Effects of Fire on Pinyon-Juniper Soils

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Pinyon-juniper woodlands occupy between 25 and 32 million ha in the western United States (Arnold et al. 1964, Clapp 1936, Kuchler 1964,) and more than 5.7 million ha in Arizona and New Mexico (Springfield, 1976). Pinyon-juniper woodlands in Arizona and New Mexico are located at elevations from 1300 to 2300 m. These woodlands are characterized by a mosaic of pinyon and juniper trees surrounded by interspaces, occupied by sparse to dense herbaceous and shrubby vegetation. The principal tree species are: pinyon pine (Pinus edulis), Mexican pinyon (P. cembroides Zucc.), Utah juniper (Juniperus osteosperma), one-seed juniper (J. monosperma), alligator juniper (J. deppeana) and Rocky Mountain juniper (J. scopulorum). The dominant understory species in southwestern pinyon-juniper is blue grama [Bouteloua gracilis (H.B. K.) Lag.] although other herbaceous and shrubby plants may be present (Pieper 1977, Springfield 1976). These pinyon-juniper woodlands occur in the transition zone between semiarid vegetation (i.e., chaparral, desert shrub or grasslands) and coniferous forests.

Not only do pinyon-juniper stands vary widely in structure and species composition, but also they occupy soils derived from a broad range of parent materials including granite, basalt, cinders, limestone, sandstone, and mixed alluvium (Aldon and Brown 1971). Soils vary in texture from stony, cobbly and gravelly sandy loams to clay loams and clay, and vary in depth from shallow to deep (Springfield 1976, Pieper 1977).

In pinyon-juniper woodlands, a soil nutrient mosaic pattern develops where carbon, nitrogen (N), and available phosphorus (P), are concentrated in the upper soil layers under the tree canopy. This pattern reflects the accumulation of litter by different plant species (Barth 1980, Charley and West 1975, Everett et al. 1986, Lyons and Gifford 1980, Klopatek 1987). Tree growth rates vary widely between sites in close proximity to one another. Although N is usually considered the most limiting nutrient in forest ecosystems (Maars et al. 1983), it appears P and potassium (K) may also be limiting in pinyon-juniper ecosystems (Barrow 1980, Bursderson et al. 1985).

Wildfires were common in the pinyon-juniper type before European settlement (Leopold 1924) and probably restricted the establishment of pinyon-juniper woodlands in savannas to isolated stands of trees occupying shallow, rocky soils which would not support grasses (Burkhardt and Tisdale 1969, O'Rourke and Odgen 1969, Johnsen 1962). Heavy grazing in the late 1800's and early 1900's eliminated fuel continuity, and this, combined with an active fire suppression policy, decreased fire occurrence throughout this type (Wright et al. 1979). Fire exclusion, coupled with decreased grass competition, may have encouraged tree invasion into former grasslands (Wright et al. 1979).

Prescribed burning has been used in pinyon-juniper in four situations: (1) broadcast burning, (2) burning individual trees, (3) burning grassland areas, and (4) burning slash (Arnold et al. 1964). The first three burning situations are used mainly for range improvement. Slash burning is used both during range improvement and after fuelwood harvesting. However, fire severity (used here to mean relative heating and impact on ecologic processes) and behavior and its effect on the soil resource is very different under these four burning situations. Very severe fires are prescribed to consume as much of the tree as possible if the objective is to kill mature trees. Grassland areas are burned primarily to kill invading seedlings and younger trees; for this, the fire is mainly a light fire that is carried by the grass cover. Slash disposal during range improvement programs involves burning mature trees that have been killed mechanically or chemically. If the slash is piled and burned, severe soil heating can occur because large

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Abstract—The purpose of this paper is to synthesize published information on fire effects in pinyon-juniper and other forest and woodland types to draw inferences about likely effects on soils in pinyon-juniper woodlands in the Southwest. In contrast to many other types, fire effects in pinyon-juniper vary greatly from point to point because of the spatial heterogeneity of the fuels.
amounts of fuel are burned on small areas. Some sites east of Flagstaff, where slash has been pushed into piles with bulldozers and then burned have remained devoid of vegetation for well over twenty years (personal observation). When the slash is broadcast and burned, fuel loading is less and fire effects are spread out over a larger area. If these fine fuels (small diameter, i.e., <1-2 inches in diameter, branches, twigs, and needles) are piled, intense fires may severely affect small localized areas of soil under the piles.

In summary, fire effects in pinyon-juniper are not well understood. Pinyon-juniper woodlands vary widely both geographically and from point to point within a particular location. Although some research has been reported on nutrient relationships in pinyon-juniper soils (Barth 1980, Bunderson et al. 1985), few studies have been done on the effects of burning on nutrient availability or other soil characteristics (DeBano et al. 1987, Gifford 1981). The purpose of this paper is to synthesize published information regarding the effects of fire, both wildfire and controlled burning, on soils in pinyon-juniper woodlands in the Southwest. The intended audience for this paper is managers and others interested in fire management of pinyon-juniper woodlands. For fire effects on some soil properties, there are no studies in pinyon-juniper woodlands. In these cases we have drawn inferences from studies in other types and from our understanding of general principles relating to fire effects in forests and woodlands. However, the reader should be cautious about an overreliance on research based on other types.

Related Literature

Several review papers serve as useful references for fire effects in pinyon-juniper woodlands. Wells et al. (1979), in the state-of-knowledge review of fire effects on soil, present an excellent overview of fire effects on soil in general and contains several references to pinyon-juniper woodlands. In a parallel publication, Lotan et al. (1981) review the effects of fire on flora, including two pages on pinyon-juniper woodlands. Fire effects on fuels have been summarized by Martin et al. (1979), in that same state-of-knowledge series. The final review paper we recommend that managers read is by Wright et al. (1979), in which they review the role and uses of fire in pinyon-juniper woodlands as well as sagebrush-grass communities.

Fire Effects In Pinyon-juniper

Nutrient Distribution in Pinyon-juniper Woodlands

Pinyon pine and juniper trees cycle nutrients both horizontally (Tiedemann 1987) and vertically (DeBano et al. 1987). Tree roots penetrate into interspace soils between tree canopies where they absorb nutrients and incorporate them into tree biomass. A large portion of the nutrients captured from interspaces are deposited on the soil surface under trees during leaf fall, where they are released in an available form by decomposition, thereby enriching the upper soil layers. Trees also translocate nutrients vertically to the soil surface from deeper in the soil profile by a similar process. However, little is known about variations in the quantity of nutrients cycled by trees.

Published information on nutrient patterns in pinyon-juniper woodlands clearly portrays strong vertical and horizontal distribution patterns developing from the above described nutrient cycling processes. The most important vertical compartments are: aboveground biomass, litter, and soil. Nutrients are also distributed and exchanged horizontally between trees and interspaces. The quantities of nutrients stored in soils under tree canopies have been reported by some authors to be greater than those in interspaces (Everett et al. 1986, Tiedemann 1987), but in other cases no significant differences could be detected (DeBano et al. 1987). We used information presented in the literature on N, P, and K to develop a model portraying vertical nutrient distribution patterns under trees and in associated interspaces for a typical pinyon-juniper ecosystem (table 1). Data on N presented in table 2 for a pinyon-juniper ecosystem were taken from Tiedemann (1987). Distributions of P and K were taken from DeBano et al. (1987) where soils data for the 0-3.8-cm depth was extrapolated linearly to 60 cm.

Important features of the vertical distribution pattern are: (1) less than 20 percent of the total nutrient pool resides in plant biomass and litter, and (2) differences in the proportion of a nutrient stored in living biomass and litter were present among the three nutrients. For example, under tree canopies higher proportions of N are present in litter and above-ground biomass compared to P and K. About 98 percent of total P in the tree dominated patches is contained in soil compared to 93 percent for K, and 82 percent for N. Horizontally, N, P, and K are concentrated in a mosaic pattern corresponding to litter and canopy distribution. Although total N, P, and K in the soil may, or may not, differ significantly beneath tree canopies and interspaces, more total N, P, and K accumulates in live tree boles, stems, and leaves and in litter under tree canopies than in interspace vegetation (DeBano et al. 1987).

Nutrient Availability

A delicate balance exists between available and total nutrients in unburned pinyon-juniper woodlands because only a small percent of the total nutrient pool is in a readily
available form. Available nutrients exhibit vertical and horizontal distribution patterns similar to total nutrients. Horizontal patterns of nitrate and ammonium are influenced by tree canopy distribution, with higher concentrations of ammonium being found in the surface soil under tree canopies compared to interspaces (DeBano et al. 1987). In contrast, nitrate may or may not differ between trees and interspace areas (DeBano et al. 1987, Klopatek 1987, Thran and Everett 1987).

**Amount and Consumption of Fuels**

Little data are available for fuels and fuel consumption during prescribed burns although some qualitative estimates have been made of fuel consumption during wildfires (Martin et al. 1979). A study of sixteen wildfires in Arizona showed that fires occurring on flat to gently rolling terrain tend to burn intensely — consuming all available ground fuels, killing most of the trees, and leaving the dead skeletons of the trees standing (Arnold et al. 1964). Natural ground fuels are rarely heavy in pinyon-juniper stands and probably never exceed 1 to 3 tons per acre. Wildfires occurring during strong winds, low relative humidities, and air temperatures above 90°F can destroy nearly all the trees and remove all the understory vegetation and litter (Arnold et al. 1964).

Nomograms have been developed for singleleaf pinyon (Pinus monophylla) and Utah juniper (Juniperus osteosperma) trees which relate different-sized fuels quantitatively to crown area (Meeuwig et al. 1979). These relationships were originally developed for estimating biomass and fuel loading from aerial photos. Although these nomograms were developed in Utah and Nevada, Utah juniper is an important component of southwestern pinyon-juniper woodlands making these relationships useful for estimating fuel consumption from wildfires or prescribed burning used as part of fuelwood harvesting and range improvement projects.

The fuel distribution presented in table 2 indicates that during severe wildfires where all the tree and litter are consumed by fire, about 19 kg/m² of pinyon and 11 kg/m² of juniper biomass would be lost, in addition to 7.5 kg/m² of litter. Intense prescribed fires burning under extreme conditions would be similar to wildfires and could also consume nearly all the plant and litter biomass. Likewise, the same level of biomass loss

<table>
<thead>
<tr>
<th>Table 1. Amounts of nitrogen, phosphorus, and potassium (kg/ha) in aboveground biomass and the 60-cm soil depth under trees and associated interspaces in pinyon-juniper woodlands and percent in each ecosystem compartment.</th>
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<tr>
<td>Ecosystem compartment</td>
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<td>Trees</td>
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<td>Twigs</td>
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<td>Wood</td>
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<td>Litter</td>
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<td>Soil (0 - 60 cm)</td>
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<td>Interspaces</td>
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<td>Soil</td>
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<sup>1</sup> Data from Tiedemann 1987
<sup>2</sup> Data from DeBano et al. 1987
<sup>3</sup> Percent of total nutrient pool made up by a particular ecosystem compartment.

<table>
<thead>
<tr>
<th>Table 2.—Amount (kg/m²) of different-sized fuels and litter directly under the canopies in pinyon and juniper trees having an average canopy diameter of 6.5 m (from Meeuwig et al. 1979).</th>
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</thead>
<tbody>
<tr>
<td>Fuel</td>
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<tr>
<td>Foliage</td>
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<tr>
<td>Stems &lt;64 cm</td>
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<td>Stems (64-2.5 cm)</td>
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<td>Stems (2.5-7.5 cm)</td>
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<tr>
<td>Stems (&gt;7.5 cm)</td>
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<td>Litter</td>
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<sup>1</sup> Number represents kg/m² of tree canopy area.
<sup>2</sup> Number is percent of the total tree biomass.
would occur during a fuelwood harvesting operation if all the slash were completely burned and surface litter destroyed. There are opportunities to reduce nutrient losses during a fuelwood operation by burning only litter accumulations produced by former tree canopies. It is also possible during slash burning operations to burn under cooler burning conditions so that not all the slash is consumed. Under the most conservative slash burning operation most of the foliage and stems less than 2.5 cm in diameter would most likely be consumed, leaving about 20 percent of the total plant biomass on the site.

Effect of Heating on Soil Properties

The spatial distribution of soil properties in soils under pinyon-juniper woodlands makes some soil properties more vulnerable to surface heating than others. Living organisms and soil organic matter are concentrated on, or near, the soil surface and decrease exponentially with depth. This surface location exposes organic matter directly to heat radiated downward during burning. As a result, organic material and related soil properties are more likely changed than those concentrated in subsurface layers which are insulated against surface heating.

Soil chemical, physical, and microbiological properties strongly dependent on organic matter are susceptible to being changed by soil heating. For example, soil structure, cation exchange capacity, available nutrients, and microbial activity are all highly dependent upon organic matter, which begins changing chemically when heated to 200°C and is completely destroyed at 450°C (Hosking 1938). Soil organic matter is also important for maintaining aggregate stability and soil structure, which, in turn, affects infiltration and other hydrologic properties of soils. Microbiological properties most affected by heating are: heterotrophic bacteria, nitrifying bacteria, fungi, and mycorrhizae.

Effects on Nutrients Contained in Plants and Litter

The immediate effects of fire on nutrient content of the soil are the result of the interaction of nutrient volatilization and mineralization of nutrients stored in organic matter. Nutrients are volatilized at different temperatures, with N, P, and S having low volatilization temperatures and Ca, Mg, and K having relatively high volatilization temperatures (see DeBano, this volume). Thus, burning volatilizes much of the N, P, and S, but Ca, Mg, and K are left behind in ash, primarily as oxides.

Information on nutrient distributions from tables 1 and 2 can be combined with estimates of fuel consumption and used to assess the effect of fuelwood harvesting, or range improvement activities, on nutrient cycling and loss. Fuelwood harvesting alone, without using prescribed fire, would remove about 133 kg/ha of N in the woody material. However, if prescribed fire was used for slash disposal following harvesting, an additional 277 kg/ha of N would be volatilized from twigs and leaves (assuming 95 percent of the N is volatilized) in addition to variable amounts of the 1000 kg/ha of N contained in the litter. If large amounts of litter were consumed by fire during slash disposal operations then an additional loss of up to 400-500 kg/ha of N could occur. Fuelwood harvesting would have a lesser impact on P and K because it would remove only a small percentage of the P (5 kg/ha) and K (21 kg/ha). Substantial losses of P would also occur if the leaves and twigs were burned following fuelwood harvesting. Non-particulate losses up to 50% of the total P (16 kg/ha) could occur if these fine materials were totally consumed during burning (Raison et al. 1985). A variable amount of the P contained in the litter could also be lost depending on the intensity of the fire. Similar percentages of K may also occur because it volatilizes at the same temperature as P (Raison et al. 1985).

Effects on Nutrients in Soil

In addition to the immediate effects of fire on soil nutrients, fire may change the rates of: (1) nutrient mobilization (because of changes in allelopathic chemicals, moisture balance, temperature, and general soil chemistry), (2) nutrient leaching (through changes in vegetation cover and infiltration rates), and (3) nitrification (because of high ammonium substrate available for conversion to nitrate).

Since N and P have been shown to be the most limiting nutrients for a wide variety of forest and woodland types, we will concentrate our review on those elements.

Soil Chemical Properties and Nutrient Availability

Although large amounts of total nitrogen and phosphorus are lost during the combustion of plants and litter, available forms of these nutrients are higher in the ash and upper soil layers following a fire (Christensen 1973, DeBano et al. 1979, DeBano et al. 1987, DeBano and Klopatek 1988).

In southern Utah, slash burning in pinyon-juniper has been shown to increase soil P, total Kjeldahl N (TKN), K, and percent organic matter under the burned slash piles to a depth of 4 inches (Gifford 1981). Covington et al. (1986) found that slash burning caused immediate increases in ammonium proportional to the amount of fuel consumed. DeBano et al. (1987) found that slash burning in central Arizona caused a shift from ammonium to nitrate.
Covington et al. (in review), using a time series approach, found that most of the changes in N were in the first 5 years after slash burning in northern Arizona pinyon-juniper. During the first year ammonium increased from 1 ppm on unburned sites to over 100 ppm under burned slash piles. Nitrate was little changed at first; however, by year 2 after burning nitrate was over 50 ppm on burned sites and less than 0.5 ppm on unburned sites. These changes over time were attributed to a lag in the nitrification process. By 5-7 years after burning, ammonium and nitrate had returned to pretreatment levels.

Inorganic P is also released by burning, but it also is quickly immobilized chemically (DeBano and Klopacke, 1988) and may no longer be readily available for plants. The increased levels of extractable phosphorus produced during a fire slowly decrease and reach prefire levels in about one year. Highly available nitrogen and phosphorus provide a post-fire fertilizing effect until plant communities become established and are able to utilize this supply of available nutrients.

Soil pH Changes

Soil pH in some forest types has been shown to increase after burning (e.g., Grier 1975, DeBylde and Packer 1976) because of the deposition of Ca, Mg, and K oxides and their subsequent hydration into bicarbonates. As these bicarbonates are leached into the mineral soil they can cause an increase in pH up to 7 or so. Heating has also been shown to increase pH in some soils (Tarrant 1956). However, in soils which approach a neutral pH, such as occur throughout most of the pinyon-juniper type, no meaningful change in pH would be expected. This has been shown to be the case in southwestern ponderosa pine following prescribed burning, where both burned and control sites had pH's of 6.2-6.5 (Ryan and Covington 1986), near the equilibrium pH for bicarbonate.

Soil Moisture Relations

Burning can cause changes in soil moisture relations through its effects on interception by vegetation and litter, evaporation, transpiration, infiltration, and soil moisture tension. Since we could find no studies of fire effects on soil moisture relations in pinyon-juniper, we will have to rely on results from other types. However, again we caution the reader that these inferences should be regarded as tenuous until research in the pinyon-juniper type can be done.

Changes in interception of precipitation and transpiration would be greatest when burning kills pinyon and juniper trees and they are replaced by herbaceous vegetation, which has a lower plant surface area. The removal of tree cover, and the forest floor material occurring under the tree canopy, substantially reduces the interception surface of the ecosystem (Anderson 1976, Campbell et al. 1977). Reductions in interception would reduce evaporation and, all other things being equal, increase the amount of precipitation delivered to the soil surface.

Since interception plays such an important role in controlling evaporation from most arid and semiarid forest and woodland types, the net result should be an overall decrease in evaporation. However, higher soil temperatures resulting from the change in albedo (darker soil surface) most likely increases evaporation from the soil surface.

Once the water is delivered to the soil surface, the next factor is whether it infiltrates into the soil body or runs off as overland flow. Buckhouse and Gifford (1976) found decreased infiltration on pinyon-juniper sites where chaining debris had been burned and the sites had been seeded and grazed. However, research from other forest types shows a wide range of responses to burning, from decreases in infiltration (e.g., Zwolinski 1971, McMurphy and Anderson 1969), to no change (e.g., Veihmeyer and Johnson 1944), to increases (e.g., Scotter 1964). The extent to which water repellency may be involved in decreasing infiltration losses is unknown. However, based on work in chaparral (DeBano et al. 1976) and in southwestern ponderosa pine (Campbell et al. 1977), one would expect water repellancy on coarse textured soils (with less than 5% clay [DeBano et al. 1970]) under slash which has been burned. Although it has not been reported in burned stands, Scholl (1971) did observe a water repellent layer immediately beneath the litter of Utah juniper (Juniperus osteosperma); thus the potential for fire-induced water repellancy in pinyon juniper is likely. Nonetheless, since reports are so variable, it would be best to withhold judgement regarding the likely effects of burning on infiltration in southwestern pinyon-juniper woodlands for the time being.

The next factor is whether fire alters the capacity of the soil to retain water. Water holding capacity may be reduced by burning in some forest types, depending on the fire intensity. Where heavy fuels burn (e.g., slash piles) one would expect a reduction in water holding capacity in pinyon-juniper. However, the net effect on soil moisture content varies widely (Wells et al. 1979). Soil moisture tension might be expected to increase after burning in proportion to the amount of fuel consumed because of the increased ions leached from the ash. Finally, fire may reduce the amount of water taken up by plants by reducing the transpiring surface of the vegetation through mortality.

Soil Temperature

Soil temperatures during burning vary with depth and are affected by
fuel load, fuel moisture content, soil moisture content, and soil texture. The greatest heating and the highest temperatures would occur where heavy, dry fuels (e.g., slash piles) are burned over dry, coarse textured soils. However, the temperature gradient is typically steep.

For example, in relatively cool prescribed burns in ponderosa pine and incense cedar, duff temperatures were approximately 260 degrees C, surface temperatures reached only 93 degrees C, and at 2 inches the temperature was barely affected (Agee 1973). By comparison burning heavy windowed eucalyptus slash and logs caused temperatures of 666 degrees C just below the soil surface and 112 degrees C at a depth of 8.5 inches (Cromer 1967, Cromer and Vines 1966).

Pinyon-juniper slash burning should be intermediate between these two examples in its effects on soil temperatures.

**Effects on Soil Microbes**

Soil heating directly affects microorganisms either by killing them directly or altering their reproductive capabilities. Indirectly, soil heating alters organic matter, which increases nutrient availability, and stimulates microbial growth. Although complex interrelationships exist between soil heating and microbial populations in soils, it appears that duration of heating, maximum temperatures, and soil water all affect microbial responses (Dunn et al. 1979, 1985).

Microbial groups differ significantly in their sensitivity to temperature and can be ranked in decreasing sensitivity as: fungi > nitrite oxidizers > heterotrophic bacteria (Dunn et al. 1985). Fire has been reported to decrease vesicular-arbuscular mycorrhizae propagules in pinyon-juniper soils when soil temperatures reached 60°C or greater (Klopatek et al. 1988).

**Summary and Management Implications**

Before European settlement, wildfires burning at 10- to 30-year intervals restricted pinyon and juniper trees to rocky soils and outcrops throughout much of what today is extensive pinyon-juniper woodlands. Heavy grazing and active fire suppression allowed the encroachment of pinyon and juniper seedlings into what had previously been grassland.

Pinyon-juniper woodlands vary substantially widely from location to location and from point to point within a location. Fire is being used in pinyon-juniper woodlands for a variety of purposes including: (1) eradication of pinyon-juniper from areas of grassland it has invaded, (2) broadcast burning of fuelwood harvesting slash, and (3) burning of piled slash. Thus fire effects vary widely, depending upon the characteristics of the pinyon-juniper area being burned and the type of burn.

Generally speaking, the greatest impacts occur where fuel loads and fuel consumption are the greatest. Fuel loads in uncut stands are heaviest directly under the tree canopies. In harvested stands, fuel loads are greatest where slash is piled on top of canopy litter. Fuel loads are somewhat less when slash is piled in the interspaces, and much less when slash is broadcast. Fuel loads are least where herbaceous vegetation is dominant. Thus, the greatest impacts of fire in pinyon-juniper are very localized, occurring immediately under burned slash piles and burned canopy litter.

As is the case for other forest and woodland types, fire effects are the greatest at the soil surface, declining exponentially with depth. Burning volatilizes varying amounts of N and S (Tiedemann 1987), which are critical nutrients in limiting ecosystem productivity. However, cations (Ca, Mg, and K) as well as some P, N, and S are left behind in the ash. The nutrients in this ash plus some N as ammonium may be transferred into the soil thereby increasing soil fertility (the ashbed effect).

Although we could find no research on fire effects on soil moisture or temperature, some inferences can be drawn from research in other forest types. Soil moisture relationships after burning may be improved, degraded, or have no effect.

Soil temperatures produced during burning are affected by amount of fuels consumed, soil moisture, and soil texture. Lethal temperatures are very likely to be produced under burned slash piles and heavy canopy litter to some depth. Burning herbaceous vegetation and broadcast slash is not likely to increase soil temperatures substantially. These increased soil temperatures under heavy fuels most likely kill soil organisms and propagules.

Our review of the literature suggests that to minimize negative impacts of burning on the soil resource, if slash is to be burned at all, it should be broadcast in interspaces before being burned. Although some nutrients are lost to volatilization, this practice should result in moderate increases in nutrient availability and in short term productivity. However, other impacts of broadcast burning (such as possible reductions in understory production and tree seedling establishment) should be evaluated also.

Because burning unharvested pinyon-juniper is usually done under severe conditions (similar to a wildfire), soil heating and potentially negative impacts on soils are likely to occur under current fuel loadings.

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