Fire Effects on Ponderosa Pine Soils and Their Management Implications[1]

W. W. Covington and S. S. Sackett[2]

Abstract.—Fire in southwestern ponderosa pine induces changes in soil properties including decreasing the amount of nutrients stored in fuels (forest floor, woody litter, and understory vegetation), increasing the amount of nutrients on the soil surface (the "ashbed effect"), and increasing the inorganic nitrogen and moisture content in the mineral soil. Soil temperatures are increased above lethal levels under heavy fuels, probably killing both microbes and roots. Soil pH appears not to be substantially affected by burning in this forest type. The greatest changes in soil properties occur where heavy fuels are consumed; therefore, the magnitude of the impacts for most soil characteristics should decrease along the sequence from piled slash, to old growth substands, to pole substands, to sapling stands.

Fire has played an important role in southwestern ponderosa pine *(Pinus ponderosa)* forests from pre-settlement times. Fire exclusion was the general protection policy throughout the first half of this century. Now, prescribed burning is being used in southwestern ponderosa pine forests, in large part as a response to extensive crown fires resulting from heavy fuel accumulations during the earlier fire suppression period.

Wright (1978) and Lotan et al. (1981) provide general information on fire effects on vegetation in ponderosa pine forests. Both of these references will lead the reader to earlier works. The effects of fire on soils in ponderosa pine have not been synthesized before this. However, Wells et al. (1979) present a general review of fire effects on soils in North America and it has several references to fire effects in ponderosa pine. Many of the general principles drawn from fire effects literature in other forest types are discussed by Covington and DeBano (this volume). We will not repeat those discussions in this paper.

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[2]Professor, School of Forestry, Northern Arizona University, Falgstaff, AZ 86011; and Research Forester, Pacific Southwest Forest and Range Experiment Station, at the Station's Forest Fire Laboratory, 4955 Canyon Crest Drive, Riverside, CA 92507.

This paper synthesizes information regarding the effects of fire on soils in southwestern ponderosa pine. The intended audience for this paper is managers and others interested in ponderosa pine fire management in the Southwest. Where specific studies of fire effects on some soil properties in the Southwest are lacking, we have drawn inferences from studies conducted in other regions and other forest types. We have clearly identified where the inferences are based on research in other types, but the reader. should be cautious about these extrapolations.

SOUTHWESTERN PONDEROSA PINE FORESTS

Ponderosa pine forests cover almost 11 million of the 26.5 million acres of commercial forest land in Arizona, Colorado, New Mexico, and Utah (Schubert 1974). Although individual ponderosa pine trees occur at elevations below 1,830 m (6,000 ft) and above 3,050 m (10,000 ft), ponderosa pine forests reach their best development in the Southwest between 2,130 and 2,380 m (7,000 and 7,800 ft) (Schubert 1974). At lower elevations ponderosa pine forests usually abut pinyon-juniper woodlands or chaparral; at higher elevations they grade into mixed conifer forests. Southwestern ponderosa pine forests are characteristically a mosaic of small, even-sized patches of: (1) large old-growth trees, which became established before European settlement in the 1870's, (2) intermediate sized trees, which became established around the turn of the century, and (3) small saplings, which became established around 1914-1930 (Cooper 1960, Schubert 1974, A. White 1985). The following tabulation presents general size and age classes for these substands as suggested by Covington and Sackett (1984).

Substand type	d.b.h. (inches)	Age (years)
Old growth	> 11	200-500
Pole	4-10.9	80-120
Sapling	0-3.9	60-70

Ponderosa pine is the dominant tree species, but there is often an admixture of Gambel oak *(Quercus gambelli)*, pinyon pine *(Pinus edulis)* and junipers *(Juniperus spp.)*. The dominant understory species are usually grasses such as Arizona fescue *(Festuca arizonica)*, mountain muhly *(Muhlenbergia montana)*, and blue grama *(Bouteloua gracilis)*. Shrubs occurring in this type include buckbrush *(Ceanothus fendleriana)*, locust *(Robinia neomexicana)*, and currants *(Ribes spp.)*.

Southwestern ponderosa pine forests occur on a wide variety of soil types derived from igneous, metamorphic, and sedimentary parent materials. Soil depths and textures also vary greatly, with textures ranging from stony, cobbly sands and loams through clays and clay loams. Ponderosa pine site index is generally positively correlated with soil depth (Cox et al. 1960, Myers and Van Deusen 1960) and with the proportion of material less than 0.2 mm in diameter (Schubert 1974).

FIRE ECOLOGY

Frequent low intensity natural fires have shaped ecological patterns and processes in southwestern ponderosa pine ecosystems for millennia (Biswell et al. 1973, Cooper 1960, Pyne 1984, Weaver 1951). Natural fires burned through pre-settlement ponderosa pine forests in northern Arizona at intervals of 2-5 years (Di eterich 1980) However, following settlement the natural fire regime was disrupted. Beginning in mid-1870's, heavy livestock grazing decreased herbaceous fuel continuity and broke the continuity of the forest floor. Thus grazing, coupled with active fire suppression from the early 1900's, has resulted in the absence of natural fires from many of these ecosystems for over 100 years.

This fire exclusion has caused major changes in the fire regime and hence in the spatial pattern and ecosystem processes of these ecosystems (Kilgore 1981). Ponderosa pine forests have changed from open savannahs with relatively high herbaceous productivity to closed forests, where most of the production is in the trees. In addition to this shift in production, there is evidence for stagnation in both decomposition and nutrient recycling processes because of fire exclusion. The long absence of natural fire has been blamed for everything from dangerously high fuel loads (with an associated shift from frequent, low intensity understory fires to infrequent high intensity crown fires) to reduced productivity and stagnated nutrient cycles (e.g., Arnold 1950, Cooper 1960, Biswell 1972, Weaver 1974, and Covington and Sackett 1984).

Nitrogen volatilization from fuels consumed by burning has been a concern in ponderosa pine (e.g., Klemmedson 1976, Covington and Sackett 1984). On the other hand, fire exclusion in southwestern ponderosa pine may degrade the N economy of ponderosa pine forests by allowing litter to steadily accumulate, blocking the recycling of organically bound N into inorganic N forms (ammonium and nitrate), which are available for plant uptake (Biswell 1972, Covington and Sackett 1986). Since ponderosa pine ecosystem productivity is limited by low N availability (e.g., Wagle and Beasley 1968, Heidmann et al. 1979, Cochran 1979, Powers 1980), a major concern has been fire effects on inorganic N concentrations in the mineral soil.

Nitrogen distribution in ponderosa pine forests is correlated with the general pattern of the overstory vegetation. Overstory, litterfall, and forest floor biomass are greatest in old growth patches, intermediate in pole-sized patches, and least in sapling patches (Covington and Sackett 1986, Ryan and Covington 1986). Estimates of unburned forest floor characteristics of ponderosa pine substands at the Chimney Spring Interval Burning Study Area (Covington and Sackett, unpublished) are presented in the following tabulation.

Characteristic	**Old growth**	**Pole**	**Sapling**
Forest floor (g/m^2)	106,900	55,200	35,200
Litterfall (total <10cm diameter, in g/m^2)	4,500	3,090	2,030
Decomposition rate (k)	0.042	0.056	0.058

Understory vegetation biomass is lowest immediately under the canopy of the old growth trees, highest in the openings between patches, and intermediate in the pole and sapling patches (Harris and Covington 1983, Oswald and Covington 1984, Andariese and Covington 1986). Thus, old growth patches have the greatest amount of nitrogen susceptible to burning, pole patches have an intermediate amount, and sapling patches have the least.

These differences are slight in unburned stands (Covington and Sackett 1986).

Substand Type	**Ammonium**	**Nitrate**
	(ppm)	
Old growth	1.51	0.18
Pole	0.96	0.01
Sapling	0.64	0.01

Nitrogen concentrations in the mineral soil are highest in old growth patches, intermediate in pole patches; and least in sapling patches; within a patch, the greatest concentrations are in the top horizons, decreasing with depth (Ryan and Covington 1986, Covington and Sackett 1986). Distribution patterns for other nutrients are not available.

Fire Effects on Plant and Litter Nutrients

The immediate impact of burning on soil nutrients is conversion of much of the organically bound nutrients in the forest floor, woody debris, and herbaceous vegetation into their inorganic forms. Whether these inorganic nutrients remain on site as solids or are lost through volatilization depends upon the temperatures reached during the burning and the differential volatilization temperatures of the nutrients (Wells et al. 1979, DeBano, this volume). Nutrients with a relatively low volatilization temperature (N, P, and S) are likely to have some loss to the atmosphere in most fires, whereas nutrients with high volatilization temperatures (Ca, Mg, and K) are, for the most part, left behind in ash.

The greatest loss of volatile nutrients and the greatest ash deposits from the less volatile nutrients occur where fuels are highest, such as in the old growth patches or in piled slash. (Covington and Sackett 1984, 1986; Ryan and Covington 1986). Klemmedson (1976) estimated the impacts of slash burning on N budgets in ponderosa pine near Flagstaff, Arizona. He found that approximately 58 kg/ha of N was lost from the slash and forest floor 10 months after burning. However, he pointed out that it was not possible from his study to determine how much of this unaccounted for N had actually been lost. Some nutrients volatilized from the forest floor and slash are transferred to the mineral soil (see below). To minimize risk of N loss, slash piles should be put where forest floor loads are low (Klemmedson 1976).

Fire Effects on Soil Nutrients

Soil Nitrogen

Inorganic nitrogen concentrations in the mineral soil have been shown to increase after burning. Burning increased soil ammonium by as much as twentyfold in ponderosa pine near Flagstaff (table 1).

Numerous processes may be involved in long term changes in N in the mineral soil, such as higher microbial mineralization after burning, leaching from ash, and decreased uptake because of root mortality, (e.g., Ryan and Covington 1986, Covington and Sackett 1986). However, measurements of soil N after burning in ponderosa pine indicate ammonium increases within the first 24 hours (Covington and Sackett,1990). Transfer of ammonia from the burning fuel is the most likely source. Ammonium can be produced during a fire through pyrolysis of organic nitrogen compounds (Christensen 1973, DeBano et al. 1979, Mroz et al.1980). Since N is transferred from the burning fuel to the mineral soil, unless increases in mineral soil N after burning are accounted for, one would tend to overestimate the amount of N lost by volatilization to the atmosphere.

Inorganic N increases were greatest in old-growth substands, intermediate in the pole substands, and least in the sapling substands (Covington and Sackett 1986; Ryan and Covington 1986). Fuel loads and proportion of forest floor burned were highest in the old growth, intermediate in the pole, and least in the sapling substands, and ammonium concentrations followed a similar pattern. This correlation between fuel consumption and ammonium concentration suggests that differences in post-burn ammonium concentrations were due to differences in fuel consumption (Covington and Sackett, 1990).

These increases in inorganic N concentrations in the mineral soil are short lived, in the absence of repeated burning. By 4 years after an initial burn in ponderosa pine near Flagstaff, AZ, differences between burned and control plots were slight (around 1 ppm for ammonium-nitrogen. (Covington and Sackett 1986). However, burning at shorter intervals (1-2 years) maintained inorganic N concentrations (ppm) in the mineral soil which were 6-15 times higher than controls (Covington an Sackett 1986).

Substand type	**Controls**	**Burns** 2-yr interval	**Burns** 4-y interval
Old growth	1.51	10.64	2.8
Pole	0.96	11.37	2.0
Sapling	0.64	10.90	2.0

Table 1.—Inorganic nitrogen concentrations (ppm) in the 0-5 cm depth of the mineral soil immediately after burning (Covington and Sackett, 1990).

Substand type	Ammonium		Nitrate	
	Control	Burn	Control	Burn
Old growth	2.33	45.10	0.11	0.18
Pole	1.34	26.72	0.01	0.06
Sapling	1.29	8.28	0.01	0.02

Soil pH

Burning in some forest types may cause increases in soil pH (e.g., Grier 1975, DeByle and Packer 1976). Because most southwestern ponderosa pine forest soils are near neutral already, however, one would expect little change in pH after burning in this type. After prescribed burning ponderosa pine near Flagstaff, Arizona, Ryan and Covington (1986) found no significant change in soil pH on a basalt site (pH ranged between 6.2 and 6.5). Campbell et al. (1977) also found no difference in pH for soils with sedimentary parent material between burned and unburned soils after a wildfire in ponderosa pine in northern Arizona (pH was 5.9). However, Fuller et al. (1955) found an increase of up to 1.1 pH units in both duff and mineral soil following burning in ponderosa pine on a sedimentary derived soil. It is not clear why Fuller et al. (1955) found changes while Campbell et al (1977) and Ryan and Covington (1986) did not.

Soil Moisture

By changing the amount and type of vegetation and the forest floor, as well as the soil texture and wettability, fire can cause both short and long term changes in soil moisture relations. Fire in southwestern ponderosa pine has been shown to increase soil moisture content (Milne 1979, Ryan and Covington 1986, Ower 1985, Haase 1986). Campbell et al. (1977) found that runoff efficiency increased from around 0.8 percent for unburned areas to 3.6 percent from areas severely burned by a wildfire in ponderosa pine. Peak flows were almost 400 times greater from the severely burned areas. They attributed these effects to reductions in vegetation and forest floor cover and to the formation of hydrophobic layers in the soil; infiltration was only 2.5 cm/hr on severely burned areas as compared with 6.9 cm/hr on unburned areas.

Soil Temperature

Fuel load, fuel moisture, amount of fuel consumption, soil moisture content, and soil texture all influence the amount of total heating and the peak temperatures reached in the mineral soil after burning (Wells et al.1979). The amount of fuel consumed is the single most important factor in determining temperature change with burning. Under slash, natural woody debris, or the deep forest floors under old growth patches, soil temperatures can be quite high after burning. Sackett (unpublished data) has found lethal temperatures to a depth of 15 cm where heavy forest floors were almost completely consumed.

Over the longer term, burning can alter soil temperatures indirectly because of fire-induced changes in the albedo and shading of the soil. Darker, unshaded soils with little forest floor would tend to have warmer soils with wider swings in diurnal temperature than unburned soils (Wells et al.1979). At a site near Flagstaff, Milne (1979) observed that soil temperatures were higher by 4-5 degrees centigrade at 6-15 cm depth on burned plots 1 year after burning compared with control plots.

Soil Microbes

Burning can alter microbial activity either directly through sterilization or indirectly through changes in soil temperature, moisture, and pH, or by changing organic matter quality and allelopathic properties. Little direct evidence of the effects of fire on soil microbes in ponderosa pine is available. However, forest floor decomposition was increased after prescribed burning in ponderosa pine near Flagstaff (Covington and Sackett 1984).

There is also evidence in the literature for increased microbial nitrification after prescribed burning in ponderosa pine. Using a laboratory incubation method, C. White (1985) found substantial increases in nitrifycation 6 months after prescribed burning in ponderosa pine in New Mexico. Higher nitrification *in situ* might be caused by warmer soil temperatures and higher soil moisture conditions after burning (Milne 1979, Ryan and Covington 1986), as well as by fire-caused decreases in allelopathy. Lodhi and Killingbeck (1980) found evidence for allelopathic inhibition of nitrification in both the forest floor and the mineral soil of ponderosa pine stands. C. White's (1985) results provide evidence for the role of fire in denaturing these allelopathic agents.

The high temperatures reached where slash piles, woody debris, and heavy forest floors are consumed undoubtedly cause extensive mortality of some microbes. The delay in nitrate increases after burning in ponderosa pine may be attributed to sterilization effects on nitrifiers (Ryan and Covington 1986, Covington and Sackett, 1990). As noted by Dunn et al. (1979), sensitivity to temperature is greatest for fungi, intermediate for nitrifiers, and least for heterotrophic bacteria.

IMPLICATIONS FOR PRODUCTIVITY

An important question that needs to be answered to assess the impacts of burning on ecosystem processes is this: What is the fate of the additional soil N availability? Some of the nutrients are undoubtedly leached from the site. However, since most of the inorganic N is in the ammonium form, which is tightly held on cation exchange sites in the soil (Ryan and Covington 1986, Covington and Sackett 1986), one would expect little to be leached from the ecosystem. Since these soils rarely have anaerobic conditions, denitrification losses would also be minimal. The most likely fate of the additional soil N availability is uptake by vegetation and immobilization by microbes. Evidence for uptake by vegetation comes from observations of higher N concentrations (mg/g) in grasses, pine needles, and needle fall on burned sites (data are from Harris and Covington 1983 and Covington and Sackett, unpublished).

Component	**Nitrogen**	
	Control	**Burn**
Grasses	13.9	18.9
Pine needles	11.7	13.1
Needle fall	3.4	4.3

The large increases in available N in the mineral soil after burning are likely the primary cause of (1) increased seedling establishment of both herbaceous vegetation (Vose 1984, Vose and White 1987) and ponderosa pine (Sackett 1984), and (2) higher herbaceous production and greater foliar N concentrations (Harris and Covington 1983, Oswald and Covington 1984, and Andariese and Covington 1986). This mechanism is supported in part by results from Harris and Covington (1983) who found the greatest increases in foliar N in their old growth substands with moderate increases in poles and saplings, consistent with the pattern for soil N described above.

Increased nitrogen availability after burning may enhance revegetation after burning in ponderosa pine ecosystems. The most severe fires and the greatest understory (Vose 1984, Vose and White 1987) and overstory (personal observation) mortality typically occur in the old growth patches where fuels are the heaviest. In these same patches, available N is the highest after burning. This nutrient enrichment enhances revegetation and recovery of the severely burned sites.

Revegetation of the severely burned old growth substands is rapid Nose 1984, Vose and White 1987). Growth rates of individual plants can be exceptional. Sackett (1984) reported 6-yr old ponderosa pine seedling heights of up to 60 cm on nearby prescribed burned plots in contrast with a normal height of 15-20 cm for 6-yr old ponderosa pine seedlings on similar unburned sites.

These diverse lines of evidence point to the conclusion that prescribed burning in southwestern ponderosa pine increases N availability and ecosystem productivity.

SUMMARY AND MANAGEMENT IMPLICATIONS

Burning in southwestern ponderosa pine increases soil nitrogen and moisture availability. These increases in nitrogen result in higher nutrient concentrations both in the understory and in the overstory vegetation. Greater ponderosa pine seedling establishment and growth as well as increases in understory production may be attributed in part to this increased N and moisture availability.

In the absence of repeated burning, these ameliorated soil conditions appear to be short lived. At one site, burning at a 2 year interval (which approximates the natural fire regime for that site) seemed to maximize soil N availability.

The effects of burning on forest floor mass, soil N, and understory production vary widely among old-growth, pole, and sapling patches. Burning prescriptions for ponderosa pine that fail to account for this spatial variability in both pre-treatment conditions and post treatment response ignore a fundamental ecological characteristic of this type and are likely to produce unforeseen consequences. This is especially important in decisions regarding reintroducing natural fires, managing wilderness, or maintaining old growth.

For stands which, because of harvesting or wildfire, do not have this spatial heterogeneity, the land manager can now better predict the consequences of prescribed burning. However, caution should be exercised in extending the results from the literature, especially for the old growth and sapling substands (which cover small areas), to larger areas (e.g., hundreds of hectares).

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