Prescribed Burning in Southwestern Ponderosa Pine

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Abstract.--Prescribed burning is an effective way of restoring the fire process to ponderosa pine *(Pinus ponderosa* Dougl. ex Laws.) ecosystems of the Southwest. If used judiciously, fire can provide valuable effects for hazard reduction, natural regeneration, thinning, vegetation revitalization, and in general, better forest health. Relatively short burning intervals are required to maintain the benefits of fire.

INTRODUCTION

Prescribed burning in the United States has been a long tradition, especially in long-needled pine ecosystems. This mimicking of naturally occurring fire is increasingly being used as a silvicultural tool in many western and southeastern forests for restoration of natural processes. Fire stimulates the physical, chemical, and biological environment of forest types and thereby improves health, diversity, and tolerance to disturbances. To sustain valuable recreational, wildlife, as well as commercial products, fuels are reduced systematically by fire to lessen the possibility of extensive replacement of forest communities by inevitable fire. In so doing, other valuable benefits are achieved that have been seriously degraded when naturally occurring fires were replaced by human activities.

Naturally occurring fires will likely never play a role in most ecosystems again because of the changes that have occurred with Euro-American settlement. Therefore prescribed burning should be a highly considered alternative that allows for benefits to be achieved in fire adaptive ecosystems. Developing priorities becomes a crucial part of a prescribed burning program.

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FIRE IMPACTS ON ORGANIC MATTER

Because of changes associated with settlement of the Southwest, ponderosa pine forests developed a cluttered, unhealthy nature, as evidenced by unusually high volumes of dead and living biomass. Instead of having open vistas reported by early explorers and settlers, these forests have become dense and unproductive. As Euro-American settlement increased, the desire to eliminate fire has resulted in a steady increase in flammable organic material.

Almost two decades ago, average loadings of naturally occurring fuels in southwestern ponderosa pine stands were more than 22 tons per acre (Sackett 1979). Loadings from the 62 stands surveyed ranged from 8 to 48 tons. Harrington (1982) verified the heavy fuel loadings from southeastern Arizona, with an average of 34 tons per acre.

The hazard these large amounts of forest floor material represent, because of their burnability, strongly suggest the need for reduction, not to mention other associated problems. Trees of all sizes in these forests have generally poor vigor and reduced growth rates (Cooper 1960, Covington and Moore 1994, Sutherland 1989, Weaver 1951). This condition is likely due to reduced availability of soil moisture caused by intense competition, and by moisture retention in the thick forest floors (Clary and Ffolliott 1969, Harrington 1991). The thick forest floor also indicates that soil nutrients, especially nitrogen, may be limited because they are bound in unavailable forms (Covington and Sackett 1984, Covington and Sackett 1986, Covington and Sackett 1990, Covington and Sackett 1992).

Some of the earliest prescribed fires in the Southwest were on the Fort Apache Indian Reservation in Arizona with about 3,000 acres being burned in the late 1940's (Kallender 1969). From 1950 to 1970, over 300,000 acres were burned, primarily for hazard reduction. The effectiveness of the Fort Apacheburning program in reducing size and severity of subsequent wildfire has been documented (Biswell and others 1973, Knorr 1963). Cool, dry, late fall conditions were the basis for initial fuel reduction burns to moderate fire behavior. Fires were strategically ignited, then allowed to burn 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 percent and dead woody material was reduced by 64 to 80 percent. The effects of this burning operation were evident the following year by a dramatic reduction in the number of wildfires and in the acreage burned (Weaver 1952).

Later, in November 1956, a large scale burn was conducted on the Fort Apache Indian Reservation, under cool, clear days with moderately high drought index and low rate-of-spread index (Lindenmuth 1960). Fires were allowed to spread unchecked for 33 days within prescribed boundaries. Under these burning conditions, fuel reduction on 75 percent of the area was deemed unsatisfactory because the reduction was minimal.

In another burn in central Arizona, two distinctly different sites were burned under similar fuel moisture and weather conditions. One site had 75 percent more fuel, and 85 percent greater overstory basal area (Davis and others 1968) than the other site. Consumption was greatest on the site with the most fuel, but 2 years later the net fuel change, including consumption by fire and subsequent litter accumulation, was greater on the site with less initial fuel (37 percent reduction) compared to the heavy fuel site (23 percent reduction). The indication is that more damage was done on the site of higher fuel loading resulting in greater post burn fuel accumulation. This indicates that prescribed burning should be a continuing process, not a one-time event.

In 1976, a research study was initiated in northcentral Arizona to investigate the use of interval prescribed burning (repeated burns at specified intervals) to reduce and maintain low hazard fuel conditions (Sackett 1980). On the Fort Valley Experimental Forest near Flagstaff, Arizona, research plots were burned in November to start an interval burning study that includes six different burning rotations. Because of warm, dry conditions that fall, the initial burn was conducted. at night. Forest floor material was reduced by more than 60 percent and large, woody material by 70 percent. Consumption was greatest where forest floors were deepest, mostly around large mature trees.

One year later at Long Valley Experimental Forest, a companion study was set up to investigate rotational prescribed burning on another soil type. After a very wet summer, the initial burns at Long Valley were ignited during the day. Even though litter moisture was similar in the two burns, humus moisture was 10 to 15 percent higher at Long Valley; therefore, consumption was considerably less (40 percent). Both study areas had about 15 tons per acre of forest floor material before burning.

In a series of summer burns in southeastern Arizona, Harrington (1987) found that humus moisture and preburn forest floor depth were positively correlated with percent of forest floor reduction.

Additional research burns were conducted at Fort Valley within stands of contrasting structure in 1982 (Covington and Sackett 1992) under low humidities (15 to 24 percent) and moderate air temperature (52° to 62° F). Surface fuel moisture ranged from 7 to 10 percent, and humus moisture ranged from 12 to 20 percent. In stagnated sapling stands (doghair thickets), about 34 percent of the 12 tons per acre loading was consumed, 52 percent of the 16 tons per acre in the pole stands was consumed, and 89 percent of the 55 tons per acre was burned in the mature yellow pine stands. Again, like Harrington's (1987) prediction equation points out, there is a high positive correlation between percent forest floor consumed and preburn loading.

Prescribed burning in southwestern ponderosa pine can greatly, but only temporarily, reduce fuel hazard (Harrington 1981, Sackett 1980); 0.6 to 1.8 tons per acre of needle litter can be cast annually (Davis and others 1968, Sackett 1980). Easily ignitable litter fuels accumulate rapidly to hazardous levels after initial fuel reduction burns. Continual reburns are essential to remove the accumulation and to generally maintain low fuel hazard (Harrington 1981, Sackett 1980). Consumption of the litter layer lessens ignitability and rate-of-spread potential. As more duff, ladder fuels, and large logs are consumed, a reduction in potential fire intensity, total energy release, and resistance to control are realized.

FIRE IMPACTS ON THE STAND

Extensive structural and compositional changes have beset ponderosa pine forests of the Southwest over the past century and a half. Numerous references document the open, park-like nature of presettlement pine stands (Biswell and others 1973, Brown and Davis 1973, Cooper 1960, Covington and Moore 1994). Fires were a regular event of these forests, burning the light surface fuels at intervals usually averaging less than 10 years and as often as 2 years (Dieterich 1980, Weaver 1951). Change began during extensive livestock grazing in the late 1900's (Faulk 1970). As grazing intensified, herbaceous vegetation could not respond, and its coverage greatly declined. This decline led to two subsequent changes: reduced fire spread because of the decrease in fine fuel, and an eventual increase in ponderosa pine regeneration because of reduced competition and fire mortality, and more mineral soil seedbeds (Cooper 1960). Early forestry practices, including fire suppression, further reduced the spread of inevitable fires, and contributed to unprecedented fuel accumulations, and stagnation of seedling and sapling thickets.

Dense sapling thickets which were uncharacteristic to the presettlement ponderosa pine ecosystems are today well represented. Sackett (1980) and Harrington (1982) reported typical stands averaging 2,000 trees per acre, of which 65 percent were 1 to 4 inches d.b.h.. Mechanical thinning has been a tool of choice to improve stand structure and health, but as human and monetary resources become more scarce, intensive treatments are rapidly eliminated.

During previous centuries, fire was the natural thinning agent that kept southwestern ponderosa pine forests open (Cooper 1960). Today, fire can still be used effectively to reduce overstory competition and keep natural regeneration from exceeding the space available for healthy growth. Using fire in current forest conditions is much different than firethinning that occurred naturally years ago. Stagnated thickets generally consist of 65- to 80-year old trees, which contrasts to the presettlement fire-thinning of mostly less than 20-year-old trees. In addition, even though trees are small in diameter, they possess thick bark. Instead of being able to girdle or scorch a young, short, thin-barked tree, excessive heat concentrations in the crown are required to effectively kill these taller, thicker-barked trees.

Some investigators have dealt with the use of fire as a thinning tool, and it has been viewed with mixed feelings. Tests on the Fort Apache Indian Reservation showed that, though thinning was spotty from fall fires, the fire did a "reasonably effective and conservative job of thinning" (Weaver 1952). Gaines and others (1958) wrote a supplement to Weaver's report providing data that more or less supported his previous observations. Their conclusions were not as optimistic because of the injury to the commercial overstory. Wooldridge and Weaver (1965), reporting on a prescribed fire designed to thin dense sapling stands on the Colville Indian Reservation, concluded that prescribed fire was a rough and largely unpredictable thinning tool.

Ffolliott and others (1977) reported an effective thinning response from an experimental prescribed fire near Flagstaff, Arizona. They concluded, however, that basal area was not reduced enough for optimal growth of the residual stand. As stated before, one fire does not correct problems associated with more than 100 years of fire exclusion, especially as it applies to thinning.

Using fire to reduce logging slash after a shelterwood cut on the Apache National Forest, Buck (1971) observed considerable overstory mortality. Although the prescribed fires were not designed as a thinning tool, they did accomplish some effective thinning from below. The losses (83 percent) were in suppressed and intermediate trees.

Harrington (1981) reported tree density reductions of small and suppressed tree classes to be 24 percent, 56 percent, and 43 percent on three summer prescribed burns with preburn stand densities of about 2,000 trees per acre.

On the Fort Valley initial prescribed burn mentioned earlier (Sackett 1980), stagnated reproduction and sapling stems were reduced from an average of 1,553 to 912 per acre. In the companion study at Long Valley, fire intensity and fuel consumption were lower because of wetter fuel conditions. An average of only 180 stems per acre were killed by the fires in the reproduction /sapling size classes. Virtuallynone of the small poles were killed outright by the fire.

No known studies or 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. Experiences of studies located on the Fort Valley and Long Valley Experimental Forests near Flagstaff, Arizona, and study areas in southwestern Colorado and southern Arizona, support Cooper's (1961) suggestion that quality of fuel as well as quantity is essential for producing controlled high intensity fires in dense stands.

Repeat burning in higher quality and quantity fuel does a better job of thinning stagnated stands than single burning in thick forest floors. 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 is the H layer below it. 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 (up to 3 or 4 tons per acre). Fire intensity, rate-of-spread, and flame length are much higher in response to the greatly increased available fuel.

Crown scorch and consumption are more effective mechanisms for killing trees and thinning stands than bole girdling. Many of the stagnated sapling stands arose from the famous 1913 and 1918 seed crop and subsequent regeneration. Although the trees have grown little in diameter and tree height, bark thickness has progressed normally through the past 80 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 little cambium damage.

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. Fire can be manipulated 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 than backing fires which move against the wind (or down hill) and progress very slowly with short flame lengths and low intensities. Backing fires seldom thin stands.

FIRE IMPACTS ON PONDEROSA PINE REGENERATION

Very little regeneration of ponderosa pine has taken place in the last 30 to 40 years in untreated stands because of either dense overstory, thick forest floor, or herbaceous competition. To maintain a multiaged character, pine regeneration is desired in places where the overstory is gone from stress related mortality, harvesting, or fire mortality. Ponderosa pine is 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 and others 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.

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 considered 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).

Much research and observation have shown the beneficial effect of forest floor reduction on pine establishment. Harrington and Kelsey (1979) illustrated the deleterious effect of a deep organic layer and competing vegetation on ponderosa pine 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. Pearson (1923) noted long ago that spots where slash piles burned produced large numbers of rapidly growing pine seedlings. Reduc tion of grass competition was the suggested benefit. Reports by Weaver (1952) and Ffolliott and others (1977) showed much greater pine seedling establishment on burned than unburned seedbeds. Heidmann and others (1982) studied sites of best natural ponderosa regeneration in a harvested watershed in central Arizona. Seventy percent of the sites adequately stocked, had been burned prior to a moderate cone crop.

As part of the fire research at Fort Valley Experimental Forest, burned and unburned seedbeds were surveyed after the 1976 seed crop (Sackett 1984). Burned plots had 2,600 seedlings per acre compared with 833 seedlings per acre on unburned control plots. Two years later, the burned plots still supported over 500 seedlings per acre, while no seedlings were found on the control plots. In a companion study, seeds falling on an undisturbed forest floor seldom reached mineral soil (Haase 1981). Sackett (1984) showed a high correlation (r z = 0.92) between area of fire-exposed mineral soil (square feet) and amount of stocking: 83 percent 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 competition.

A 1984 pine seedling survey at Fort Valley Experimental Forest revealed a more pronounced regeneration success as a result of burning. In 1983, seeds were cast at a rate possibly rivaling the record year of 1918. By summer, 1984, the burned seedbeds averaged over 90,000 seedlings per acre, while 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 of accumulation. Four years after this burn, 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 1,200 seedlings an acre remained on the controls.

Over the 18-year course of burning at Long Valley Experimental Forest, natural regeneration was never as pronounced as at Fort Valley. Before burning in the fall of 1995, however, seedlings were surveyed or annual, biennial, and 6-year rotation burn plots, and averages were 39,900, 9,500, and 35,200 seedlings per acre, respectively.

It is interesting to note that even the oldest seedbed (time since last burned) had excellent regeneration. Even though a 6-year litter accumulation is 3 to 4 tons per acre, it is in a form that (1) seeds can drop through to mineral soil, and (2) the needles act as a mulch against evaporation. Obviously many of these seedlings were consumed by the next fire, but for managers who would like to promote and encourage the survival of seedlings, protecting them from fire by simply not igniting in those areas would be an easy matter.

It is difficult to define specific forest floor moisture content conditions under which an optimum seedbed will result from burning because of the variable pattern of consumption. Generally, in dense, or otherwise fully stocked groups within stands, prescribed burns will create few mineral seedbeds. However, on sites where mature trees have been or will be removed, fires burn to mineral soil within a large range of forest floor moisture contents. Places that do not need seedling regeneration typically will not have much mineral soil exposed, and the places where pine regeneration is desired generally have mineral soil exposed by fire.

FIRE IMPACTS ON SOIL NITROGEN

Fire also serves as a recycling agent for nutrients that are organically bound in the forest floor, woody material, and herbaceous vegetation. During the burning process, organic nutrients may be oxidized to inorganic forms that are readily available for use by trees and herbaceous vegetation. A portion of some nutrients is volatilized and lost from the site. Loss of nitrogen (N), which has a relatively low volatilization temperature, is especially important because it is usually the most limiting plant nutrient in forest ecosystems (Maars and others 1983).

Burning at Fort Valley has produced increases in inorganic nitrogen in the soil (Covington and Sackett 1992). Concentrations of ammonium-N in mineral soil are directly related to the amount of material consumed. As with other aspects of prescribed burning, repeat prescribed burning had additional soil nutrient impacts. Inorganic N levels are short-lived without repeat burns (Covington and Sackett 1986). Four years after an initial burn, concentrations of ammonium-N approached control levels, but were elevated again following additional burns.

These fire induced increases in inorganic nitrogen probably contribute to the increased seedling establishment of both herbaceous vegetation (Vose and White 1987) and ponderosa pine (Sackett 1984), as well as higher herbaceous biomass production and greater foliar nitrogen concentrations (Harris and Covington 1983, Oswald and Covington 1984, Andariese and Covington 1986, Covington and Sackett 1990) and increased pine seedling growth (Owen 1985). Increased growth was further documented at Fort Valley where 6-year-old pine seedling heights approached 24 inches on burned plots in contrast to 6- to 8-inch heights for the same-age seedlings on unburned controls.

Diameter growth of pole-size trees was measured in 1988 at Fort Valley (Peterson and others 1994). Moderate changes in diameter growth occurred after 1984, 8 years after the largest increases of inorganic nitrogen occurred. Trees in the 1-, 2-, 8-, and 10-year rotation burns had slower growth than controls after 1984, presumably because of moderate fire stress. The 4- and 6-year rotation burns had slightly higher growth rates after 1984. Lack of large growth increases is likely due to the continued dense stocking.

FIRE PRESCRIPTIONS

Much 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.

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 tempera tures and humidities are moderate. Fall burning can begin as early as mid-September and can continue in some years into December, or later in snow-free years. However, smoke dispersal is a distinct problem in the typical stable atmosphere of the winter months.

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

Caution must be used since not all combinations within the range of temperatures, humidities, windspeeds, and fuel moistures 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 percent) and low temperatures (40 °F 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 in the Southwest 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.

Maintenance burning is necessary to keep the recurring fuel hazard to a minimum (Davis and others 1968, Gaines and others 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. Smoke management issues also decrease with maintenance burning due to the shorter duration and lower volumes of smoke generated with the less fuel. 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 of and 85 ∀F, humidities from 15 to 40 percent, windspeeds from 5 to 12 mph, and litter moisture from 5 to 10 percent. 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. However, as burning rotations increase, weather and fuel parameters during the burn need to be more moderate.

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).

Because health and stability of presettlement southwestern ponderosa pine ecosystems was keyed to frequent fire, importance of proper fire reintroduction seems clear. Prescribed fire, in mimicking the natural role of fire, can be an ideal tool for accomplishing many forest management objectives. The ideas and prescriptions presented are very general, and prescribed burning anywhere is site-specific. Managers must learn how to prescribe conditions that relate specifically to their particular resource objectives.

LITERATURE CITED

Andariese, S.W.; Covington, W.W. 1986. Changes in understory production for three prescribed burns of different ages in ponderosa pine. Forest Ecology and Management 14:193-203.

Biswell H.H.; Kallander, H.R.; Komarck, R.; Vogl, R.J.; Weaver, H. 1973. Ponderosa pine management. In Tall Timbers Research Station Miscellaneous Publication No. 2. Tallahassee, FL: Tall Timbers Research Station. 49 pp.

Brown, A.A.; Davis, K.P.1973. Forest fire: control and use. 2d ed. New York: McGraw-Hill Book Co., Inc.; 32 pp.

Buck, Bill. 1971. Rx for burning on Apache National Forest. Fire Control Notes 32(1): 10-12.

Clary, W.P.; Ffolliott, P.F.1969. Water holding capacity of ponderosa pine forest floor layers. Journal of Soil and Water Conservation. 24(1): 22-23.

Cooper, Charles F.1960. Changes in vegetation, structure, and growth of southwest pine forests since white settlement. Ecological Monographs 30(2): 129-164.

Cooper, Charles F. 1961. The ecology of fire. Scientific American 304(4): 150-160.

Covington, W.W.; Sackett, S.S. 1984. The effect of a prescribed burn in southwestern ponderosa pine on organic matter and nutrients in woody debris and forest floor. Forest Science 30(1): 183-192.

Covington, W.W.; Sackett, S.S. 1986. Effect of periodic burning on soil nitrogen concentrations in ponderosa pine. Soil Science Society of America Journal 50:452-457.

Covington, W.W.; Sackett, S.S. 1990a. Fire effects on ponderosa pine soils and their management implications. In: J.S. Krammes (ed.), Proceedings of the Symposium on Effects of Fire Management of Southwestern Natural Resources. Gen. Tech. Rep. RM-191. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. pp. 105-111.

Covington, W.W.; Sackett, S.S. 1992. Soil mineral nitrogen changes following prescribed burning in ponderosa pine. Forest Ecology Management 54:175-191.

Covington, W.W.; Moore, M.M. 1994. Southwestern ponderosa pine forest structure: Changes since Euro-American settlement. Journal of Forestry 92: 39-47.

Davis, James, B.; Ffolliott, Peter F.; Clary, Warren P. 1968. A fire prescription for consuming ponderosa pine duff. Res. Note RM-115. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 4 pp.

Dieterich, J.H. 1980. Chimney Spring fire history. Res. Paper RM-220. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 8 pp.

Faulk, O.B. 1970. Arizona: A short history. Norman, OK: University of Oklahoma Press. 266 pp.

Ffolliott, Peter F.; Clary, Warren P.; Larson, Fredric R. 1977. Effects of a prescribed fire in an Arizona ponderosa pine forest. Res. Note RM-336. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 4 pp.

Gaines, Edward M.; Kallander, Harry R.; Waganer, Joe A. 1958. Controlled burning in southwestern ponderosa pine: results from the Blue Mountain plots, Fort Apache Indian Reservation. Journal of Forestry 56: 323-327

Haase S.M.1981. Effects of prescribed burning on ponderosa pine seed germination in the Southwest. Flagstaff, AZ: Northern Arizona University; M.S. Thesis. 67 pp.

Harrington, M.G.1981. Preliminary burning prescriptions for ponderosa pine fuel reduction in southeastern Arizona. Res. Note RM-402. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 7 pp.

Harrington, M.G. 1982. Stand, fuel, and potential fire behavior characteristics in an irregular southeastern Arizona ponderosa pine stand. Res. Note RM-418. Fort Collins, CO: U.S. Department of- Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 6 pp.

Harrington, M.G.1985. The effects of spring, summer and fall burning on Gambel oak in a southwestern ponderosa pine stand. Forest Science 31: 156-163.

Harrington M.G. 1987. Predicting reduction of natural fuels by prescribed burning in southern Arizona. Res. Note RM-472. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 4 pp.

Harrington, M.G.; Kelsey, R.G. 1979. Influence of some environmental factors on initial establishment and growth of ponderosa pine seedlings. INT-230. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 26 pp.

Harris, G.R.; Covington, W.W. 1983. The effects of a prescribed fire on nutrient concentration and standing crop understory vegetation in ponderosa pine. Canadian Journal of Forest Research 13: 501-507.

Heidmann, L.J.; Johnson, Jr., Thomas N.; Cole, Quinten W.; Cullum, George. 1982. Establishing natural regeneration of ponderosa pine in central Arizona. Journal of Forestry 80: 77-79.

Kallander H.1969. Controlled burning on the Fort Apache Indian Reservation, Arizona. In: Proceedings of Tall Timbers Fire Ecology Conference, No. 9. 1969 April; Tallahassee, FL. pp 241-250.

Knorr, P.M. 1963. One effect of control burning on the Fort Apache Reservation. In: Proceedings of the Seventh Annual Watershed Symposium, Arizona Watershed Program. Tucson, AZ: 1963 September. pp 35-37.

Karson, M.M.; Schubert Gilbert H.1969a. Effect of osmotic water stress on germination and development of ponderosa pine seedlings. Forest Science 15: 30-36.

Karson, M.M.; Schubert, Gilbert H. 1969b. Root competition between ponderosa pine seedlings and grass. Res. Paper RM-54. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 12 pp.

Lindenmuth, A.W.1960. A survey of effects of intentional burning on fuels and timber stands of ponderosa pine in Arizona. USDA Forest Service Station Paper 54. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 22 pp.

Maars, R.H.; Roberts, R.D.; Skeffington, R.A.; Bradshaw, A.D.1983. Nitrogen in the development of ecosystems. In: Lee, J.A. and others, editors. Nitrogen as an ecological factor. Oxford, England; Blackwell Science Publishing: 131-137.

Oswald, B.P.; Covington, W. W.1984. Effect of a prescribed fire on herbage production in southwestern ponderosa pine on sedimentary soils. Forest Science 30(1): 22-25.

Ower, C.L. 1985. Changes in ponderosa pine seedling growth and soil nitrogen following prescribed burning and manual removal of forest floor. M.S.F. Thesis. Flagstaff, AZ: Northern Arizona University. 109 pp.

Pearson, G.A. 1923. Natural reproduction of western yellow pine in the Southwest. USDA Bulletin No. 1105, Washington, DC. 143 pp.

Pearson, G.A.1950. Management of ponderosa pine in the Southwest. Monogram No. 6. Washington, DC.: U.S. Department of Agriculture. 218 pp.

Peterson, D.L.; Sackett, S.S.; Robinson, L.J.; Haase, S.M. 1994. The effects of repeated prescribed burning on *Pinus ponderosa* growth. International Journal of Wildland Fire. 4(4): 239-247.

Rietveld, W.J.; Heidmann, L.J. 1974. Mulching planted ponderosa pine seedlings in Arizona gives mixed results. Res. Note RM-257. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 3 pp.

Sackett, Stephen S. 1979. Natural fuel loadings in ponderosa pine and mixed conifer forests of the Southwest. Res. Paper RM-213. Fort Collins: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 10 pp.

Sackett, Stephen 5.1980. Reducing natural ponderosa pine fuels using prescribed fire: Two case studies. Res. Note RM-392. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 6 pp.

Sackett, Stephen S. 1984. Observations on natural regeneration in ponderosa pine following a prescribed fire in Arizona. Res. Note RM-435. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 8 pp.

Schubert, Gilbert H. 1974. Silviculture of southwestern ponderosa pine. The status of our knowledge. Res. Paper RM-123. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 71 pp.

Sutherland, E.K.1989. The effect of prescribed burning on Southwest ponderosa pine growth. Doctoral Thesis. School of Renewable Natural Resources, Department of

Watershed Management. Flagstaff, AZ: University of Arizona.

Vose, James M. 1984. Establishment and growth of common understory plants following prescribed fire in an Arizona ponderosa pine community. Flagstaff, AZ: Northern Arizona University. M.S. Thesis. 141 pp.

Weaver, Harold. 1951. Observed effects of prescribed burning on perennial grasses in ponderosa pine. Journal of Forestry 49: 267-271.

Weaver, H. 1952. A preliminary report on prescribed burning in virgin ponderosa pine. Journal of Forestry 50: 662-667.

Wooldridge, David D.; Weaver, Harold. 1965. Some effects of thinning a ponderosa pine thicket with a prescribed fire, II. Journal of Forestry 63: 92-95.