Using Fire as a Management Tool in Southwestern Ponderosa Pine[1]

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Abstract.—Fire suppression and livestock grazing over the last century are responsible for current forest conditions of extensive stand stagnation, uncommonly high fuel accumulation, and general low productivity. From research on fire effects, knowledge is now available for using fire to reduce fuel hazards, thin dense thickets, and provide sites for ponderosa pine (*Pinus ponderosa* Laws.) establishment.

CHANGING CHARACTERISTICS OF SOUTHWESTERN PONDEROSA PINE FORESTS

The ponderosa pine *(Pinus ponderosa* Laws.) forests of the Southwest have gone through extensive structural and compositional changes in the last century. Numerous references document the open, park-like appearance of historic ponderosa pine stands (Biswell et a1.1973, Brown and Davis 1973, Cooper 1960), where herbaceous vegetation was vigorous and abundant. Fires were a regular feature of these forests, burning the light surface fuels at intervals usually averaging less than 10 years and as often as every 2 years (Dieterich 1980, Weaver 1951). The frequency of these fires resulted from the continuity of grass and pine needle fuels, the high incidence of lightning, and the warm, dry weather common to the Southwest. Light surface fuels built up sufficiently with the rapid resprouting of grasses and the annual pine needle cast. Large, woody fuels, which fall infrequently, rarely accumulated over extensive areas. When single or small groups of trees fell, they were generally consumed by subsequent fires, creating a mineral soil seedbed and reducing grass competition in microsites, favoring ponderosa pine seedling establishment (Cooper 1960). These circumstances created an uneven-aged stand structure composed of small, relatively even-aged groups.

Change began in the southwestern ponderosa pine forests during extensive livestock grazing in the late 19th century (Faulk 1970). As grazing intensified herbaceous vegetation could not respond, and its coverage declined drastically. This decline led to two subsequent changes: reduced fire spread because of the decrease in fine fuels, and an eventual increase in ponderosa pine regeneration because of reduced competition and fire mortality, and more mineral seedbeds (Cooper 1960). Beginning in the early 1900's, forestry practices, including fire control, further reduced the spread of inevitable fires, leading to unprecedented fuel accumulations and stagnation of seedling and sapling thickets.

These human-induced changes have resulted in ponderosa pine forests that have little similarity to the presettlement forests. In the uncut or lightly harvested stands, old-growth trees still stand. The open structure is gone, however, as dense sapling thickets and small pole groups have developed in the understory. Stand stagnation has been reported on many sites (Cooper 1960, Schubert 1974), and persists where natural or artificial thinning has not taken place In addition to stand changes, 75 to 100 years of general fire absence has also led to uncharacteristically large accumulations of surface and ground fuels (Kallander 1969).

Sackett (1979) reported average loadings of naturally created fuels at 22 tons per acre (range 8-48 tons per acre) for 62 southwestern ponderosa pine stands. Harrington (1982) verified the heavy fuel loadings, with an average of 34 tons per acre in southeastern Arizona. Another formerly uncommon feature is the abundance of large, woody fuels, averaging about 8 tons per acre. Much of these down, woody fuels have accumulated in sapling thickets, creating an even more severe hazard. A final characteristic of current southwestern ponderosa pine stands is the sparse understory vegetation, created from thick forest floor layers and dense pine canopies, that resulted from fire suppression (Arnold 1950).

The changes that have taken place primarily within the last century have created several undesirable conditions in the ponderosa pine forests of the Southwest. The extreme fuel hazard is probably most apparent. The combination of heavy forest floor fuel loadings and dense sapling thickets coupled with the normally dry climate and frequent lightning and human-caused ignition

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potential result in a severe wildfire threat (Biswell et al. 1973, Harrington 1982). Additionally, trees of all sizes have generally poor vigor and reduced growth rates (Cooper 1960, Weaver 1951). This condition is likely due to the reduced availability of soil moisture caused by intense competition and by moisture retention in the thick forest floor (Clary and Ffolliott 1969). The thick forest floor also indicates that soil nutrients, especially nitrogen, may be limiting because they are bound in unavailable forms (Covington and Sackett 1984).

In the past, pine regeneration generally developed in openings in the stand after fire had produced a receptive seedbed. Now, long after tree mortality and the creation of openings, a poor quality, organic seedbed remains, allowing little opportunity for establishment of pine seedlings. Also, forage production for wildlife and livestock is commonly minimal, because of severe competition with trees and the physical effect of the deep forest floor (Biswell 1972, Clary et al. 1968).

Ponderosa pine is also found with several other conifers in the higher elevation mixed-conifer forests. Fire occurred less frequently in these more mesic forests. A 22-year average interval was found in northeastern Arizona (Dieterich 1983), but its impact was still important for site preparation, species selection, disease and insect distribution, and nutrient cycling (Jones 1974). Little documentation of fire effects and burning prescriptions is available for southwestern mixed-conifer forests, therefore, this subject will not be addressed here.

This paper addresses the use of prescribed fire in southwestern ponderosa pine forests. From research and observations, recommendations are made to apply fire to reduce fuel hazards, thin dense sapling thickets, and provide conditions for natural regeneration in natural forest stands.

SOUTHWESTERN PONDEROSA PINE FUELS

The deteriorating and hazardous forest conditions described above have contributed to numerous severe wildfires in Arizona and New Mexico. Several examples include the 1951 Escudilla Mountain Fire (19,000 acres) and Gila Black Ridge Fire (40,000 acres), the 1956 Duddly Lake Fire (21,000 acres), the 1971 Carrizo Fire (57,000 acres), and the 1977 La Mesa Fire (15,000 acres) (Biswell et al. 1973, Cooper 1960, USDA 1977). The need to alleviate the hazards was recognized years ago, but widespread use of fire under specified conditions to create designated results has been adopted slowly. Reasons for this reluctance include a shortage of guidelines for prescription burning and insufficient information on fire effects.

Fire Effects on Fuels

The use of prescribed fire has increased in recent years. Some of the earliest, extensive prescribed burning took place on the Fort Apache Indian Reservation in Arizona with about 3,000 acres burned in the late 1940's (Kallander 1969). From 1950 to 1970, over 300,000 acres were burned, primarily for hazardous fuel reduction. The effectiveness of this burning program in reducing size and severity of subsequent wildfires has been documented (Biswell et al. 1973, Knorr 1963). This burning operation used the cool, dry conditions encountered in late fall to moderate fire behavior for initial fuel reduction burns. Burning was not to begin until after November 1, but dry litter and duff layers were preferred (Kallander 1969). These fires were strategically ignited, then allowed to burn, unattended, over vast acreages. In a series of three burns in 1950, this procedure was used to burn portions of 65,000 acres (Weaver 1952). Forest floor fuel loadings were reduced by 55% and dead woody fuels were reduced by 64% to 80%. Emphasis was placed on the consumption of thousands of snags and windfalls, which greatly lessened the fire hazard. The effect of this burning operation was evident the following year by a dramatic reduction in the number of wildfires and in the acreage burned (Weaver 1952).

In a well documented study in 1950, six small plots were burned under two sets of fuel moisture and weather conditions to determine fuel consumption and tree responses (Gaines et al. 1958). A low intensity burn was set at the end of September, and a high intensity burn was set in early October with higher air temperatures and lower fuel moistures, humidities, and winds. The September burn resulted in a 57% reduction in surface, ground, and aerial fuels. The October burn consumed more fuel, but also created new fuel by killing or damaging numerous trees. When the newly deadened fuels were added to the residual fuels, only a 15% reduction was realized.

Another large scale, fuel-reduction burn on the Fort Apache Reservation was conducted in November 1956 under cool, clear days with a moderately high drought index and low rate-of-spread index (Lindenmuth 1960). Fires were ignited at specific locations, but allowed to burn unchecked for 33 days within project boundaries. Fire effects were undocumented in fall 1957 (Lindenmuth 1962). Fuel reduction was deemed unsatisfactory because fuel consumption on 75% of the area was only minimal. In addition, a large portion. of the area that had good fuel reduction also had extensive tree mortality or injury.

In central Arizona, a small scale research burn was conducted on two distinct sites. The first had 75% more fuel by depth and weight, and 85% greater overstory basal area than the second

(Davis et al. 1968). Under similar fuel moisture and weather conditions, more fuel was consumed on the site with the most fuel. However, 2 years after the burns, the net fuel change including consumption by fire and litter accumulation demonstrated that the site with less initial fuel had a 37% reduction compared with a 23% reduction on the other site. This indicates more damage was done on the site with more fuels, resulting in greater fuel accumulation.

In a more recent study in uncut ponderosa pine in north-central Arizona, the importance of fuel moisture on consumption was seen (Sackett 1980). Two similar sites at Fort Valley and Long Valley Experimental Forests, maintained by the Rocky Mountain Forest and Range Experiment Station, were burned in fall under contrasting moisture and weather conditions. Surface litter had similar moisture on both sites, but the humus layers (lower duff) differed 10% to 15%. Since about 80% of the forest floor weight is in the ground fuels, the ground fuel moisture is most influential in total fuel consumption. Over 60% of the ground fuels and about 70% of the large woody fuels were consumed in the drier burn compared with only about 40% of both fuel groups in the wetter burn.

The importance of humus moisture was demonstrated further by a prediction equation for forest floor reduction developed from a series of summer burns in southeastern Arizona (Harrington 1987). In the equation,

$$FR = 37.4 - 0.8\ HM + 21.2\ FD \qquad (1)$$

humus moisture (HM) and preburn forest floor depth (FD) were highly correlated with percent forest floor loading (FR) reduction ($r^2 = 0.91$). Tree density also had a strong effect, with less fuel reduction occurring in denser stands.

Equation [1] clearly indicates that the percentage of forest floor (FR) consumed increases as the preburn amount (FD) increases. This result was confirmed by the results of an October 1982 initial fuel reduction burn at the Fort Valley Experimental Forest (Covington and Sackett in press). Under low humidities (15% to 24%) and moderate air temperatures (52° to 67° F), nine plots with differing stand structure were burned. Surface fuel moisture ranged from 7% to 10%, and humus moisture ranged from 12% to 20%. In stagnated sapling thickets, about 34% of their 12 ton per acre loading was consumed, 52% of the 16 tons per acre in the pole stands was consumed, and 89% of the 55 tons per acre was burned in the mature, yellow pine stands. A high, positive correlation was found between percent forest floor consumed and preburn loading ($r^2 = 0.89$).

Although there are valuable fuel hazard, nutrient, and regeneration benefits derived from the consumption of heavy forest floors, there are also liabilities. Consumption of large quantities of fuel generates large amounts of heat energy. Studies at the Fort Valley and Long Valley Experimental Forests and Sequoia Kings Canyon National Park show very high mineral soil temperatures curing burning. Lethal temperatures have been measured on many sites deeper than 12 inches into the mineral soil. More than 35% of the old-growth ponderosa pines, which survived numerous presettlement fires, have died at Fort Valley as a result of the first burns in 100 years.

Fires burning under these old-growth pines are unspectacular, consuming only the litter in the flaming front. Most of the forest floor is consumed by smoldering combustion, which may take 72 hours to complete. Burning for this length of time can result in either temperatures exceeding 140° F, which cause instant cambium or root death, or lower temperatures for longer durations, which also cause tissue death.

Fuel loadings under these old pines at Fort Valley ranged from 41 to 86 tons per acre, and consumption was always greater than 85%, regardless of humus moisture up to 90%. In 13 of 14 cases, 140° F was reached at 2 inches below the soil surface. At flinch depths, temperatures frequently exceeded 100° F for at least 6 hours, with some reaching 140° F. On a burn at the Long Valley Experimental Forest under wetter conditions, 69% of the 45.5 tons per acre of forest floor was consumed. Temperatures failed to reach 100° F at the 8-inch soil depth, but ranged from 140° to 210° F at the 2- to 4-inch depth.

Live ladder fuels, which also add to the hazard, need particular attention. These fuels can take the fire from ground level into the overstory crowns. The vertical fuel continuity can be broken by a reduction in ladder fuels. Some of the important live fuels are medium-sized shrubs which are easily top-killed by fire but generally resprout. Examples include Gambel oak *(Quercus gambelii),* silverleaf oak *(Q. hypoleucoides),* and wavy leaf oak (*Q. invaginata).* Gambel oak can be temporarily reduced by prescribed burning (Harrington 1985). Low crowns of ponderosa saplings also increase crown fire threat. Scorching the lower foliage is effective in relieving this hazard, but the burning procedure is difficult and requires experience (Harrington 1981, Kallander 1969).

Understory burning in southwestern ponderosa pine can greatly, but only temporarily, reduce the fuel hazard (Harrington 1981, Sackett 1980). Consumption of the litter layer lessens ignitability and rate-of-spread potential. As more of the duff, ladder fuels, and large logs are consumed, a reduction in potential fire intensity, total energy release, and resistance to control are realized. Truesdell (1969) reported a decrease in wildfire size up to 7 years after prescribed burning on the Fort Apache Indian Reservation and a 3-year reduction in suppression costs after burning on the Hualapai Indian Reservation. As mentioned, the fuel hazard reduction is only temporary as 0.6 to 1.8 tons per acre of needle litter can be cast annually depending on tree density and site productivity (Dais et al. 1968, Sackett 1980). Fuel often accumulates rapidly to hazardous levels after initial fuel reduction burns. As needles from scorched trees fall, the amount of surface litter can actually become greater than preburn levels. This litter increase is the result of the inevitable tree injury caused by consumption of the unnaturally great fuel quantities in dense stands. Therefore, reburns are essential to remove these fire-created fuels and generally maintain low fuel hazard, even when initial burns are effective (Harrington 1981, Sackett 1980).

Reducing Fuels with Prescribed Fire

A lot has been learned within the last 50 years about the use of fire in the Southwest. Many fire experts have developed their skills primarily through personal experience, learning from failures as well as successes. This type of knowledge is difficult to pass on to less experienced individuals. However, there is now enough documentation of research and operational burns to provide general guidance for fire prescription and effects. Unique combinations of stand, fuels, vegetation, and terrain may preclude the use of the following prescriptions and effects information. Therefore, we recommend a thorough assessment of site characteristics. A generalized set of fire prescription parameters was derived from the prescribed burns discussed earlier.

Season

In forested sites where fire has been absent for decades, the initial fuel reduction burns should be conducted in the fall or early spring when temperatures and humidities are moderate. Fall burning can begin as early as mid-September and can continue in some years into December.

Weather Parameters

The following prescription parameters are the primary variables that determine whether afire will burn successfully, hazardously, or not at all. On sites requiring reduction of natural fuels, maximum daytime air temperatures should be between 50° and 75° F. Below 50° F, moderately dry fuels (9% to 12% moisture) burn poorly and above 80° F extensive overstory crown scorching is likely. Minimum relative humidities should not drop below 20% or exceed 40%. Fuels subjected to a series of low humidity days become hazardously dry. Also, very low humidities are frequently accompanied by temperatures above 80° F. If minimum humidity exceeds 40%, light surface fuels are generally too moist to burn well. Windspeed at flame height should be between 3 and 8 miles per hour. Slope effects can compensate for lack of wind. A fire burning with little or no wind and no effective slope either will not spread well or will cause extensive crown heating, if fuels are dry. Windspeeds greater than 10 miles per hour can result in erratic fire behavior. Surface pine needles ideally should contain 5 to 12% moisture. Below 5%, ignition and rates-of-spread are too rapid, and above 12%, burning is patchy and incomplete with slow rates-of-spread.

Not all combinations within the range of temperatures, humidities, windspeeds, and fuel moisture described above are safe and effective. For example, if burning conditions are approaching the upper temperature and windspeed limits and the lower humidity and fuel moisture limits, a very intense, rapidly spreading fire will result. However, experienced burners can use the upper limits of one parameter to make up for a deficiency in another. For example, a combination which provides good burning conditions is low humidity (15% to 20%) and low temperatures (40° to 50° F). These situations do occur in late fall throughout the Southwest.

Because damp, cool fall weather often results in poor burning conditions, summer burning during the monsoon season has been studied as a successful alternative (Harrington 1981,1987). The amount of drying that follows fuel-saturating rains will determine fire behavior and fuel consumption. Using the same prescription ranges during the summer rainy season should permit successful fuel reduction burns. More attention to air temperature limits and erratic winds is needed, however.

Follow-up

Maintenance burning is necessary to keep the reccurring fuel hazard to a minimum (Davis et al. 1968, Gaines et al. 1958, Harrington 1981, and Sackett 1980). Since most of the light, fire-created fuels accumulate within 3 years of burning, we recommend a repeat burn within that period. Generally, repeat burns in light, needle fuels are easily managed. The window of burning season and ambient conditions is broader than for initial burns, with warmer, drier, windier situations being advantageous to the conduct of the burn (Harrington 1985). Air temperatures should range between 55° and 85°F, humidities from 15% to 40%, windspeeds from 5 to 12 miles per hour, and litter moisture from 5% to 10%. After the second or third burn, annual litter accumulation should return to a level relative to natural attrition. From this point, burning need only be conducted at intervals of about 7 to 10 years to maintain a low hazard.

If a reduction in sprouting shrubs is a major management goal for fuel and competition reduction, then a distinct program of repeat burning is needed. For Gambel oak management, we suggest an initial fuel reduction burn in fall followed by 2 or 3 mid-August burns, 2 years apart (Harrington 1985).

Predicting Fuel Consumption

The ability to predict fuel consumption from prescribed burning would be valuable to forest managers. If too little fuel is removed, the hazard might not be relieved; if too much fuel is consumed, then tree mortality might be excessive, and site quality might be compromised. Equation [1] has not been extensively tested, but should work reasonably well in stands with characteristics within the following ranges: preburn fuel loading = 25 to 40 tons per acre, large woody fuel loading = 3 to 15 tons per acre, and stand density = 800 to 2200 trees per acre (Harrington 1987). The estimation of fuel reduction was fairly accurate for fires reported by Sackett (1980). However, it was highly over estimated for fires reported by Davis et al. (1968) and Harrington (1985), because fuel loadings and stand densities were one-half or less of those used in the equation development.

Reducing Logging Slash

Reduction of fuels from silvicultural activities is also important for lessening the chance of severe wildfire in residual stands, especially in ecosystems where the wildfire potential is so great. However, little documentation exists concerning effective combinations of cutting methods and fire. Buck (1971) proposed burn prescription parameters and techniques that have worked well in reducing logging slash while causing acceptable tree damage.

During harvesting, generally a large amount of logging slash is added to the existing natural fuel component discussed earlier. This added slash creates an extreme hazard and leaves the fuel manager or silviculturalist with a complex condition to attempt to relieve. An informal proposal has been suggested in which a preharvest burn would be conducted under conditions described above to reduce natural fuels, followed by a postharvest burn to reduce activity-generated fuels and aid site preparation.

STAND DENSITY IN SOUTHWESTERN PONDEROSA PINE FORESTS

Besides reducing the wildfire hazard, thinning of such stands releases the residual trees, allowing faster growth (Schubert 1971). Domestic and wild animals also benefit from thinning of dense stands. Forage production is increased to a higher level by reducing the basal area in typical ponderosa stands (Clary and Ffolliott 1966, Jameson 1968).

Forest visitors find the dense thickets of reproduction uninviting. Access to the forest is often inhibited and esthetic values are reduced. These dense stands do not indicate a healthy ecosystem. Treatment measures that are silviculturally acceptable and economically sound are needed to improve the situation.

These "dog hair" thickets may be modified for various reasons in a variety of ways. Sometimes an entire thicket should be eradicated when infected by disease or insects, or when release potential is minimal. Fuel breaks are sometimes thinned to a low basal area for fire suppression. Stand density in travel influence zones is also reduced to improve visibility. Thinning as a silvicultural treatment is generally quite limited by cost, but some reduction of tree density could benefit over-dense stands on more than 4 million acres of southwestern ponderosa pine land (Schubert 1974).

Many of these stands need thinning to provide for more productive forests. Mechanical or hand thinning are probably the most common methods used, but they do not appear to be economically feasible over extensive areas. In addition, the hazard created by extensive thinning operations would encourage insect outbreaks and make fire protection even more difficult. Obviously any one treatment is not the answer. The problem must be spread over a number of methods, depending on circumstances and situations present.

Effects of Fire on Stand Density

There has been limited research on the use of fire to eliminate the fuels produced by thinning. One documented case of successfully thinning slash used high, green fuel moisture to minimize ponderosa pine mortality in Oregon (Smith et al. 1983). Even less information is available on the use of fire to accomplish thinning. Fire is not a very selective thinning tool, producing a rather unpredictable, patchy residual stand. However, most studies dealing with fire as a thinning tool have lacked a long-range process to accomplish the objective. A number of fires are required to reduce fuels, change the understory, and overcome the changes caused by fire exclusion.

Thinning by fire was a natural process in ponderosa pine before settlement. The degree of thinning is dependent on the quantity of fuel on the ground (Cooper 1961). The more dense the thicket, the more fuel, and the more intense the fire; thus resembling a self-regulating feedback mechanism governed essentially by stand density.

A number of investigators have dealt with the use of fire as a thinning tool-an emulation of the "natural" pine processes. Weaver (1947) reported on a comparative study of stand conditions in an area burned in September 1914 and an adjacent area not burned, on the Colville Indian Reservation in Washington. Thirty years after the fire, the 40-year-old, fire-thinned stand had substantially fewer stems per acre, greater height, and larger diameters than the adjacent unburned stand. The conclusion was that fire was an effective thinning tool. Tests on the Fort Apache Indian Reservation using prescribed fire as a thinning tool showed that thinning was spotty from fall fires, but the prescribed fire did a "reasonably effective and conservative job of thinning" (Weaver 1952). Gaines et al. (1958) wrote a supplement to Weaver's report providing data that more or less supported the previous observations. Their conclusions were not as optimistic because of the injury to the commercial overstory, and noted the need for additional information. Wooldridge and Weaver (1965) reporting on a prescribed fire on the Colville Indian Reservation designed to thin dense sapling stands, concluded that prescribed fire was a rough and largely unpredictable thinning tool. The fire drastically reduced the number of stems, had no significant effect on diameter growth, and caused a slight net reduction in height growth. Lindenmuth (1960) studied the effects of two prescribed fires in east-central Arizona near McNary and Maverick. The 1956 fires burned continuously for 33 days under a variety of topographic, fuel, and weather conditions. The fire released from competition 24.3% of the potential crop trees that needed releasing (a novel way of presenting thinning data). The fires also destroyed 10% of the potential crop trees and damaged an additional 7.4%. Lindenmuth concluded that these particular fires demonstrated an imperfect tool, and rightly so, since no specific thinning objective was intended, and because of the many varied conditions under which the fire burned.

In a study of prescribed fire in California ponderosa pine, Gordon (1967) minimized the benefits derived from fire. Using a limited data base (three fires), small areas, and severe burning conditions, he concluded that dense seedling and sapling groups would be completely killed by broadcast (prescribed) burning, and that fire is not a feasible tool for hazard reduction or thinning in eastside pine areas. Volumes of data were collected, but no regard was given to burning technique.

Ffolliott et al. (1977) reported an effective thinning response from an experimental prescribed fire near Flagstaff, Arizona. However, they concluded that basal area was not reduced enough for optimal growth of the residual stand. As stated before, one fire seldom corrects problems associated with 100 years of fire exclusion.

A study specifically designed to evaluate the effects of prescribed fire on thinning in ponderosa pine was conducted in western Montana (Henderson 1967). Small plots were set up on three different areas and burned under low, medium, and high fire intensity days as defined by fire-danger rating levels. Thinning success was dependent on "close supervision of the fire intensity through manipulation" (Henderson 1967, p. 57). He used backing fires on "high intensity days," but could not adjust to any other technique because of the severity of conditions. At low fire danger, weather and fuel conditions were not adequate to sustain an effective fire spread. Medium conditions allowed for adjustment of burning technique to regulate intensity. In general, high intensity fires eliminated more stems than did low intensity fires, but no prescriptions could be developed from the few tests and the inherent variability involved.

In test fires on the Apache National Forest with logging slash, after shelterwood cutting, Buck (1971) observed overstory mortality. Although the prescribed fires were not designed as a thinning tool, they did accomplish some effective thinning from below. Eighty-three percent of the losses were in suppressed and intermediate trees. Most experiments in thinning with fire have had their emphasis in the ponderosa pine type primarily because of the large acreages that have not burned for so long, resulting in stand stagnation.

In some recent prescribed fires in Arizona designed to reduce fuel hazards, thinning was also an important benefit. In three distinct fires in the Santa Catalina Mountains, Harrington (1981) reported tree density reductions in the small or suppressed classes of 24%, 56%, and 43% in stands with preburn densities of about 2000 trees per acre. Percent tree reduction was positively correlated with amount of fuel reduction indicating that, with more research, degree of thinning could possibly be predicted.

Two other initial fuel reduction fires netted similar results. At the Fort Valley Experimental Forest, initial prescribed fires designed to reduce natural fuels (Sackett 1980) reduced the number of stagnated reproduction and sapling stems from an average of 1553 to 912 per acre. Small poles, many of which are also stagnated in thickets, were reduced from 192 to 156 stems per acre. In a companion study at the Long Valley Experimental Forest, fewer intense fires occurred due to a wet summer preceding the fall burn. An average of only 180 stems per acre was killed by the fire in the reproduction/sapling size classes. Virtually none of the small poles were killed outright.

No known studies and reports deal specifically with the problem of developing and using definitive burning techniques for thinning. Most references deal with a single fire as an answer to the problem. From experiences at the Fort Valley and Long Valley Experimental Forests, southwestern Colorado, and southern Arizona, quality of fuel rather than quantity, as Cooper (1961) suggested, appears to be more essential for producing high intensity fires in dense stands.

Work in surface fuel characteristics and experience with many prescribed fires indicate that only the newly cast needles (L layer) and upper portion of the fermentation layer (F) actually burn as flaming combustion in heavy, old forest floor accumulations. The lower F layer is matted and bound tightly together by mycelium hyphae. As a result, the lower portion of the F layer acts more like a solid piece of fuel rather than as individual particles as in the L layer, and does not burn well.

In an undisturbed, well-developed forest floor, newly cast needles become rapidly colonized and bound by mycelium and therefore less burnable. When fire spreads over the forest floor, most of the fungi are destroyed. Needles that fall after a fire do not become readily infected and a much deeper layer of pure litter accumulates. When fire is applied a second time, all material cast since the initial fire is consumed (for up to at least 4 years accumulation). Fire intensity, rate-of-spread, and flame length are much higher in response to the greatly increased available fuel. Hence, repeat burning in higher quality and quantity fuel does a better job of thinning stagnated stands.

Crown scorch and consumption kills trees and thins stands more effectively than bole girdling. Many of the stagnated sapling stands arose from the famous

1918 seed crop and subsequent regeneration. Although the trees have grown little in diameter, tree height and bark thickness have progressed normally through the past 70 years. The unusually thick bark prevents heat of low intensity fires from penetrating enough to kill trees. Subsequent burns in deep litter result in high intensity fires which cause extensive crown damage yet do not damage the bole.

Thinning Stands with Prescribed Fire

Manipulating the Fire

The most critical element in the use of fire as a thinning tool is the burner's ability to manipulate the fire or the fire environment or both to achieve slow-dissipating, high temperature air in the crowns. Manipulation of each fire can be achieved in a number of ways. Adjusting the direction of fire spread relative to wind direction is the most common technique. Heading or uphill fires move at a speed commensurate with windspeed creating longer flame lengths, greater speed, and higher intensities. Backing fires, moving against the wind (or down hill), progress very slowly with short flame lengths and low intensities. Back fires seldom thin stands.

Using ignition techniques that interact with one another is probably the most effective way to thin stands. For example, a head fire and a back fire coming together create a vertical heat rise that is slow to dissipate and concentrates the heat in the crowns. The same effect can be accomplished by lighting a spot fire in the center of a thicket followed by a ring fire around the thicket. This technique generally eliminates the center, but leaves the outer ring of trees. Merging flank fires have the same effect as a head and back fire coming together. Junction zones created by spot fires joining will have a similar effect, yet spread the high heat concentrations around and not in a continuous path as with the other situations mentioned (Sackett 1968).

Season

Burning during different times of the year can be used to take advantage of various phenological and physiological conditions of the trees to modify their susceptibility to fire damage. Spring and summer may be superior to the traditional fall season for thinning with fire (Harrington 1987). We still recommend initial burning in fall. Repeat or rotational burns can be made at other times of the year.

Ambient Conditions

Taking advantage of ambient conditions on any given burn day is another way of manipulating the fire environment. Death of pine needles occurs when temperatures are sustained above 125° F (Hare 1961). When air temperatures are already high, needle and bud temperatures do not have to be raised much by the fire to kill plant tissue. Likewise with low humidities and drier fuels, less energy is required to evaporate moisture and therefore is more available to heat the crowns.

Thinning ponderosa pine stands with prescribed fire is an art that takes skillful manipulation of the fire environment and the fire itself. Conditions are so diverse, spatially and temporally, that the burner must skillfully prescribe the proper treatment for each thinning situation.

NATURAL REGENERATION IN SOUTHWESTERN PONDEROSA PINE FORESTS

Ponderosa pine is considered a difficult species to regenerate in the Southwest primarily because regular periods of moisture stress are caused by droughts and competition from grasses early in the growing season (Larson and Schubert 1969a, Pearson 1950). Numerous papers point out the difficulties encountered with planting, seeding, and natural regeneration (Heidmann et al. 1982, Larson and Schubert 1969b, Rietveld and Heidmann 1974). Prescribed burning is valuable for increasing the probability of obtaining natural regeneration, especially on the silty, volcanic soils of northern Arizona.

Schubert (1974) listed the optimum conditions for obtaining adequate natural regeneration:

1. A large supply of good seed.
2. A well-prepared seedbed.
3. Little or no competition from other vegetation.
4. A low population of seedeating insects.
5. Sufficient moisture for early seed germination and seedling growth.
6. Protection from browsing animals and insect pests.

Certain of the conditions are unmanageable (precipitation, seed crops), others are partially manageable (seed eaters, insects), and a few can be managed to improve regeneration success (quality seedbeds, competing vegetation). Soil moisture seems to be the most critical factor in seedling establishment. Therefore, any activity that results in an increase in available moisture or an increase in soil volume tapped for moisture by roots would be beneficial. Mineral soil with a light litter covering is generally thought to be the optimum seedbed (Pearson 1950, Schubert 1974), because it allows best seed and seedling contact with available moisture. Much precipitation can be absorbed by a deep forest floor and then lost through evaporation without reaching the root zone (Clary and Ffolliott 1969).

Fire Effects on Natural Regeneration

Removal of forest floor material is beneficial. Pearson (1923) noted long ago that spots where slash piles burned produced large numbers of rapidly growing pine seedlings. Reduction of grass competition was the suggested benefit. Reports by Weaver (1952) and Ffolliott et al. (1977) showed much greater pine seedling establishment on burned than unburned seedbeds. Heidmann et al. (1982) studied sites of best natural ponderosa regeneration in a harvested watershed in central Arizona. Of the sites adequately stocked, 70% had been burned before a moderate cone crop was produced. Harrington and Kelsey (1979) illustrated the deleterious effect of a deep organic layer and competing vegetation on ponderosa establishment in Montana. An additional finding was the much greater size of pine seedling crowns and roots in burned plots, presumably from an increase in available nitrogen.

As part of the fire research at Fort Valley Experimental Forest, burned and unburned seedbeds were surveyed after the 1976 seed crop was produced (Sackett 1984). Burned plots had 2600 seedlings per acre compared with 833 seedlings per acre on unburned controls. After 2 years, no seedlings remained on control plots, whereas burned plots still supported over 500 seedlings per acre. In a companion study, seeds falling on an undisturbed forest floor seldom reached mineral soil (Haase 1981). Sackett (1984) showed a high correlation ($r^2 = 0.85$) between quadrat bare area (square feet) exposed by fire and quadrats stocked: 83% of the new pine seedlings germinated on microsites where the forest floor was partially or totally consumed by fire. Another confirmation of this benefit came from a prescribed burning study in southwestern Colorado (Harrington 1985), where 20 times more pine seedlings per acre were located on burned units than on units with unburned forest floors and Gambel oak.

A more recent seedling survey at Fort Valley Experimental Forest revealed a more pronounced regeneration success. In 1983, seeds were cast at a rate possibly rivaling that of 1918. By summer 1984, the burned plots were carpeted with new seedlings. Plots that had recently burned were surveyed extensively, along with the unburned controls. The burned seedbeds averaged over 90,000 seedlings per acre. The unburned plots had 26,000 seedlings per acre. In fall 1984, two of the three previously burned plots were reburned as part of the burning rotation study. One plot had 4 years of litter accumulation and the other had 8 years accumulation. Four years after burning, the following seedling distribution was found: all seedlings were killed on the plots burned with 8 years of litter, 7,800 seedlings per acre remained on the plots burned with 4 years of litter, 15,000 seedlings per acre remained on the plots burned before seed fall, and only 1,200 seedlings per acre remained on the controls.

Not only does prescribed burning provide for favorable seedbeds for germination, it also enhances the growing environment for survival. Soil moisture on burned sites at Fort Valley Experimental Forest was greater than on unburned sites because moisture can reach soil unimpeded by the forest floor material (Haase 1986, Ryan and Covington 1986). Work with soil thermocouple psychrometers at Fort Valley[3] confirmed Haase's findings. On burned sites, soil moisture was slightly to significantly more available in the 6 to 12-inch soil depths than on unburned sites. Since tap roots of seedlings exhumed on burned sites at Fort Valley are generally 12 inches long after the first full growing season, more moisture apparently reaches the major rooting zones where the forest floor has been consumed.

Soil temperatures are also higher on burned seedbeds. At Fort Valley, Milne (1978) found burned soil averaged 9° F warmer than unburned soils for the time period for active pine seed germination. Since germination of southwestern ponderosa pine seed is temperature-dependent (Larson 1961), burned sites should favor earlier and more rapid seedling emergence. More extensive monitoring of soil temperatures at Fort Valley[4] showed soils to be warmer on burned sites, but rarely high enough to be damaging. Warmer soils could also result in larger-rooted seedlings (Larson 1967), which should have better survival during the normal dry periods.

Favorable seedling development on seedbeds with improved moisture conditions, and warmer soils is also enhanced by greatly improved nitrogen availability. Covington and Sackett (in press) showed a large increase in available nitrogen from initial prescribed fires and rotational burning. The increased nitrogen on burned seedbeds allows seedlings to attain deep roots and large crowns, which facilitate survival through fall drought and the first winter. Since seedlings are generally much stouter on a burned site, perhaps a greater resistance to frost heaving, common on basalt sites in northern Arizona, is developed.

Preparing Seedbeds With Prescribed Fire

The effectiveness of prescribed fire in consuming the forest floor for hazard reduction was discussed earlier in this paper. The same process produces seedbeds of various qualities. Fires that consume the forest floor, leaving little organic matter, create microsites that surpass unburned areas in moisture and nutrient status. The burn prescription parameters listed earlier for fuel reduction burning also apply to burning for seedbed production. Once the weather and surface fuel moisture conditions have been met, the humus moisture will determine the amount of forest floor consumed, and therefore the quality of the seedbed.

[3] *Data on file with Michael G. Harrington at the Intermountain Fire Sciences Laboratory, Missoula, MT.*

[4] *Data on file with Stephen S. Sackett of the Forest Fire Laboratory, Riverside, California.*

Pattern of Consumption

Even though soil with minimal organic covering is optimal for seedling establishment, the entire site need not be burned to that degree. In fact, a burn of that severity would be hazardous to conduct and would likely cause extensive damage to much of the vegetation and soils. Experience shows that a ponderosa pine forest floor burns in uneven patterns, with microsites of mineral soil alternating with unburned islands. This pattern is probably due to variations in fuel moisture, forest floor bulk density, and consumption of woody fuels. So, a burn consuming 50% to 75% of the forest floor would have a variety of partially to almost completely burned microsites. Partial forest floor consumption is preferred, because high quality seedbeds result and other site characteristics generally are not damaged.

Fuel Moisture Contents

It is difficult to propose specific forest floor moisture contents at which an optimum seedbed will result from burning. This is because of the variable pattern of consumption. Generally, in dense, or otherwise fully stocked groups within stands, prescribed burns will create few mineral seedbeds, probably because of the high forest floor bulk density. However, on sites where mature trees have been or will be removed, fires burn to mineral soil within a large range of moisture contents. Places that do not need seedling regeneration probably will not have much mineral soil exposed, and the places where pine regeneration is desired will have mineral soil exposed by fire. Given the weather conditions and surface fuel moistures mentioned earlier as general burning guides, applying fire with humus moisture contents between 25%a and 65% will likely result in adequate mineral soil exposure.

Follow-up

When a crop of seedlings establishes, it is important to defer the suggested rotational burning program for a number of years to keep from injuring the young trees. If seedlings are needed on a particular site (understocking), not much fuel will accumulate after the initial burn. We have found seedlings 6 feet high at age 10 that are growing where oldgrowth pines have died. They have survived successive fires because there was no fuel close by to scorch them. Once the trees can withstand some fire, the interval between burns should be relatively short. Less fuel produces a less intense, uneven burn, which makes it easier for seedlings to survive the fire environment.

Silvicultural Treatments

The use of prescribed fire in conjunction with different silvicultural treatments in the Southwest has not been researched. However, dense slash fuels should be reduced, just as should forest floor fuels, to facilitate pine seedling establishment. One lesson learned years ago was that large clearcuts followed by intense burning failed to promote new generations of ponderosa pine seedlings (Schubert 1974). Small group selection, shelterwood, or seed tree cuts followed by broadcast or pile burning favors seedling establishment and reduces the fuel hazard. Fire has not been effective in reducing grass or shrub competition (Schubert 1974), but research in different seasons of fire application suggest a possible alternative to the current use of mechanical scarification (Harrington 1985). Lessons can be learned from the Pacific Northwest, where fire is used with various ponderosa pine silvicultural treatments for logging and thinning slash disposal, brush reduction, mistletoe control, as well as site preparation (Barrett 1979).

CONCLUSIONS

Very few forest ecosystems compare with southwestern ponderosa pine in the importance of presettlement fire for maintenance of forest health and stability. Fire history from this region confirms this. Prescribed fire,in mimicking the natural role of fire, can be an ideal tool for accomplishing many forest management objectives.

The successful reduction of natural fire from ponderosa pine stands within the last century has created hazardous, unhealthy forest conditions. With careful fire use under the general guidance of the prescriptions and cautions presented earlier, the vigor and stability of these forests should return. With time, we may even be able to improve upon the multiple-use production of presettlement, natural conditions. The ideas and prescriptions presented here are very general. Prescribed burning anywhere is site-specific. Land managers must learn how prescribed fire relates to their resources, develop a prescription pertinent to each situation, and monitor results. Each fire is a new experience; therefore, the learning process never ends.

The state-of-the-art in using fire for fuel management, overstory thinning, and natural regeneration is only in the beginning stages of development. Other aspects of prescribed fire have not been addressed in this paper or studied. In addition to the tangible parameters, the intuitive nature or art form of fire application is the key to attaining success. Anyone who has the desire to use fire to help manage land resources must learn both the art and the science aspects. Desired results can be achieved only when practitioners master the techniques of burning and learn the principles of fire ecology.

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