TWO CASE HISTORIES FOR USING PRESCRIBED FIRE TO RESTORE PONDEROSA PINE ECOSYSTEMS IN NORTHERN ARIZONA

Stephen S. Sackett and Sally M. Haase
U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, 4955 Canyon Crest Drive, Riverside, CA 92507

ABSTRACT

Historic observations and research indicate that the ponderosa pine (*Pinus ponderosa*) ecosystem in the southwestern U.S. is now very different compared to pre-European settlement. Timber harvest, livestock grazing, and fire suppression have transformed an open ponderosa pine-bunch grass community into a dense forest overloaded with flammable organic material, which increases the likelihood of devastating wildfire. Prescribed fire research during the past 20 years has demonstrated the benefits and potential problems with reestablishing burning techniques into one of the most fire-dependent ecosystems in the U.S. Two case histories in northern Arizona illustrate that using prescribed fire on a frequent basis has transformed a dense, stagnated ponderosa pine site into one that now has adequate natural regeneration, manageable fuel levels, increased vertical fuel heights, substantially higher nutrient levels, and a variety of other attributes that are similar to presettlement conditions. This long-term research has shown the importance of fire as a natural agent in the perpetuation of this important forest species.

Citation: Sackett, Stephen S., and Sally M. Haase. 1998. Two case histories for using prescribed fire to restore ponderosa pine ecosystems in northern Arizona. Pages 380–389 *in* Teresa L. Pruden and Leonard A. Brennan (eds.). Fire in ecosystem management: shifting the paradigm from suppression to prescription. Tall Timbers Fire Ecology Conference Proceedings, No. 20. Tall Timbers Research Station, Tallahassee, FL.

INTRODUCTION

For centuries the ponderosa pine (*Pinus ponderosa*) forests in the dry climate of the southwestern U.S. experienced natural fires that maintained the open structure of the forest. After European settlement and a gradual elimination of the fire process, the ecosystem was completely restructured so that current presummer fire seasons common to the region result in hazardous wildfires. Because of the lack of these natural fires, trees of all sizes in these forests have generally poor vigor and reduced growth rates (Weaver 1951, Cooper 1960). This condition is likely caused by the reduced availability of soil moisture because of intense competition and moisture retention in the thick duff on the forest floors (Clary and Ffolliott 1969, Harrington 1991). The thick duff layer 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). In addition, Sackett (1979) found that in a survey of 62 ponderosa pine stands in the area, forest floor fuel loadings ranged from 8 to 48 tons per acre (17.9 to 107.6 megagrams per hectare), which exacerbates the already hazardous conditions.

To determine the benefits and potential problems of reestablishing burning techniques to manage these forests, prescribed fire studies have been implemented for the past 20 years on the Chimney Spring prescribed fire research area in northern Arizona. The USDA Forest Service's Fort Valley Experimental Forest, the oldest experimental forest, had not experienced fire for 120 years (Dieterich 1980), although prescribed burning had occurred elsewhere in the Southwest since the 1940's (Kallander 1969). During 1976, a long-term study was initiated on the site to investigate the use of interval prescribed burning (number of years between burning treatments) to reduce and maintain low hazard fuel conditions (Sackett 1980). Eighteen of twenty-one 2.5 acre (1 hectare) plots were initially burned in the evening of 4 November 1976. Three replicates at 1-, 2-, 4-, 6-, 8-, and 10-year intervals constitute the burning treatments. Three plots were set aside as unburned controls. Forest floor material was consumed by more than 60% and large woody material by 70%. Consumption was greatest where forest floors were deepest, mostly around large mature trees.

A companion study, referred to as Limestone Flats and located on the Long Valley Experimental Forest in northern Arizona, was initiated 1 year later to investigate rotational prescribed burning on a different soil type (limestone-sandstone sedimentary soil), compared to the basalt soils found at Chimney Spring (Sackett 1980). After a very wet summer, the initial burns at Long Valley were ignited during the day. Even though litter moisture was similar at the two sites, humus moisture was 10% to 15% wetter at Limestone Flats than at Chimney Spring; therefore, the consumption was considerably less (40% compared to 60%). Both study areas initially had about 15 tons per acre (33.6 megagrams per hectare) of fuel on the forest floor. Rotational burns were applied to each of three, 2.5-acre (1 hectare) plots each year with varying degrees of success at each study site. Fall burning conditions span from extremely dry to wet. Nevertheless, fire has been applied according to schedule over the 20-year period.

This paper presents the results of long-term studies on two case histories at Chimney Spring and Limestone Flats in northern Arizona that used prescribed burning to restore dense, stagnated ponderosa pine sites into those with adequate natural regeneration, manageable fuel levels, increased vertical fuel heights, substantially higher nutrient levels, and a variety of other attributes similar to presettlement conditions.

METHODS

During the 20 years of fire research at Chimney Spring and Limestone Flats, numerous facets of prescribed fire effects have been studied. In doing so, we have used a number of different statistical sampling methods to determine those effects.

Prior to and after the initial burns at both areas, we took 36, 1 square foot (0.09 square meter) forest floor samples from each of the 21, 2.5 acre (1 hectare) plots to determine fuel loading and consumption (Sackett 1980). We estimated the larger fuels on 168 sampling planes using the sampling scheme devised by Brown (1974). We determined forest floor fuel loadings on subsequent burns by extracting 64, 1 square foot (0.09 square meter) samples. For estimates of forest floor accumulations between burns, we installed ¼ inch (6.35 millimeter) grid hardware cloth screens 18 × 18 inches (45.7 × 45.7 centimeters) square at 32 systematically placed locations on each plot.

When the three year burning rotations were established, we extracted 100, 1 square foot (0.09 square meter) forest floor samples from three replicates of sapling overstory plots and pole overstory plots (Covington and Sackett 1992). On old-growth plots, we extracted multiple samples from different distances away from individual trees to encompass the range of forest floor depths. At each sample extraction point, we measured the thickness (depth) of each sample and later developed a regression equation where weight was predicted from depth. To define fuel loading and fuel consumption at old-growth sites, concrete reinforcing rods are installed so that a wire marker on the rod marks the top of the forest floor. After each fire, depth of forest floor consumed and total forest floor depth are measured at each rod. We then average the measurements. Prediction equations from previous sampling of forest floor depth and weight are used to estimate fuel loading and consumption over the area (Sackett and Haase 1992).

We estimated natural regeneration counts using 8 one-quarter mil-acre (1.10 square meter) quadrates systematically spaced on each plot (Sackett 1984). Additional information was gathered from permanent transects installed to inventory understory vegetation. We estimate understory vegetation at Chimney Spring from 4 transects, 328 feet (100 meters) long, with 200 individual 3.94 × 7.87 inch (10 × 20 centimeter) sample quadrates evenly spaced along each transect. Numbers of plants by species are noted, and the relative cover of each. We estimate understory vegetation at Limestone Flats from 6, 1 × 2 foot (30.5 × 61.0 centimeter) quadrates evenly spaced along 5, 75 foot (22.9 meter) long transacts systematically placed on each plot.

We used dendroecological methods to evaluate the effect of periodic burning on long-term tree growth (Peterson et al. 1994). Transects 32.8 feet (10 meter) wide were established through the center of each plot. The first 20 trees located along the transect that fit the sampling criteria were selected to represent growth on each plot. Two cores were extracted with an increment borer from the cross-slope sides of each tree at breast height (4.5 feet, 1.4 meter). We measured ring width to the nearest 0.0004 inch (0.01 millimeter) with an incremental measuring machine interfaced with a digital encoder and microcomputer to record measurements.

We determined mineral soil nutrient concentrations by compositing 7 randomly located samples, from 0–2 inches (0–5 centimeters) and 2–6 inches (5–15 centimeters) depths using a 1 inch (2.5 centimeter) diameter soil sampling tube (Covington and Sackett 1986). We extracted 3 samples from each of 3 overstory stratifications, on each of 3 replicates of each fire treatment and control plots.

We sieved each composite sample in the field through a 0.079 inch (2 millimeter) screen. A 0.34 ounce (10 gram) subsample for NH_4^+-N and NO_3^--N analysis was added to a 4.2 ounce (125 milliliter) bottle containing 3.5 ounces (100 milliliters) of 2N KCl (acidified with HCl to pH=2.5). Mineral nitrogen was determined colorimetrically on the KCl extract using a Technicon Auto Analyzer or a TRAACS 2000 analyzer.

RESULTS

Fuel Conditions

The forest floor of the ponderosa pine forests at both sites in our study consisted of the litter (L) layer, recently cast organic material consisting of needles, twigs, and cones; the fermentation (F) layer, material starting to discolor and breakdown because of weather and microbial activity; and the humus (H) layer, where decomposition has advanced (Figure 1). The loosely packed L layer and upper portion of the F layer provide the highly combustible surface fuel for flaming combustion and extreme fire behavior during fire weather watches and red flag warnings. This we define as the fire intensity (FI) layer of the forest floor (Figure 1). The lower more dense part of the F layer and the H layer comprise the ground fuel that generally burns as glowing combustion. This combined layer of the forest floor can be considered the fire severity (FS) layer (Sackett and Haase 1996).

The first fire to burn through the Chimney Spring area since 1876 altered the fuel and stand conditions considerably (Table 1). Fire consumed the surface needles (L and F) on 94% of the area. Mineral soil was exposed on 16% of the area. Fuel less than or equal

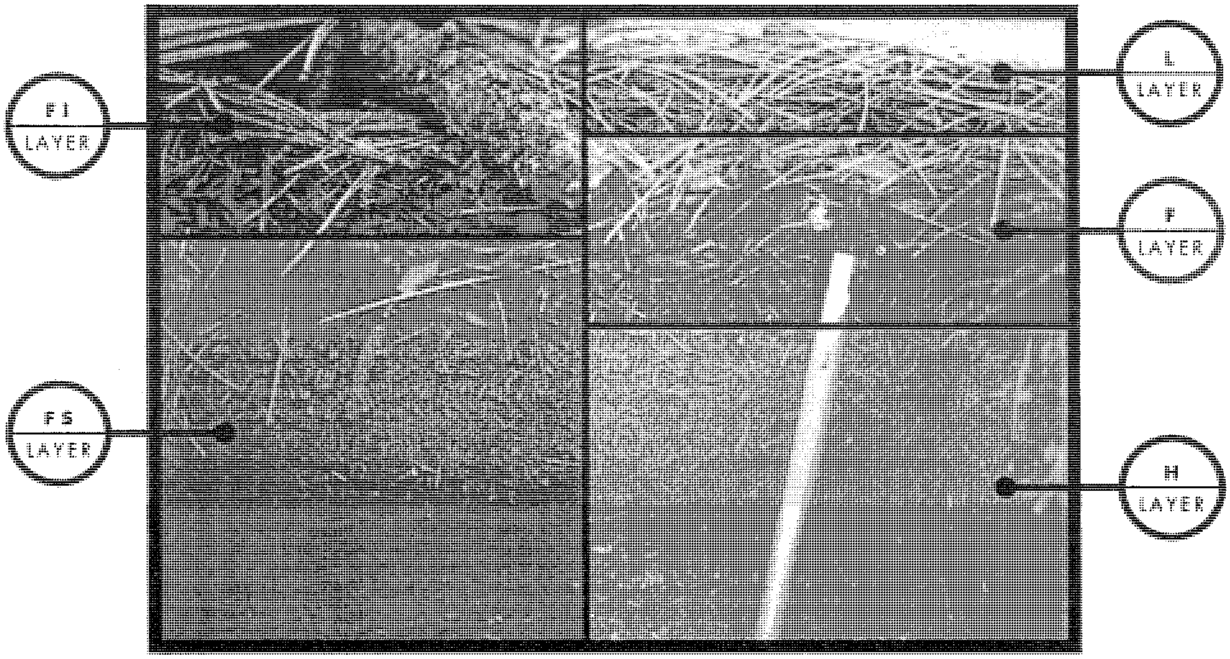

Fig. 1. Section of heavy forest floor material indicating fire intensity (FI) layer of fuel and fire severity (FS) layer of fuel in relation to the three layers of forest floor material (L, F, and H) (Sackett and Haase 1996).

Table 1. Mean dead fuel reductions and standard error (SE) from initial prescribed fires at Chimney Spring (1976) and Limestone Flats (1977) (Sackett 1980).

Dead fuel component	Fuel loading before fire	Fuel loading after fire	Percent fuel reduction
	tons per acre [megagrams per hectare]		
Chimney Spring			
Surface and ground fuel			
Needles and humus	12.19 (0.25) [27.33]	4.06[1] [9.10]	67
0 to 0.25 inch (0–04 cm)	0.79 (0.07) [1.77]	0.27 [0.61]	66
0.25 to 1 inch (0.64–2.54 cm)	1.31 (0.18) [2.93]	0.99 [2.22]	24
Other material	0.88 (0.16) [1.97]	0.35 [0.78]	60
Total	15.17 (0.30) [34.00]	5.67 (0.17) [12.71]	63
Large woody fuel			
1 to 3 inch (2.54–7.62 cm)	0.81 (0.08) [1.82]	0.37 (0.07) [0.83]	54
Over 3 inch sound (7.62 cm)	2.09 (0.56) [4.68]	1.79 (0.50) [4.01]	14
Over 3 inch rotten (7.62 cm)	4.26 (1.46) [9.55]	0.04 (0.03) [0.09]	99
Total	7.16 (1.85) [16.05]	2.20 (0.55) [4.93]	69
All dead fuel	22.33 (1.85) [50.05]	7.87 (0.70) [17.64]	65
Limestone Flats			
Surface and ground fuel			
Needles and humus	11.09 (0.19) [24.86]	6.57 (0.39) [14.72]	41
0 to 0.25 inch (0–0.64 cm)	0.48 (0.04) [1.08]	0.29 (0.05) [0.65]	40
0.25 to 1 inch (0.64–2.54 cm)	2.11 (0.23) [4.73]	1.15 (0.12) [2.58]	46
Other material	1.90 (0.09) [4.26]	1.06 (0.17) [2.38]	44
Vegetation	0.13 (0.01) [0.29]	0.07 (0.01) [0.16]	46
Total	15.71 (0.23) [35.22]	9.14 (0.41) [20.49]	42
Large woody fuel			
1 to 3 inch (2.54–7.62 cm)	2.19 (0.23) [4.91]	1.21 (0.11) [2.71]	45
Over 3 inch sound (7.62 cm)	5.22 (1.63) [11.70]	2.76 (0.66) [6.19]	47
Over 3 inch rotten (7.62 cm)	9.15 (1.45) [20.51]	5.37 (1.29) [12.04]	41
Total	16.56 (2.96) [37.12]	9.34 (1.98) [20.94]	44
All dead fuel	32.27 (2.83) [72.34]	18.48 (1.65) [41.43]	43

[1] Component weights for Chimney Spring surface/ground fuel were determined from one burning rotation treatment. All other weights based on all six rotation treatments.

to 1 inch (2.5 centimeters) in diameter (needles, twigs, cones, etc.) were reduced from 15.17 to 5.67 tons per acre (SE=0.30 and 0.17 respectively, n=684 square foot [0.09 square meter] samples) (34.0 to 12.7 megagrams per hectare) or 63%. Ground fuel was reduced from an average depth of 1.7 to 0.6 inches (4.3 to 1.5 centimeters).

Of the surface and ground fuels, needles and humus were reduced the most, by 8.13 tons per acre (18.2 megagrams per hectare). These are the fuels (especially L layer needles) that cause most of the dynamic behavior in a fire in these ponderosa pine forests. Eliminating needles removes the fire hazard of the dead forest fuels. As the needles continue to accumulate, the hazard reappears. Thus, hazard reduction must be a continual process; it cannot be accomplished by a single fire.

The greatest fuel reductions occurred around the bases of the old pines usually greater than 18 inches (45.7 centimeters) d.b.h. In most cases, the fire consumed literally all dead fuel around these trees as far as the dripline, and as deep as to the mineral soil. Fuel sampling around the bases of these old pines showed fuel loadings as high as 2.34 pounds per square foot (11.4 kilograms per square meter), equivalent to 51 tons per acre (114 megagrams per hectare), before burning. However, around pole size trees 4 to 11 inches (10.2 to 27.9 centimeters) d.b.h. the area that burned to mineral soil generally extended out only a few inches from their bole. In the doghair thickets (< 4 inches [10.2 centimeters] d.b.h.), only the L layer needles and small twigs were consumed. In fact, the fires did not carry well through the thickets. Mineral soil was exposed to a very limited amount around the bases of some saplings.

Woody fuel 1 to 3 inches (2.54 to 7.62 centimeters) in diameter was reduced by 54%. Large woody fuel (greater than 3 inches [7.62 centimeters] in diameter) was reduced by 71%. Virtually all of the large rotten logs (91%) were totally consumed (99% weight reduction), but only about 14% of the large sound material weight was burned. The number of large sound logs remained essentially the same, indicating that the resistance to control was not completely eliminated. Loading of sound material was reduced by a decrease in the diameter of the pieces. By consuming the rotten punky material, however, part of the potential threat of firebrand (pieces of burning material) production and receptive ignition sites was eliminated. Where large woody fuels were totally consumed, the fine surface and ground fuels under and close to those large fuels were also consumed to mineral soil. White ash beds were common after the fires.

Despite the relatively moist burning conditions, the initial fire of our study at Limestone Flats in 1977 and the first fire since the turn of the century changed the fuel and stand conditions considerably (Table 1). An estimated 86% of the entire area burned. Fires did not travel well in the grassy area where green material was present. The fire exposed mineral soil on about 16% of the area, mostly around large, old pines. Dead fuel loading was reduced by about 43% (Table 1). High moisture content in the H layer was the cause of most of the difference between fuel consumption at Limestone Flats compared to Chimney Spring. Because the large fuels were wet, much of them remained. The number of sound logs was reduced by 60% and the number of rotten logs was reduced by only 34%; weights were reduced by 47% and 41%, respectively.

Potential rates-of-spread of surface fires were temporarily reduced at Limestone Flats by eliminating 86% of the surface fuels of the area during the initial burn. The lack of total consumption of large fuels leaves the resistance to control still present, but not nearly as great. Thus, prescribed burning in southwestern ponderosa pine can greatly, but only temporarily, reduce fuel hazard (Sackett 1980, Harrington 1981, Harrington and Sackett 1990). 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. However, because the fuel hazard reduction is temporary, 0.6 to 1.8 tons per acre (1.35 to 4.03 megagrams per hectare) of needle litter can be cast annually (Davis et al. 1968, Sackett 1980). Rapid burning litter fuels accumulate rapidly to hazardous levels after initial fuel reduction burns. Continual reburns are essential to remove the accumulation and generally maintain low fuel hazard (Sackett 1980, Harrington 1981).

Even though some plots in our study have been burned as many as 20 times, forest floor organic material is still substantial. Observations and measurements over the span of our study indicate that fires seldom consume more than the accumulation of material since the last fire (Figure 2). Organic material from remaining fires is generally not conducive to burning because of its physical condition (small, short, segmented needles, bark, and twigs) and because of the char layer that develops from the initial burn and is perpetuated by each successive burn. This char layer tends to retard ignition of material below it.

Tree Density Reductions

Fuel loadings that range from 8 tons per acre (17.9 megagrams per hectare) on yearly burn rotations to more than 13 tons per acre (29.1 megagrams per hectare) accumulating after 10 years without fire, suggest that the current southwestern ponderosa pine ecosystem probably is not comparable to the fuel loadings of open, parklike conditions attributed to presettlement conditions. In addition to a large amount of material on the ground impairing the reestablishment of Arizona fescue (*Festuca arizonica* Vasey) fuel continues to accumulate because of the density of the of the stands.

One objective of restoring fire to southwestern ponderosa pine is to thin the dense stagnated overstory. The initial burns at both research areas were instrumental in reducing some trees in the small diameter size classes. Because of heavy initial fuel loadings,

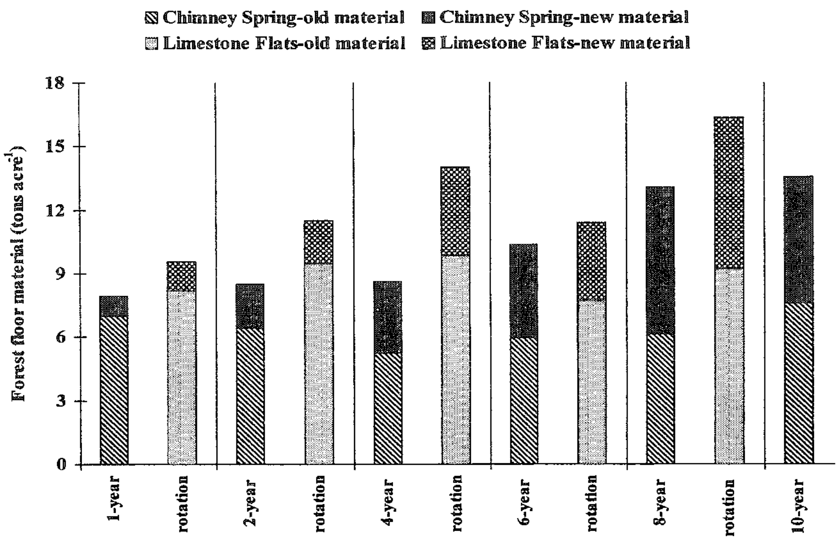

Fig. 2. Forest floor residual organic material (old) and material accumulated between burning rotations (new) at Chimney Spring and Limestone Flats study areas near Flagstaff, Arizona (Sackett and Haase 1996). To convert to metric use the following equation: megagrams per hectare = 2.2417 tons per acre.

fire behavior was restrained so that the overstory would not be severely damaged. As rotational burning progressed, we made a concerted effort to thin stagnated sapling thickets and dense small pole stands.

Historically, fire was the natural thinning agent that kept southwestern ponderosa pine forests open (Cooper 1960). Currently, fire can still be used effectively to reduce overstory competition and prevent natural regeneration from exceeding the space available for healthy growth. Using fire in current forest conditions is much different than the thinning that occurred naturally years ago. Stagnated thickets now generally consist of trees established in the 1914 and 1919 seed years (Schubert 1974). Therefore, trees are small in diameter, yet possess heavy bark. Instead of successfully girdling a young, thin-barked tree, excessive heat in the crown has been used to effectively kill individual trees in the current stands.

Current research has not dealt specifically with the problem of developing and using definitive burning techniques for stand thinning; most studies used only a single fire as an answer to the problem. From our results at Chimney Spring and Limestone Flats, quality of fuel appears to be essential for producing high-intensity fires in dense stands (Sackett et al. 1996 a), as well as quantity of fuel as Cooper (1961) suggests. Many of the prescribed fires ignited in our study resulted only in the newly cast needles (L layer) and upper portion of the F layer (FI layer) actually burning as flaming combustion in heavy, old forest floor accumulations (Sackett and Haase 1996). The lower F layer and H layer were matted and bound tightly together by mycelium hyphae. As a result, the lower portion of the F layer and H layer (FS layer) reacted more like solid pieces of fuel rather than like individual particles found in the well-aerated L layer. Thus, these layers did not burn well to thin the denser stands.

In an undisturbed, well-developed forest floor, newly cast needles can 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 or most of the material cast since the previous fire is consumed (for up to about 3 or 4 tons per acre [6.7 to 9.0 megagrams per hectare] of accumulation). Fire intensity, rate-of-spread, and flame length are much higher in response to the greatly increased available fuel. Therefore, repeat burning in higher quality and quantity fuel more effectively thins stagnated stands.

From observations of our study, we found that crown scorch and consumption kills trees and thins stands more effectively than bole girdling. Many of the stagnated sapling stands arose from the famous 1914 and 1919 seed crops and subsequent regeneration. Although the trees have grown little in diameter, height and bark thickness have progressed more normally during the past 80 years. The unusually thick bark has prevented heat of low-intensity fires from penetrating and killing the trees. Subsequent burns in deep litter have resulted in high-intensity fires that cause extensive crown damage, yet do not damage the bole.

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 downhill), progress very slowly with short flame lengths and low intensities. Backing fires seldom thin stands of small diameter trees.

Using ignition techniques that interact with one another is probably the most effective way to thin stands (Sackett 1968). For example, a heading fire and a backing 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 heading and backing 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).

Natural Regeneration

Current fuel loadings contribute to the lack of natural regeneration in southwestern ponderosa pine. Fuel depth around large mature trees, where new seedlings would be most appropriate to perpetuate the stand, can average more than 3.5 inches (8.9 centimeters) with corresponding average weight of roughly 39 tons per acre (87.4 megagrams per hectare) (Sackett 1984). This thick mat of dead material can reduce the chance for seeds to reach mineral soil, where germination can take place most effectively. Forest floor material in the F layer in undisturbed stands is tightly held together by mycelium hyphae. Haase (1981) found that the bond is even tighter at the F and H layer interface and that 85% of the seeds never penetrate the H layer to reach mineral soil under these mature ponderosa pines. Heavy forest floor layers also inhibit moisture penetration. Although seeds will germinate in duff moistened by summer rains, the seedlings usually die when their roots fail to reach mineral soil before the onset of fall drought conditions.

There was a banner seed year at Chimney Spring during 1976. The results of that seed cast became apparent when seedlings began to appear soon after the summer rains started in mid-July 1977 and were concentrated in areas where forest floor consumption was sufficient to expose some mineral soil, generally on mature pine sites and where heavy fuels were consumed (Sackett 1984). Surveys showed burned plots had 2,600 seedlings per acre (6,425 seedlings per hectare) compared with 833 seedlings acre per (2,058 seedlings per hectare) on unburned control plots. Two years later, burned plots still supported 500 seedlings per acre (1,236 seedlings per hectare) whereas none remained on the control plots.

A 1984 seedling survey at Chimney Spring revealed a more pronounced regeneration success. During 1983, seeds were cast at a rate possibly rivaling that of 1919. By summer 1984 the burned plots were carpeted with new seedlings. One plot each of the 4-, 6-, and 8-year rotation treatment replicates was randomly selected and surveyed extensively, as well as one of the unburned control plots. The burned seedbeds averaged over 90,786 (SE=17,572) seedlings per acre (224,332 seedlings per hectare). The unburned plot had 26,354 seedlings per acre (65,121 seedlings per hectare). In fall 1984 the 4- and 8-year burning rotation plots were reburned. By 1988, the following seedling distribution was found: all seedlings were killed on the plots burned with 8 years accumulation of litter, 7,840 seedlings per acre (19,373 seedlings per hectare) remained on the plot burned with 4 years accumulation of litter, 15,464 seedlings per acre (38,212 seedlings per hectare) remained on the 6-year rotation plot burned before seed fall, and only 1,252 seedlings per acre (3,094 seedlings per hectare) remained on the controls.

Over the 18-year course of burning at Limestone Flats, natural regeneration was never as pronounced as at Chimney Spring (Sackett et al. 1996 b). Before burning in the fall of 1995, however, seedlings were surveyed on annual, biennial, and 6-year rotation burn plots. Newly germinated seedlings (average number per acre) were measured +/− 1 standard error (SE) on each of the three treatment plots before burning: 1-year, 39, 930 (12,184) [98,667 per hectare]; 2-year, 9,529 (1,040) [23,546 per hectare]; 6-year, 13,166 (6,041) [32,533 per hectare].

Even the oldest seedbed (time since last burned) had excellent regeneration. Despite that a 6-year accumulation of litter is as much as 3 to 4 tons per acre (6.73 to 8.97 megagrams per hectare), it is in a form that (1) seeds can drop down through to mineral soil, and (2) the needles act as a mulch against evaporation. Obviously, many of these seedlings were consumed by the fall fires, but for managers who would like to promote and encourage the survival of their seedlings, protecting them from fire would be a simple process.

Nitrogen Cycling

In addition to the accumulation of unnaturally large amounts of hazardous fuels in southwestern ponderosa pine forests, there is also the concern that productivity may be reduced and nutrient cycling may be stagnated (Arnold 1950, Cooper 1960, Biswell 1972, Weaver 1974). Fire exclusion has been blamed for degrading the nitrogen status because it results in the accumulation of organic material in an environment of very low decomposition rates. Decomposition rates for southwestern ponderosa pine borders on desert-like conditions (Harrington and Sackett 1992). This ultimately binds nitrogen in forms unavailable for plant uptake.

At Chimney Spring an additional set of plots was established in 1982 to study effects not considered when the original study was established and to add a 3-year burning rotation treatment. Nitrogen cycling was investigated as a result of burning in initial fuel loads associated with the three major overstory groups in the ecosystem: saplings, poles, and mature old growth (Covington and Sackett 1992). Before burning, these different stands of overstories had 12.0 (SE=0.19), 17.5 (SE=2.28), and 55.1 (SE=1.51) tons per acre (26.9, 39.2, and 123.5 megagrams per hectare) of forest floor fuel, respectively. Unburned control plots had similar loadings (Table 2). Burned under warm, dry, fall weather, consumption of forest floor

Table 2. Mean and standard errors (SE) of forest floor loadings before and after initial burns at Chimney Spring, 1982 (from Covington and Sackett 1992).

	Preburn loading	Postburn loading	Percent consumption
	tons per acre [megagrams per hectare]		
Burned plots			
Old-growth	55.1 (1.51) [123.52]	11.2 (1.79) [25.11]	79.7
Poles	17.5 (2.28) [39.22]	7.5 (1.10) [16.81]	57.1
Saplings	12.0 (0.19) [26.90]	7.9 (0.42) [17.71]	34.2
Unburned plots			
Old-growth	40.6 (4.77) [91.01]	—	—
Poles	17.8 (1.04) [39.90]	—	—
Saplings	11.5 (0.55) [25.78]	—	—

material ranged from 34% in sapling stands to more than 79% in old-growth groves.

Results from these additional study plots showed burning caused immediate changes in ammonium-nitrogen (NH_4^+-N) concentrations, but had no major immediate impact on nitrate-nitrogen (NO_3^--N) concentration. The greatest postburn NH_4^+-N concentrations were in the 0–1.97 inch (0–5 centimeter) soil depth of the old-growth stands, intermediate in the pole, and least in the sapling (Table 3). One year later, after the microrganisms started converting NH_4^+-N to NO_3^--N, concentrations of NO_3^--N rose drastically in the old growth from 0.109 (SE=0.004) to 18.6 (SE=2.6) milligrams per kilogram of soil, and substantially in the pole stands. Regression analysis revealed that forest floor consumption is directly proportional to preburn forest floor loading (Covington and Sackett 1992) and that postburn NH_4^+-N concentration in the 0–1.97 inch (0–5 centimeter) layer in the soil was directly proportional to consumption.

After initial burns had been applied to the two study areas, interval burn treatments commenced. Inorganic nitrogen concentrations were examined periodically over the course of burning. During 1980, at Chimney Spring, 1-, 2-, and 4-year rotations were sampled before and after the burn treatment for that year (Covington and Sackett 1986). By then, the annual plots had one initial burn and three repeat burns; the 2-year plots had one initial burn and one repeat burn; and the 4-year plots had only an initial burn. Soil samples collected before burning revealed elevated nitrogen levels on the 1- and 2-year rotations (Table 4). The 4-year rotation was considerably lower, indicating the surge in inorganic nitrogen from repeat burning only lasts for 3 or 4 years.

Effects on Understory Vegetation

In southwestern ponderosa pine forests, understory vegetation has declined steadily from the presettlement era to the present. The decline has long been attributed to the exclusion of fire and the subsequent increase in heavy forest floor accumulations and overstory densities (Cooper 1960, Biswell 1972). Burning at Chimney Spring and Limestone Flats has resulted in substantial changes in the understory (Sackett et al. 1994). Most evident is the abundance of disturbance invader species like mullein (*Verbascum thapsus* L.), toadflax (*Linaria dalmatica* L. Mill), and thistle (*Circium pulchellum* [Greene] Woot and Standl.). Mullein and toadflax are dominant on heavily burned sites around large old-growth trees that have died since the initial burns. Although some animals use these plants (Patton and Ertl 1982), none are considered favored by wildlife or cattle.

Table 3. Mean concentrations and standard errors (SE) of NH_4^+-N and NO_3^--N in ponderosa pine soils at the 0–1.97 inch depth (0–5 centimeter) (from Covington and Sackett 1992).

Overstory	Control	Preburn	Postburn
	milligrams per kilogram soil		
NH_4^+-N			
Old-growth	1.92 (0.05)	2.33 (0.06)	45.10 (1.81)
Poles	0.74 (0.04)	1.34 (0.21)	26.72 (2.22)
Saplings	0.76 (0.01)	1.29 (0.09)	8.28 (1.68)
NO_3^--N			
Old-growth	0.003 (0.029)	0.176 (0.004)	0.109 (0.014)
Poles	0.010 (0.001)	0.003 (0.000)	0.060 (0.004)
Saplings	0.013 (0.001)	0.008 (0.001)	0.023 (0.003)

Grass species respond to prescribed fires and wildfires differently, as noted throughout the literature. Generally, grass production is increased, but this depends on fire severity, season of burn, and overstory characteristics. Individual species will also respond differently. Arizona fescue and squirrel tail (*Sitanion hystrix* [Nutt.] J.G. Smith) usually show an increase in production 1 year after a fire (Harris and Covington 1983, Vose 1984), whereas mountain muhly (*Muhlenbergia montana* [Nutt.] Hitche.) requires a longer recovery period.

During 1992, vegetation was surveyed at the Chimney Spring study area on the control, 1-, 2-, 4-, and 8-year rotation plots before burning. Individual

Table 4. Mean concentrations and standard errors ( ) of NH_4^+-N for southwestern ponderosa pine surface soils burned at different intervals (from Covington and Sackett 1984).

Overstory Soil depth	Burning interval (number of burns) 1 yr. (4)	2 yr. (2)	4 yr. (1)
	milligrams per kilogram soil		
Old-growth			
0–1.97 inches (0–5 cm)	13.8 (1.66)	10.6 (1.06)	2.8 (0.38)
1.97–5.91 inches (5–15 cm)	10.5 (0.72)	8.0 (0.55)	2.0 (0.11)
Pole			
0–1.97 inches (0–5 cm)	11.9 (1.31)	11.4 (1.13)	2.0 (0.09)
1.97–5.91 inches (5–15 cm)	8.9 (0.60)	8.9 (0.60)	2.0 (0.06)
Sapling			
0–1.97 inches (0–5 cm)	14.3 (1.32)	10.9 (1.19)	2.0 (0.15)
1.97–5.91 inches (5–15 cm)	10.0 (0.85)	8.6 (0.48)	2.1 (0.10)

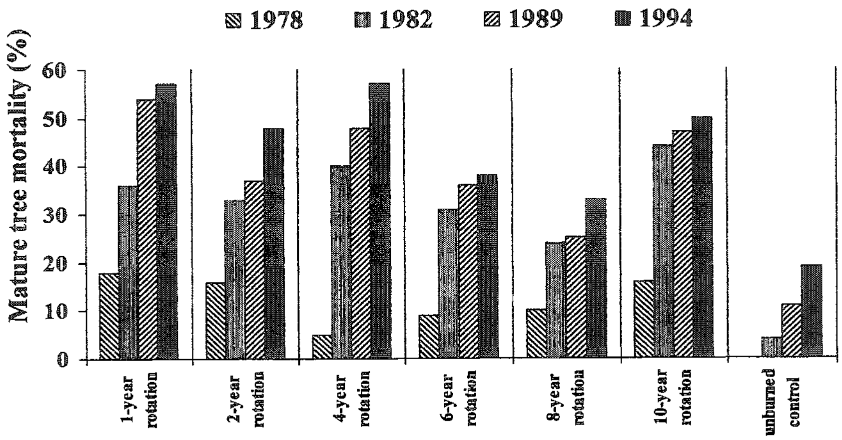

Fig. 3. Cumulative large tree mortality (%) occurring on different burning rotations at the Chimney Spring research area from 1978 to 1994.

plant occurrences were measured on subsample plots. Preliminary review of the data substantiates previous research. Production of mountain muhly and buckbrush (*Ceanothus fendleri* Gray) was reduced immediately after the prescribed burn. On the 4-year interval plots, mountain muhly had almost recovered to the level of the control plots (46 observations on burned plots, 53 observations on control plots), and the 8-year rotation plots had a much greater number of observations (92-burned, 53-control). The 2-year interval plots showed a small increase in the number of observations from the 1-year interval plots (38 and 32, respectively). Buckbrush appears to require a longer recovery time also. The 1-, 2-, and 4-year rotations had substantially fewer observations (6, 2, and 6, respectively) than the 8-year rotation and the control plots (17 and 19, respectively).

These data reflect density differences between burning rotation treatments. Evaluation by cover class shows that overall biomass production is greater in the burned plots because plants were visibly larger than those in the control plots. Current vegetation-response research focuses on the effect of small even-aged groups of ponderosa pine (Harris and Covington 1983, Oswald and Covington 1984, Vose 1984). The results show that the greatest vegetation response occurs in open mature timber stands or directly beneath the mature timber canopies. Generally, little change in vegetation is seen in pole stands or in the dense sapling stands.

Most current studies have measured responses on fall prescribed fires. If an increase in vegetation production is achieved by burning in the unnatural time of year (the fall), then an even larger increase in production could be expected by burning in the natural burning season of May to early July when green grass is not readily consumed. Also, burning in the fall eliminates the seed source, especially of Arizona fescue, by burning the seed heads.

Effects on Overstory

Diameter growth measurements were made in 1988 at Chimney Spring on pole stands within all burning rotation plots and control plots (Peterson et al. 1994). Dendroecological analysis showed only small changes in tree growth (compared to controls) in the first few years after the initial fire treatment, despite large fuel reductions and thinning. Moderate changes in growth compared to control trees were apparent after 1984. The 1-, 2-, 8-, and 10-year rotations had lower growth than controls, while 4- and 6-year rotations had slightly higher growth (Peterson et al. 1994). The reasons that only two of the rotations showed an increase are unclear. We have observed that 4- and 6-year rotations generally burn better with heavier forest floor consumption creating more NH_4^+-N release without causing undue damage to the pole overstory. Duplicate investigations at Limestone Flats that have not yet been analyzed may provide more insight to the question.

Prescribed fire at Chimney Spring and Limestone Flats has demonstrated its value for reduced fuel hazard, nutrient release, thinning, and regeneration through the consumption of heavy forest floors, but not without some liabilities. Consumption of these large quantities of fuel generates considerable amounts of heat. Temperature monitoring at the two sites shows very high mineral soil temperatures during burning (Sackett 1988). Lethal temperatures have been measured deeper than 8 inches in mineral soil on some sites. The initial burn at Chimney Spring killed more than 40% of the initial 302 old-growth ponderosa pine trees (Figure 3), which had survived numerous presettlement fires (Dieterich 1980). Mortality did not appear until several years after the initial burns and has continued to be greater than on unburned sites.

Fires under these old-growth pines are often unspectacular, consuming only the loosely packed upper layer of the forest floor (Fl layer) in the flaming fire front and with most of the forest floor (FS layer) being consumed as glowing and smoldering combustion, which is often unnoticed. As glowing and smoldering combustion continues for up to 72 hours, ash is formed from the top down in most cases, creating an insulating cover (Sackett 1988). The insulation prevents much of the heat from escaping, causing it to penetrate the soil.

Burning for long periods of time can result in either temperatures exceeding 140°F (60°C), which causes instant cambium or root death, or lower temperatures for longer durations that can also kill plant tissue.

Preburn fuel loadings in the mature ponderosa pine sites selected to measure temperatures ranged from 32 to 86 tons per acre (71.7 to 192.8 megagrams per hectare) or 1.47 to 3.95 pounds per square foot (7.18 to 19.3 kilograms per meter) where soil temperatures were actually measured. Consumption was always greater than 85%, despite humus layer moisture content up to 90%. In 22 of 25 cases the temperature 2 inches (5.1 centimeters) below the soil surface reached 140°F. At the 8-inch (20.3-centimeter) depth, temperatures exceeded 100°F (38°C) in 21 cases and averaged 138°F (59°C). Even at 12 inches (30.5 centimeters) below the soil surface, temperatures reached greater than 115°F (46°C).

Tree cambiums are also affected by the consumption of heavy forest floor accumulations. Sloughed bark and heavy dense duff compressed against the tree's bole generate considerable heat during burning. Temperatures measured at the cambium, where forest floor material was consumed, ranged from 61°F (16°C) to more than 230°F (110°C). The average for 14 test fires was 144°F (62°C), high enough to kill cambium tissue. We are now testing economical methods to protect old-growth trees deemed essential by managers.

SUMMARY

After 19 and 20 years of research at Limestone Flats and Chimney Spring, respectively, considerable information has been gleaned from more than 310 individual fires that were conducted on these sites. This paper summarizes only a small portion of the data from these fires. As old questions are answered, a whole new crop of questions arise. Although the use of prescribed fire by itself may not be the only tool to restore southwestern ponderosa pine ecosystems to a semblance of their former state, it is restoring a valuable process back into an environment that evolved with fire.

The benefits of restoring fire to southwestern ponderosa pine ecosystems through prescribed burning far outweigh any detrimental effects that developed during a century of fire exclusion. Substantial benefits accrue from repeated burning on a frequent timetable. We hope the benefits highlighted in this paper will provide an impetus for forest managers to incorporate prescribed fire into their ecosystem management plans.

LITERATURE CITED

Arnold, J.F. 1950. Changes in ponderosa pine-bunchgrass ranges in Arizona resulting from pine regeneration and grazing. Journal of Forestry 48:118–126.

Biswell, H.H. 1972. Fire ecology in ponderosa pine-grassland. Tall Timbers Fire Ecology Conference Proceedings 12:69–96.

Brown, J.K. 1974. Handbook for inventorying downed woody material. General Technical Report INT-16, U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT.

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

Cooper, C.F. 1960. Changes in vegetation, structure, and growth of southwest pine forests since white settlement. Ecological Monographs 30:129–164.

Cooper, C.F. 1961. The ecology of fire. Scientific American 304: 150–160.

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

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

Covington, W.W., and S.S. Sackett. 1990. Fire effects on ponderosa pine soils and their management implications. Pages 105–111 *in* J.S. Krammes (ed.). Proceedings of the symposium on effects of fire management of southwestern natural resources. General Technical Report RM-191, U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO.

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

Davis, J.B., P.F. Ffolliott, and P.W. Clary. 1968. A fire prescription for consuming ponderosa pine duff. Research Note RM-115, U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO.

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

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

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

Harrington, M.G. 1991. Soil water potential in burned and unburned ponderosa pine sites in Arizona. Proceedings of the Fire and Forest Meteorology Conference 11:343–351.

Harrington, M.G., and S.S. Sackett. 1990. Using fire as a management tool in southwestern ponderosa pine. Pages 122–133 *in* J. Krammes (technical coordinator). Effects of fire management on southwestern natural resources. General Technical Report RM-191, U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO.

Harrington, M.G., and S.S. Sackett. 1992. Past and present fire influences on southwestern ponderosa pine old growth. Pages 44–50 *in* M.R. Kaufmann, W.H. Moir, and R.L. Bassett (technical coordinators). Old growth forests of the Southwest and Rocky Mountain Region—proceedings of a workshop. General Technical Report RM-213, U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO.

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

Kallander, H. 1969. Controlled burning on the Fort Apache Indian Reservation, Arizona. Tall Timbers Fire Ecology Conference Proceedings 9:241–250.

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

Patton, D.R., and M.G. Ertl. 1982. RUNWILD wildlife/habitat relationships. Wildlife food plants of the Southwest. Wildlife Unit Technical Series, U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO.

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

Sackett, S.S. 1968. A field trial for regulating prescribed fire intensities. Fire Control Notes 9:5–6.

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

Sackett, S.S. 1980. Reducing natural ponderosa pine fuels using prescribed fire: two case studies. Research Note RM-392, U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO.

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

Sackett, S.S. 1988. Soil and cambium temperatures associated with prescribed burning in two mature ponderosa pine stands in Arizona. Page 281 *in* D.M. Baumgartner and J.E. Lotan (eds.). Proceedings ponderosa pine the species and its management. Washington State University, Pullman.

Sackett, S.S., and S.M. Haase. 1992. Measuring soil and tree temperatures during prescribed fire with thermocouple probes. General Technical Report PSW-131, U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, Albany, CA.

Sackett, S.S., and S.M. Haase. 1996. Fuel loadings in southwestern ecosystems of the United States. Pages 187–192 *in* P.F. Ffolliott, L.F. DeBano, M.B. Baker, Jr., G.J. Gottfried, B. Solis-Garza, C.B. Edminster, D.G. Neary, L.S. Allen, and R.H. Hamre (technical coordinators). Effects of fire on Madean Province ecosystems. General Technical Report RM-289, U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO.

Sackett, S.S., S.M. Haase, and M.G. Harrington. 1994. Restoration of southwestern ponderosa pine ecosystems with fire. Pages 115–121 *in* W.W. Covington and L.F. DeBano (technical coordinators). Proceedings-Sustainable ecosystems: implementing an ecological approach to land management. General Technical Report RM-247, U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO.

Sackett, S.S., S.M. Haase, and M.G. Harrington. 1996a. Prescribed burning in southwestern ponderosa pine. Pages 178–186 *in* P.F. Ffolliott, L.F. DeBano, M.B. Baker, Jr., G.J. Gottfried, B. Solis-Garza, C.B. Edminster, D.G. Neary, L.S. Allen, and R.H. Hamre (technical coordinators). Effects of fire on Madean Province ecosystems. General Technical Report RM-289, U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO.

Sackett, S.S., S.M. Haase, and M.G. Harrington. 1996b. Lessons learned from fire use for restoring southwestern ponderosa pine ecosystems. Pages 54–61 *in* W.W. Covington and P.K. Wagner (technical coordinators). Conference on adaptive ecosystem restoration and management: restoration of Cordilleran conifer landscapes of North America. General Technical Report RM-278, U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO.

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

Vose, J.M. 1984. Establishment and growth of common understory plants following prescribed fire in an Arizona ponderosa pine community. Thesis. Northern Arizona University, Flagstaff.

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

Weaver, H. 1974. Effects of fire on temperate forests: western U.S. Pages 279–310 *in* T.T. Kozlowski and C.E. Ahlgren (eds.). Fire and ecosystems. Academic Press, New York.