | C | Douglas-fir | Veblen and others (2000) |
| Southern Rocky Mountains: | | | | | | | |
| North-central Arizona | 3.7 | | | | C | Ponderosa pine | Fulé and others (1997) |
| | 7.4 | | | | C | Ponderosa pine | Fulé and others (2003) |
| | 8.7 | | | | C | Mixed conifer | Fulé and others (2003) |
| Arizona | 4-12 | 4 | | | | Ponderosa pine | Weaver 1951 |
| Arizona | 1.8 | 6 | | | | Ponderosa pine | Dieterich 1980 |
| Southwest New Mexico | 5-8 | 5 | -- | | | Ponderosa pine | Swetnam and Dieterich (1985) |
| | | -- | | P | | | |
| | | -- | | C | | | |
| | | | | C | | | |

[1] Weibull median probability interval

## Seasonality

Fire in ponderosa pine systems varies somewhat by season and geographic region within the species range as a result of regional weather patterns. Seasonality of presettlement fires can be determined using dendrochronology techniques that examine the position of each fire scar relative to ring development, such as during earlywood and latewood development or after the cessation of latewood growth (Baisan and Swetnam 1990). In north-central Washington, Wright and Agee (2004) found that 80 percent of presettlement fires occurred late in the growing season (during late-wood formation) or in early fall (after cambial dormancy) for seral ponderosa pine growing on Douglas-fir, dry grand fir, and wet grand fir plant association groups (PAGs). Heyerdahl and others (2001) found that in the southern Blue Mountains a higher proportion (26 percent) of fires occurred during earlywood and latewood formation, while on more mesic sites in the northern Blue Mountains most fires occurred after cessation of ring growth. In northern California, 93 percent of fires occurred during the dry midsummer through early fall period (Taylor and Skinner 2003). In a study in southwestern ponderosa pine where season could be determined, Fulé and others (1997) found that approximately 40 percent of the presettlement fires occurred in spring (late April to June) and 60 percent in the summer (July to early September). There appears to be a north-south gradient of seasonality within the Medeterranean Climate zone of southwestern Oregon (Klamath Mountains) to the southern Sierra Nevada in California. Fire scars are mostly (>90%) at the ring boundary in the Klamath Mountains, indicating mostly late-summer/early-fall fires. In the southern Sierra Nevada, fire scars are mostly (>80%) within the rings, indicating many early- to mid-summer fires (Skinner 2002)

## Historic Forest Structure

Presettlement ponderosa pine forests throughout its range were typified by open, park-like stands of large-diameter trees with few seedlings and saplings in the understory (Langille and others 1903, Munger 1917, Weaver 1943, Morrow 1985, Arno 1988, Fulé and others 1997, Youngblood and others 2004, Moore and others 2004). Stands were typically uneven-aged, with many stands containing a few large individual trees 400 to 600 years old (Munger 1917, Morrow 1985, Arno and others 1995, Youngblood and others 2004). Historic photos depict the open character of old-growth ponderosa pine on the Klamath Indian Reservation in south-central Oregon (Figure 3). Other turn-of-the-century photos depict similar forest conditions, although historic photos locations are not randomly located. In addition, the understory plant community may have also been influenced by livestock grazing not readily apparent in most historic photos. Many rangelands and adjacent ponderosa pine forests were heavily grazed during settlement from the late 1860s through the early 1900s (Hessburg and Agee 2003).

**Figure 3** -- Harold Weaver standing in an open park-like stand of old-growtth ponderosa pine on the Klamath Indian Reservation in south central Oregon in the 1930s. Note the open understory. (BIA photo)

In an early survey of ponderosa pine forests in Oregon, Munger (1917) found ponderosa pine forests contained approximately 30-99 (12-40 per acre) large-diameter (> 30.5 cm (12 in) DBH) trees per hectare across several sites (Table 2). In both a climax ponderosa pine site in central Oregon and a ponderosa pine-dominated mixed conifer (dry) site in northeast Oregon very few seedlings and saplings are present (Figures 4a,b), and both stands have a relatively low stand density index (SDI) (Reineke 1933) compared to ponderosa pine stands today. Even on the more productive mixed conifer site, there are few seedlings and saplings of ponderosa pine and "other" species, which are likely grand fir and Douglas-fir. Because of frequent fire, presettlement ponderosa pine stands probably had low levels of snags and large woody debris (Skinner 2002). The following quote taken from Munger (1917, page 17) sums up his observations on the historic character of ponderosa pine forests:

> *"In most of the pure yellow-pine forests of the State the trees are spaced rather widely, the ground is fairly free from underbrush and debris, and travel through them on foot or horseback is interrupted only by occasional patches of saplings and fallen trees."*

***Table 2*** **--** Historic trees per hectare of trees greater than 30.5 cm DBH for several sites in Oregon (from Munger 1917).

| **Location** | **Hectares Surveyed** | **Trees per Hectare >30.5 cm** |
|---|---|---|
| Looking Glass Creek | 109 | 99 |
| Austin & Whitney | 638 | 77 |
| Winlock | 49 | 42 |
| Embody | 74 | 79 |
| LaPine | 99 | 30 |
| Klamath Lake | 393 | 86 |

Other reconstructive studies have shown similar low stand densities in presettlement ponderosa pine forests across its range (Weaver 1943, Cooper 1961, Morrow 1985, Habeck 1985 (cited in Arno 1988), Taylor and Skinner 2003, Youngblood and others 2004).

The stems of trees within ponderosa pine stands also show a distinct spatial pattern. Historically, many old-growth pine stands had a groupy-patchy stem pattern (Munger 1917, Weaver 1943, Cooper 1961, Biswell and others 1973, Habeck 1985 (cited in Arno 1988), Morrison 1985, Arno and others 1995, Kaufmann and others 2001,Youngblood and others 2004). For example, Youngblood and others (2004) examined the spatial stem pattern of mature trees in old-growth ponderosa pine stands in central Oregon and northern California and found that trees on 24 out of 27 large plots were moderately to strongly grouped (Figure 5), most likely the result of past fire, insect, and regeneration patterns. The open and groupy nature of old-growth ponderosa pine forests affords additional fire resistance because the canopy is broken up by gaps between groups of different sizes and ages of trees, leaving the overall stand less vulnerable to crown fire.

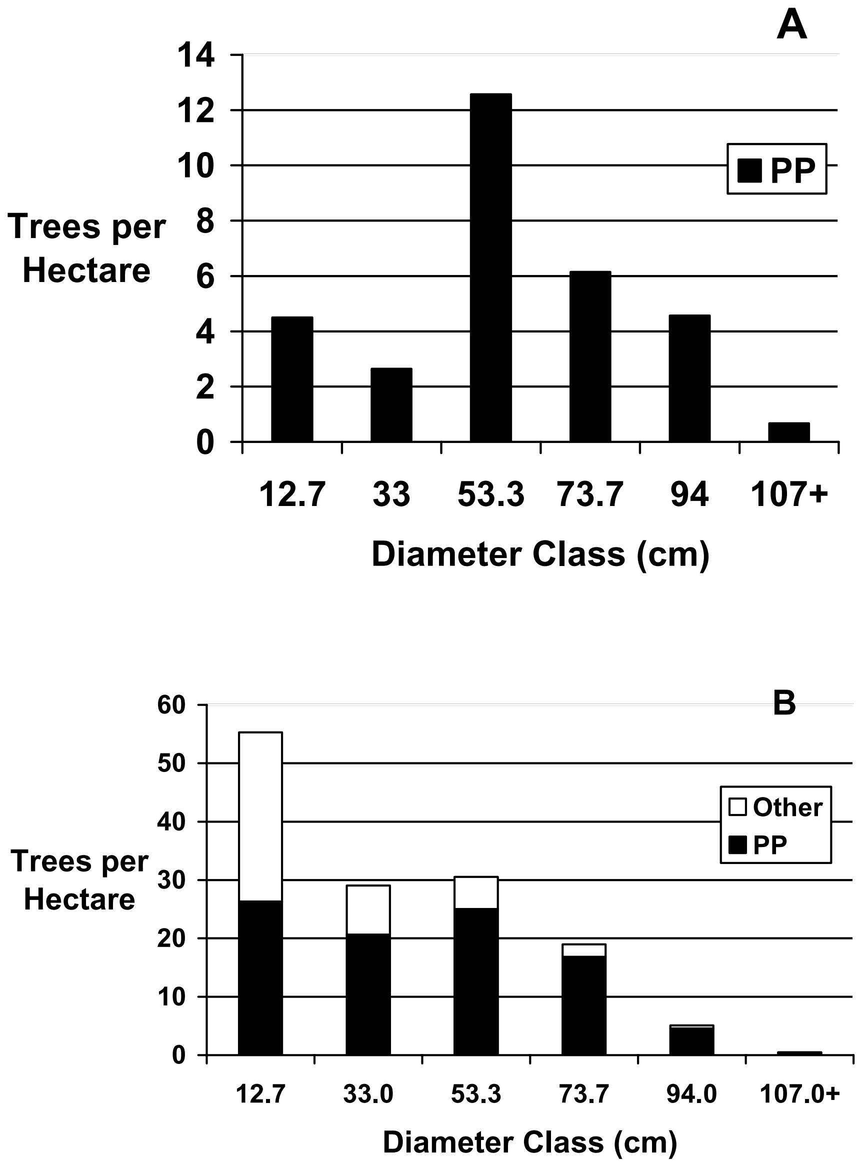

**Figure 4** – (A)Trees per acre by diameter class on a climax ponderosa pine site in central Oregon and (B) on a ponderosa pine-dominated mixed-conifer site in northeastern Oregon (from Munger 1917).

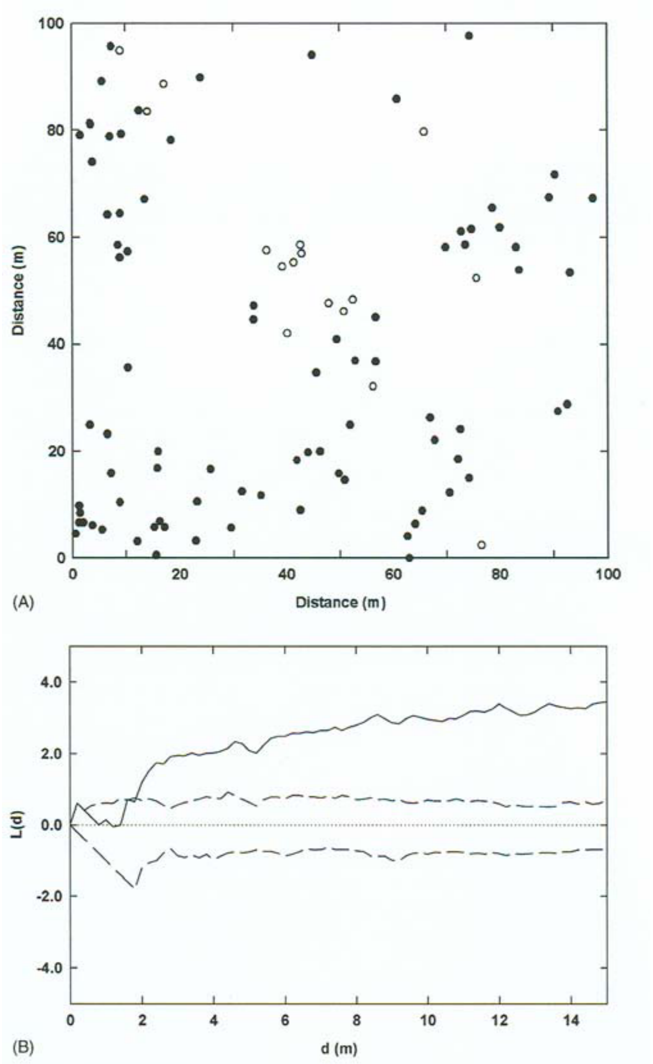

**Figure 5** – (A) Spatial pattern of large (•) and dead (o) trees in the upper canopy of old growth plot 23 at Metolius study area and (B) the results of Ripley's *K(d)* analysis on these 99 trees, with empirical cumulative distribution of *L(d)* shown as a solid line, the expected random distribution as a dotted line with mean equal to zero, and point-wise 95% confidence envelop around the expected distribution of complete spatial randomness shown by dashed lines (from Youngblood and others 2004).

## *Changes in Forest Structure, Fuels and Fire Regime*

Ponderosa pine forests have undergone great ecological change in the last 140 years since settlement (Hessburg and Agee 2003), and not for the better from a fire and forest health perspective. Heavy grazing in the late 1800s and early 1900s, active fire suppression after 1910, and other land uses have disrupted the natural fire regime in ponderosa pine ecosystems. This has allowed succession to proceed unchecked resulting in above-normal fuel accumulations and abundant tree regeneration. In addition, early selective logging removed the large, fire-resistant ponderosa pine, western larch, and Douglas-fir, creating openings that favor the development of shade-tolerant Douglas-fir and true firs in the understory and mid-canopy layers (ladder fuels) on more mesic sites.

These past land use activities have produced cascading ecological effects that are manifested today in altered ecological processes (Weatherspoon 1996, Keane and others 2002). Forest stand structure has changed from open park-like stands dominated by large, fire-resistant trees to over-dense even-aged stands (Weaver 1943, Covington and Moore 1994, Moore and others 2004) that are more susceptible to crown fire (Weatherspoon and others 1992, Skinner and Chang 1996), and contain trees that are less likely to survive fire because of their smaller diameter, thinner bark and low hanging crowns (Agee 2002). In ponderosa pine stands in the southwest, forest density increased from 148 trees (65 ponderosa pine and 80 oaks) per hectare in 1883 to 1265 trees per hectare in 1995 (Fulé and others 1997). Similar changes in stand density have been documented in the northwest and elsewhere (Weaver 1943, 1959, Morrison 1985, Arno 1988, Agee 1993, Adams 1995, Weatherspoon 1996, Taylor and Skinner 2003, Youngblood and others 2004). In some cases these changes in succession and stand density have been documented from long-term study plots and time-series photography (Smith and Arno 1999).

Recent coarse-scale assessments have documented changes in the potential fire regime from frequent, low-intensity fires confined mostly to the understory to more lethal high-intensity fires that have the potential to consume entire stands across large landscapes (Figure 6) (Quigley and others 1996, Schmidt and others 2002). On more mesic sites, forest composition has changed from stands dominated by ponderosa pine and western larch to those dominated by Douglas-fir and true firs both of which are more susceptible to insects, disease, and drought (Filip 2002).

Remaining old-growth ponderosa pine forests are in jeopardy as well, due to elevated risk to insect attack, some diseases, and stand-replacement fire (Harrington and Sackett 1992, Weatherspoon 1996, Fitzgerald and others 2000, Keane and others 2002, Moore and others 2004). Management action is needed in these stands to maintain this important structure on the landscape for wildlife that depend on mature, old-growth forest conditions and for human benefits. Because many ponderosa pine forests lie adjacent or in close proximity to the wildland-urban interface, homes and communities are increasingly at risk from high intensity wildfires starting in and spilling over from dense, fire-prone forest conditions. Without efforts to restore ponderosa pine forests to some semblance of natural forest conditions, large intense wildfires will continue, producing detrimental ecological effects and continued deterioration of forest and watershed health (Wickman 1992, Mutch and others 1993).

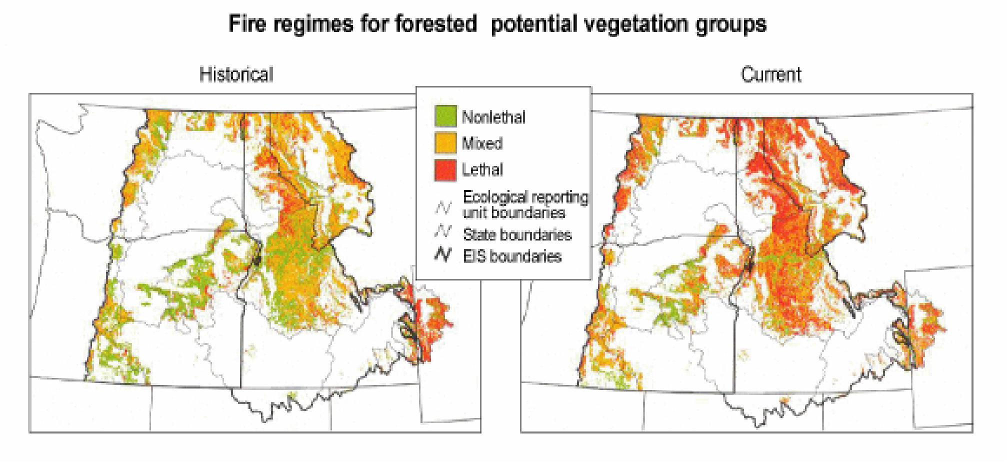

**Figure 6** – Historic and current fire regime for the Inland Northwest (from Quigley and others 1996). The increase darker grey areas indicate a change to more lethal fire regimes across the region under current conditions.

## Rebuilding Fire Resilient Ponderosa Pine Ecosystems

### *Fire Behavior and Forest Structure*

Fire behavior is affected by the interaction of fuel, weather, and topography, known as the fire behavior triangle (Figure 7). Aspects of fire behavior that managers are primarily interested in include how fast a fire moves (rate of spread), how hot it burns (intensity), torching of tree crowns (passive crown fire), crowning (active crown fire), firewhirls, and spotting. Spotting occurs when fire brands (glowing embers) are lofted up and out ahead of the main fire front, igniting spot fires that then feed back into the main fire front, creating very extreme (and dangerous) fire conditions. A change in any one of these three main factors during the course of combustion will influence a fire's behavior. For example, a surface fire will move (spread) faster upslope because flames are tilted toward the slope and more efficiently dry and preheat fuels in front of the fire. Other topographic features such as saddles and draws affect wind patterns by funneling air and intensifying fire behavior. Weather, too, is a dominant factor in fire behavior. A change in weather from hot and dry to cooler and more moist conditions will reduce fire intensity and rate of spread. Often firefighters have to wait for a change to cooler and wetter weather before they can safely attack a wildfire head on. We have no control over topography and weather, but fire managers often take advantage of favorable weather conditions or topographic features to attack and suppress wildfires.

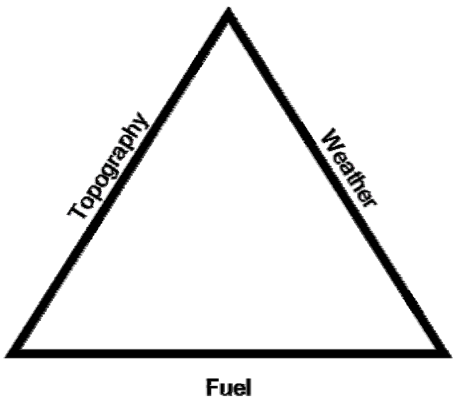

**Figure 7** – The fire behavior triangle.

Fuel comprises the third leg of the fire behavior triangle. How much fuel (fuel loading in tons per hectare), and its vertical (within stands) and horizontal (across landscapes) arrangement affects fire intensity and the ability of surface flames to begin torching tree crowns or support active crown fire for a given set of weather and topographic conditions. Fuels can be comprised of dead biomass (needles, fallen branches, dried herbaceous material, and coarse woody debris) or of live trees and other vegetation, such as shrubs. Some shrubs, such as bitterbrush, contain volatile oils and have higher heat content and, because of their air-to-volume ratio, produce long flame lengths when ignited, initiating torching. Torching is the movement of surface flames up into individual tree crowns or into the crowns of tree groups. Torching is the precursor to active crown fire.

Fire exclusion over the last century in ponderosa pine forests has allowed fuels to build up on the forest floor (surface fuels) and shrub cover and tree regeneration to increase. This buildup has created “fuel ladders” where surface fuels are now connected to the overstory canopy by dense understory and mid-story saplings and medium-sized trees, making it easier for surface fires to move up and torch tree crowns and, under the right weather conditions and topographic setting, support active crown-to-crown fire spread. Crown fuels are comprised of needles, twigs, and small branches. Crown fuels are quantified by *crown bulk density*, which is the weight of needles, twigs, and small branches in kilograms per cubic meter of crown volume. Dense, even-aged ponderosa pine stands with crown bulk densities above 0.10 kg/m$^3$ are more vulnerable to active crown fire because fire can easily spread from tree crown to tree crown under weather and topographic conditions conducive to crown fire initiation and spread (Graham and others 1999, Agee and others 2000, Graham and others 2004).

In short, the structure of the forest and the fuels contained within have a major influence on fire behavior and severity (Agee and others 2000, Graham and others 2004, Peterson and others 2005). The amount and arrangement of fuel is the only element in the fire behavior triangle that managers have some influence over, and it is this concept that drives all fire control efforts from direct fire suppression tactics to proactive or pre-fire fuel reduction treatments.

## Treatments to Reduce Fire Intensity and Severity

Keeping wildfire on the surface is important for reducing fire intensity and excessive damage to vegetation and watersheds. Factors that affect a surface fire's transition to a crown fire include foliage moisture content, surface flame length, and height to the base of the canopy (Agee 1993, Agee and others 2000). Moisture content of foliage at the beginning of the summer can be as high as 300 percent in new foliage, but declines to less than 100 percent as the summer progresses and is more easily ignited by surface flames (Agee and others 2002). In years of drought, foliage moisture content declines earlier in the season. We have no influence over foliage moisture.

Surface flame lengths depend on the amount, energy content, and moisture content of surface fuels. Removing accumulated surface fuels, or targeting the removal of specific fuels such as bitterbrush because of its high energy content, reduces flame lengths making it more difficult to initiate torching of tree crowns. In addition, the higher the base of tree crowns, the more difficult it is for surface flames to combust and torch tree crowns.

Once a fire begins torching and moving up into the canopy, the rate of spread (a function of wind speed) and crown bulk density determine the likelihood for development of an actively moving crown fire. Increasing the space between tree crowns reduces the opportunity for fire to spread from tree crown to tree crown, and allows a crown fire to transition back to a surface fire.

Following the principles of Agee (2002) (Table 3), four actions will improve fire-resilience in ponderosa pine ecosystems: reducing surface fuels, removing ladder fuels, leaving large, fire resistant trees, and spacing tree crowns (in that order). These conditions can be achieved with a variety of methods including prescribed burning, mowing, pruning and thinning.

## Prescribed Burning

Prescribed burning is used in ponderosa pine stands to remove accumulated surface fuels, consume slash generated from thinning activities, kill and thin out encroaching trees in the understory, and rejuvenate herbaceous plants and shrubs (Ffolliott and others 1977, Sackett 1980, Walstad and others 1990). Prescribed burning also scorches and kills lower branches of trees, which, in the long run, results in lifting the canopy much like pruning, increasing the height from the forest floor to the lower canopy and increasing fire resistance. Periodic burning can prevent the development of ladder fuels and can be used as to maintain stands in a fire-resilient condition over time.

However, in most ponderosa pine stands prescribed burning is limited as a first-entry fuels treatment because of heavy accumulations of surface and ladder fuels. In most cases, other mechanical treatments are needed prior to prescribe burning in order to reduce fuels to a level that prescribed burning can be used in subsequent treatments without undue damage to the residual stand. Preparatory treatments, such as mowing, pruning, and thinning, improve fire control and safety, reduce the risk of escape, reduce damage to residual trees, and significantly reduce the level of smoke production and effects on air quality and human health in nearby communities.

## *Mowing and Mechanical Fuel Reduction*

Mowing involves using a 4-wheel drive tractor or a tracked-vehicle outfitted with a mowing head. The operator essentially mows the understory shrubs and small trees (< 7 cm (3 in) diameter) reverting back to a grass-dominated understory. Mowing cuts and grinds up surface fuels and the smaller ladder fuels to small particle sizes, which decay rapidly when in contact with the forest floor. This mechanical treatment is limited to gentle topography and has been implemented on the Deschutes National Forests near wildland-urban interface areas. Mowing costs are approximately $40 per acre. Stands to be underburned can be first treated with mowing to reduce surface fuels and improve fire safety and control. Because many shrubs species resprout, mowing is a short-term fuel reduction treatment.

There are several other mechanical methods for reducing shrubs and small trees. These include various kinds of excavators outfitted with a rotating head mounted on a hydraulic arm. The operator moves the head back and forth along the ground to mulch up shrubs or smaller trees (saplings). On larger trees (10 to 20 cm dbh (4 to 8 inches)) the tree can be ground up by mulching from the top of the tree down to the base. These treatments can cost up to $350 to $400 per acre, depending on terrain and density of shrubs and small trees. However, they cut and mulch all in one pass, thus eliminating subsequent costs for piling and burning slash often associated with manual hand cutting.

## *Pruning*

Pruning removes the lower branches of trees and lifts the crown, creating more distance between potential surface flames and the bottom of the tree canopy. Pruned branches need to be piled and burn. This technique is particularly useful in young stands where crowns are low and close to surface fuels (grass/shrubs).

## *Thinning*

Thinning can be used to change stand and fuel characteristics (e.g., ladder and crown fuels) and lessen the chance of passive and active crown fires (Graham and others 1999, Scott 1998, Agee and others 2000, Fulé and others 2001, Graham and others 2004, Peterson and others 2005). Thinning from below, also referred to as low thinning, removes trees in the subordinate lower crown classes (Figures 8 and 9) leaving the larger, more vigorous trees. Thinning from below removes ladder fuels, reduces canopy bulk density, and leaves trees that have higher crowns, thicker bark, and better ability to survive fire. In mixed conifer stands, thinning should leave the most fire resistant species, such as ponderosa pine, western larch, and Douglas-fir. Thinning can be done incrementally such that the stand is progressively opened up over time or, if fire risk is high, thinning more heavily to a wider spacing in one operation. The latter situation would be appropriate for ponderosa pine stands adjacent to the wildland-urban interface and where the risk of wind throw is low.

Following thinning, the amount of remaining surface fuel should be assessed (Weatherspoon 1996). Where excessive slash is found to exist, slash must be removed either by piling and burning or with prescribed underburning to prevent high-severity surface fire (Brown 1980). Wildfire in thinned stands and in stands thinned in combination with other fuel treatments experience reduced fire intensity, lower rates of spread, less severe tree damage and lower overall fire severity

(Graham 2003). However, thinning also opens up the stand and changes the microclimate, allowing surface fuels to dry out more completely and within-stand wind speeds to increase (Weatherspoon 1996). These changes can increase both the rate of spread and intensity of subsequent surface fires. However, the increased intensity and spread rates are why the original forests had frequent fires. Thinning in this manner creates stands similar to pre-settlement conditions. Thus, the reduction in fire hazard with thinning generally more than makes up for potential increases in fire spread and intensity. This also makes fire suppression, when deemed necessary, more efficient. Thus, if heavy fuels are removed, the residence time (or duration) of the fire is reduced, often resulting in a non-lethal surface fire.

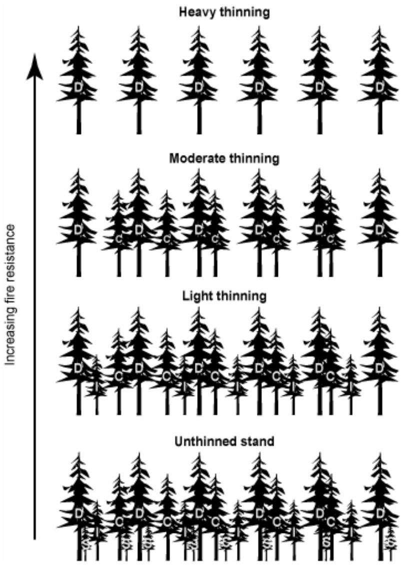

**Figure 8** – Thinning to improve fire resistance. Thinning from below removes smaller trees in the stand leaving the larger, more fire resistant trees (adapted from Graham 1999).

**Figure 9** – A 90-year old ponderosa pine stand thinned from below on the Sun Pass State Forest, Oregon. Note the more open canopy and high crowns. The fire resistance in this stand has been significantly improved.

Thinning from below can also benefit large, old-growth ponderosa pine trees in stands that have developed a dense understory and are under increasing competitive pressure. Thinning from below not only reduces ladder fuels and the risk of torching, but by reducing stand density tree vigor is improved and risk to bark beetle attacked reduced (Figure 10) (Fitzgerald and others 2000, Latham and Tappeiner 2002, McDowell and others 2003). Because the extent of old-growth ponderosa pine forests is limited across western North America, thinning from below to restore and maintain existing old-growth forests can better insure their survival over the long term, until other areas develop old-growth conditions and serve as replacement old-growth habitat in the future.

**Figure 10** -- This old-growth ponderosa pine stand was thinned from below and later underburned to reduce competition and restore a more historic stand structure.

Thinning ponderosa pine stands (from below) to improve fire resistance typically involves removing non-commercial trees (<23 cm dbh (9 in)) and trees containing small to medium-size sawlogs (25-46 cm dbh (10-18 in)). In most cases the value and volume removed in small to medium-size sawlogs is not enough to cover all the costs of removing non-commercial trees and to conduct follow up treatments. Net costs to treat stands have ranged from $247 to $1976 per ha ($100 to $800 per acre). Thus, subsidies are needed to accomplish fuel treatments at the landscape level. However, some thinning treatments can show a modest profit, depending on stand conditions, thinning diameter, basal area limits, and markets (Scott 1998, Barbour and others 2004, Larson and Mirth 2004). This profit could then be used to offset costs in stands that do not produce any net revenues, thus increasing the overall acreage treated. Although there is resistance to paying for these treatments on federal lands through Congressional appropriations, improving fire-resilience in ponderosa pine ecosystems through subsidies is far less expensive than the cost of wildfire suppression that can approach $7410 per ha ($3000 per acre), not to mention the loss in timber value, cost of watershed rehabilitation, the risk and loss of homes, and the loss of ecosystem values and services (Butry and others 2001, Fairbanks and others 2002, Morton and others 2003, Lynch 2004, Mason and others 2004).

***Table 3*** -- Principles for creating fire-resilient forests (after Agee 2002).

| **Principle** | **Effect** | **Advantage** | **Concerns** |
|---|---|---|---|
| Reduce surface fuels | Reduce potential flame length | Less torching, control easier | Surface disturbances, less with fire than with mechanical techniques |
| Increase height to live crown | Requires longer flame length to begin torching | Less torching, control easier | Opens up understory, may allow surface winds to increase |
| Decrease crown density | Makes tree-to-tree crown fire less probable | Reduces crown fire potential, control easier | Surface wind may increase and surface fuels may be drier |
| Keep larger trees | Thicker bark and higher crowns | Increase the survivability of trees | Removing smaller trees is less economically profitable |

## Summary

Over the last 140 years ponderosa pine ecosystems have changed immensely and bear little resemblance to their presettlement condition. The original old-growth ponderosa pine forests were once considered an endless resource to early pioneers and settlers, and the vast “yellow pine” forests were utilized to fuel economic growth and the development of western North America. Past and current land use activities along with active fire suppression eliminated natural surface fires from these forests and the disturbance patterns that controlled their development and helped sustained them over the millennia.

This elimination of fire has profoundly changed the structure of the original ponderosa pine forests, and not for the better. Today, ponderosa pine forests contain an overabundance of fuel, high stand densities across large landscapes and few old growth trees. These conditions have contributed to declining tree health and have helped sustain increases in large, uncharacteristic wildfires across the west. The ponderosa pine ecosystems are in trouble, and the problem will not go away or take care of itself. In the Pacific Northwest timber stand improvement activities, such as thinning, are down 60 percent compared to over a decade ago (FY 1988), and the level of funding for silvicultural treatments has declined over the last decade, resulting in a huge backlog of forest requiring some level of treatment (Powell and others 2001). However, doing nothing will result in forests that continue to deteriorate over time because wildfire today no longer operates in its historical fashion, that of frequent low-intensity surface fires.

Restoration treatments should return ponderosa pine forests to within their natural range of variation for both stand and landscape structure where possible. Ongoing research to determine reference stand conditions (density, tree size, tree pattern, gaps, etc) should establish conditions across broader landscapes, which would provide a “blueprint” for restoration activities (Covington and Moore 1994, Fulé and others 1997). Restoration also needs to re-introduce processes, like fire, to maintain stands and promote the sustainable development of younger ponderosa pine stands.

Craig and others (2002) outline in detail 16 principles to consider for the restoration of southwestern ponderosa pine. These same principles could be adapted and applied to most ponderosa pine forests of western North America. The first of these principles, and probably the most important in the near term, "reduce the threat of crown fire," is needed to *first* stop the cycle of uncharacteristic wildfires to prevent loosing critical forest structures, important wildlife habitat, and genetic reservoirs, like old-growth. Treatments that move stands closer to conditions of pre-European settlement (Table 3) are likely to reduce the chance of crown fires and improve fire-resiliency. Treatments to reduce fire intensity and severity have been shown to work (Agee and others 2000, Graham 2003, Martinson and Omi 2003, Graham and others 2004). To make a real difference at the landscape level, however, will require a suite of treatments (prescribed fire, thinning, and combinations) that are prioritized. In addition, long-term Congressional investments will be needed to treat the millions of acres of ponderosa pine forests on federal lands in need of restoration (U.S. General Accounting Office 1999).

Finally, without intelligent, science-based intervention in the near term to restore fire-resiliency, we cannot expect ponderosa pine forests of western North America to continue to produce all the ecological and social values that the public desires in the long term.

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