Effects of Fire on Chaparral Soils in Arizona and California and Postfire Management Implications[1]

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Abstract: Wildfires and prescribed burns are common throughout Arizona and California chaparral. Predicting fire effects requires understanding fire behavior, estimating soil heating, and predicting changes in soil properties. Substantial quantities of some nutrients, particularly nitrogen and phosphorus, are lost directly during combustion. Highly available nutrients released during a fire are deposited on the soil surface where they are immobilized or lost by erosion. Information on the effect of fire on physical, chemical, and biological soil properties provides a basis for discussing short- and long-term consequences of postfire rehabilitation treatments on total. nutrient losses, changes in nutrient availability, decreased infiltration rates, and erosion. Arizona and California chaparral show both similarities and differences.

Chaparral occurs mainly in Arizona and California. It covers 1.3 to 1.5 million ha as a discontinuous band across Arizona in a northwest to southeast direction (Hibbert and others 1974). California chaparral, and associated woodlands, cover about 5 million ha extending from Mexico north to the Oregon border (Wieslander and Gleason 1954; Tyrrel 1982).

Prescribed burns and wildfires occur frequently throughout chaparral in Arizona and California. In California, wildfires can occur during any month of the year, although they are most severe during Santa Ana winds in late summer and fall. Most severe fire conditions in Arizona are in spring and early summer before summer rains start and then again during late fall after the summer monsoon season has ended. Prescribed burning can be done in both types throughout the year, although most burns are conducted during periods of less severe burning conditions. Because both wild and prescribed fires occur frequently throughout chaparral, land managers are continually asked to assess fire effects on different resources while developing postfire rehabilitation plans. The objectives of this paper are to (1) compare Arizona and California chaparral, (2) outline an approach for assessing fire effects in chaparral soils, (3) present a detailed summary of fire effects on soil properties in chaparral, and (4) discuss postfire management concerns.

ARIZONA AND CALIFORNIA CHAPARRAL

Both California and Arizona chaparral originated from Madro-Tertiary geoflora during the Cenozoic era (Axelrod 1958). The two types separated during the mid-Pliocene Epoch in response to major topographic-climatic changes, which produced the present climates in both ecosystems. Greatest climatic differences between the two regions are in amount and distribution of precipitation. Arizona chaparral receives about 400-600 mm precipitation annually, distributed bimodally with approximately 55 percent occurring during the winter from November through April, and the remaining 45 percent during summer convection storms in July through September (Hibbert and others 1974). California chaparral developed under a Mediterranean-type climate, which receives about 660-915 mm precipitation annually, primarily during the cool winters, the summers being hot and dry (Mooney and Parsons 1973). This difference in climate is reflected in the growth patterns of the two chaparral ecosystems. Growth in California chaparral occurs primarily during winter and spring, contrasted to a spring and summer growing season for Arizona chaparral. Differences in plant genera and species also exist between Arizona and California chaparral. Arizona chaparral is devoid of the "soft chaparral" or coastal chaparral communities [composed of black sage (*Salvia* spp.) and buckwheat (*Eriogonum* spp.)] and chamise chaparral (*Adenostoma* spp.), both of which are common in California (Horton 1941). Several genera, however, are common to both Arizona and California [e.x.: oak (*Quercus*), ceanothus (*Ceanothus*), and mountainmahogany (*Cercocarpus*)]. Several species found in the Lower Sonoran desert--catclaw acacia (*Acacia*

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[1]Presented at the Symposium on Fire and Watershed Management, October 26-28, 1988, Sacramento, California.

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greggi Gray), catclaw mimosa (Mimosa biuncifera Benth), mesquite (Prosopis juliflora Swartz DC)--extend into the Arizona chaparral (Knipe and others 1979). Also, postfire successional patterns differ slightly between the two ecosystems in that dense stands of short-lived deervetches (Lotus spp.) and lupines (Lupinus spp.) are sometimes present in immediate postfire seral stages in California chaparral, but are absent in Arizona.

Comparative information on aboveground biomass and soil nutrients in Arizona and California chaparral is sketchy, although published data show similar amounts of total nitrogen (N) and phosphorus (P) in litter and soils, indicating both ecosystems have adapted similarly to edaphic and climatic limitations of their respective environments (DeBano and Conrad 1978; Mooney and Rundel 1979; Pase 1972; DeBano, unpublished data[3]). Comparative data available on readily extractable ammonia- and nitrate-N in unburned soils show the upper soil layers under Arizona chaparral contain higher concentrations of ammonia-N (5-20 •g/g) than California chaparral (1-2 •g/gm), but both ecosystems containing similar nitrate-N (1-2 •g/gm) (Christensen and Muller 1975; DeBano and others 1979a; DeBano, unpublished data[3]). Nitrogen and phosphorus are limited in both ecosystems, and vegetation growth responds to these fertilizers (Hellmers and others 1955; DeBano, unpublished data[3]).

Although differences in vegetation composition, successional patterns, climate, and soil nutrients exist between Arizona and California chaparral, it is unlikely that these differences substantially affect the general relationships and conclusions concerning fire effects presented below. Similarity of fire behavior probably overwhelms any inherent differences present in the two ecosystems. Known quantitative differences between the two systems will be indicated where data are available.

ASSESSING FIRE EFFECTS

Predicting fire effects in soils is a three-stage procedure; namely: (1) characterizing fire intensity, (2) relating fire intensities to soil heating, and (3) predicting changes in chemical, physical, and biological soil properties in response to different soil heating regimes. Characterizing fire intensity and its relationship to soil heating will be discussed briefly, but more detail is published elsewhere (DeBano 1988).

[3]Data on file, Rocky Mountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture, Tempe, Ariz.

Characterizing Fire Behavior and Intensity

Large differences in fire behavior commonly experienced between prescribed burns and wildfires in most forest ecosystems makes data on fire effects studies in forested ecosystems of limited value when predicting fire effects in chaparral. The reason for this being that wildfires in forests spread rapidly through the crowns of standing live and dead trees. As a result, large amounts of canopy (leaves, twigs, and in some case boles) are consumed along with substantial amounts of surface needles and leaf litter. This releases large amounts of thermal energy very rapidly, causing substantial soil heating. In contrast, prescribed fires in forests behave much differently, because they are designed to burn much cooler, thereby consuming only part of the surface needles and litter. These are often referred to as "cool" fires. However, fire in chaparral is carried through the shrub canopy during both wild and prescribed fires. As a result, fire intensity and the resulting soil heating during prescribed burns compared to wildfires in chaparral are not as great as occurs between these two types of fire in forests. For example, only minimal soil heating occurs during a cool burning prescribed fire in forests compared to low intensity fires in chaparral (fig. 1A, B).

Although canopy consumption occurs during prescribed burning in chaparral, fire intensities in chaparral vary considerably and, as a result, produce different amounts of soil heating (fig. 1B, C). Marginal burning conditions produce less intense fires, which consume only part of the canopy, leaving substantial amounts of unburned litter on the soil surface. Although not all the canopy may be consumed during a fire, the remaining tops will die and contribute to dead fuel loading for a future fire. Recently improved aerial ignition techniques have allowed successful prescribed burning to be done during marginal, and safer, burning conditions, which also reduces the impact of fire on the underlying soil. The availability of new research information along with these modern ignition techniques allows managers to develop burning prescriptions, which can minimize fire intensity, and thereby reduce the fire effects on chaparral soils.

Predicting Soil Heating

Fire intensity can be characterized in several ways, but those indices related to rate of combustion and amount of aboveground biomass and litter consumed during a fire are probably most applicable for assessing soil heating. Heat produced during burning is both dissipated upward into the atmosphere and radiated downward toward the soil and litter surface. If heat radiates directly on dry soil not having a litter layer, the heat will be transmitted slowly into the soil. When thick litter layers are present, secondary combustion can occur in the litter, further contributing to soil heating.

Soil heating can best be illustrated by a conceptual model depicting a soil profile being exposed to surface heating by energy radiated downward from the burning canopy. Although most of the energy generated during combustion is lost upward into the atmosphere, a small, but significant, quantity is absorbed at the soil surface and transmitted downward into the soil. It has been estimated that about 8 percent of the total energy released during a chaparral fire is transmitted into the underlying soil (DeBano 1974). Heat impinging on surface of a dry soil is transferred by particle-to-particle conduction and convection through soil pores. Heat transfer in wet soils is mainly by vaporization and condensation of water. Dry soil is an excellent insulating material, and heat is conducted into the underlying soil slowly. In contrast, wet soil conducts heat more rapidly at temperatures below the boiling point of water. Differences in heat capacity of dry and wet soil also exist, with wet soils absorbing more heat per degree of rise in temperature than dry soils, because water has a greater specific heat capacity than mineral soil.

Although abundant information is available on fire intensities in different vegetation types, only a few attempts have been made to develop mathematical models relating fire intensity to soil heating (Albini 1975; Aston and Gill 1976). These models have not been particularly successful and, as a result, semi-quantitative methods are being used instead. One such method for chaparral involves classifying fire intensity as light, moderate, or intense, based on the visual appearance of burned brush and litter (Wells and others 1979). After burning intensity has been placed in one of the above classes, soil heating can be estimated from curves developed by DeBano and others (1979b). These soil temperatures can then be used to predict changes that will be produced in different soil properties. Currently a slightly different approach is being developed for estimating N and P losses. This method is based on the relationship developed by Raison and others (1984) between nutrient loss and percent consumption of organic matter.

EFFECT OF HEATING ON SOILS

The spatial distribution of soil properties in a typical soil profile makes some properties

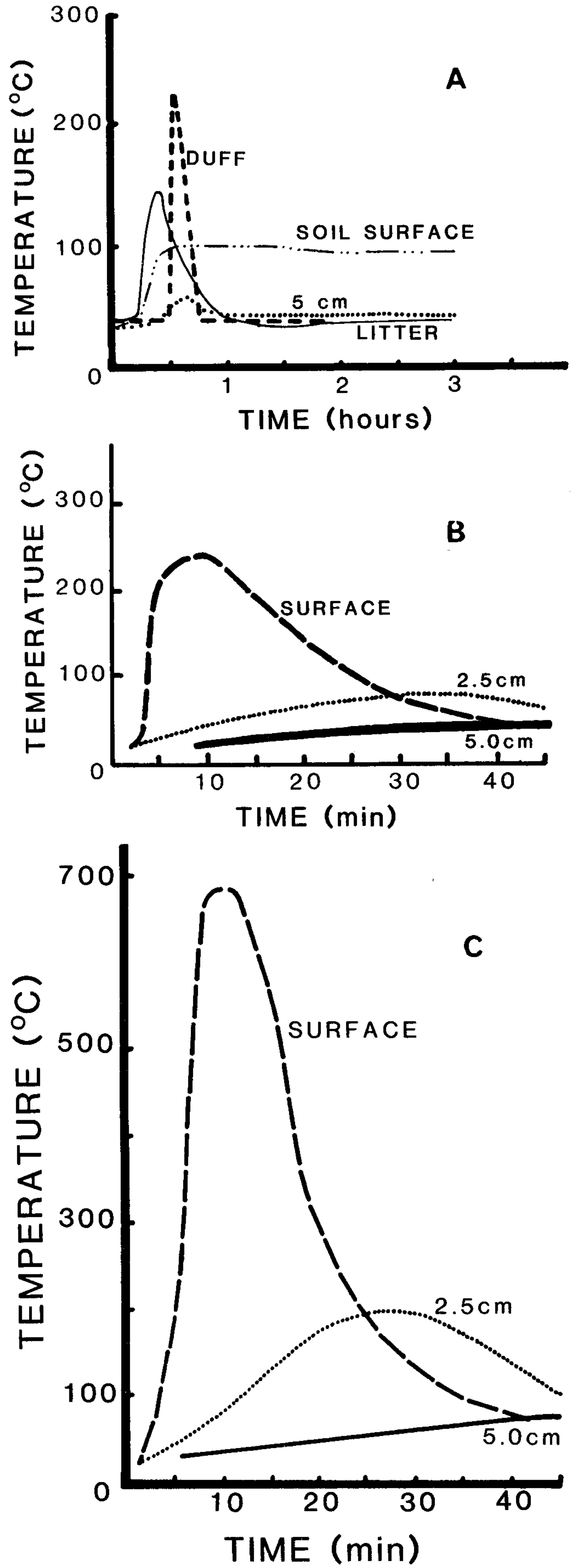

Figure 1--Soil and litter temperatures during A, a cool-burning prescribed forest fire; B, a low-intensity prescribed fire in chaparral; and C, a chaparral fire approaching wildfire intensities (DeBano 1979).

more vulnerable to surface heating than others. For example, living organisms and soil organic matter are concentrated at or near the soil surface and decrease exponentially with depth. Therefore, organic matter is directly exposed to heat radiated downward during a fire. As a result, soil chemical, physical, and microbiological properties most strongly related to organic matter are most 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). Cation exchange capacity of a soil depends not only on humus, but also on clay colloids. Humus is concentrated at, or near, the soil surface and thereby directly exposed to heating. In contrast, clay formed by pedogenic processes is usually concentrated deeper in the soil profile, although sometimes clays are found near the surface. Soil organic matter is also important for maintaining aggregate stability and soil structure, which in turn affects infiltration and other hydrologic properties of soils such as water repellency. Soil chemical properties most readily affected are total and available forms of N, P. and sulfur (S); and cation exchange capacity. Microbiological properties regulating input, loss, and availability of nutrients may also be significantly changed by soil heating. These include organic matter decomposition, N-fixation, and nitrification.

Soil Chemical Properties and Plant Nutrients

Fire acts as a rapid mineralizing agent that releases plant nutrients from organic fuel materials during combustion and deposits them in a highly available form in the ash on the soil surface (St. John and Rundel 1976). Large amounts of some nutrients such as N, S, and P can be volatilized during a fire (Raison and others 1984; Tiedemann 1987). Over 150 kg/ha of total N has been reported lost during a chaparral fire (DeBano and Conrad 1978). Cations such as calcium (Ca), magnesium (Mg), potassium (K), and sodium (Na) are not volatilized, although small amounts can be transferred from the site in smoke (Clayton 1976).

Although large amounts of total N and P are lost during burning, extractable ammonium-N and P are increased in the ash and upper soil layers (Christensen and Muller 1975; DeBano and others 1979a). Ammonium-N is highest immediately after burning, but is quickly converted to nitrate-N by nitrification. A study in Arizona showed ammonium-N in surface 0-2 cm layer was increased from 6 to 60 •g/g, nitrate-N remained at about 2 •g/g, and extractable P increased from 6 to 16 •g/g during a prescribed fire (DeBano, unpublished data3). Similar responses have been measured in California chaparral, but the levels of ammonium-N and nitrate-N are generally less (Christensen and Muller 1975; DeBano and others 1979a). Available N and P produced during the fire increase the supply of available nutrient in the soil until plants become established and are able to utilize them. The elevated levels of available N and P found immediately after burning decrease to prefire levels in about 1 year.

Soil Physical Properties

Soil physical properties dependent on organic matter, such as soil structure and infiltration, are directly affected by fire. The destruction of soil structure reduces pore size and restricts infiltration. More importantly, burning decreases soil wettability (DeBano 1981). During fires, organic matter in the litter and upper soil layers is volatilized. Most of the volatilized organic matter is lost upward in the smoke, but a small amount moves downward into the soil and condenses to form a water-repellent layer that impedes infiltration. Downward movement of vaporized materials in soil occurs in response to steep temperature gradients present in the surface 5 cm of soil. The degree of water repellency formed depends on the steepness of temperature gradients near the soil surface, soil water content, and soil physical properties. For example, coarse-textured soils are more susceptible to heat-induced water repellency than finer textured clay soils. Water-repellent layers can totally restrict infiltration and produce runoff and erosion during the first rainy season following fire (DeBano 1981; Wells 1981).

Soil Microbiology and Seed Mortality

Soil heating directly affects microorganisms by either killing them directly or altering their reproductive capabilities. Indirectly, soil heating alters organic matter, increasing nutrient availability and stimulating microbial growth. Although the relationship between soil heating and microbial populations in soil is complex, it appears that duration of heating, maximum temperatures, and soil water all affect microbial responses (Dunn and others 1979, 1985). Microbial groups differ significantly in their sensitivity to temperature; they can be ranked in order of decreasing sensitivity as fungi>nitrite oxidizers>heterotrophic bacteria (Dunn and others 1985). Nitrifying bacteria appear to be particularly sensitive to soil heating; even the most resistant *Nitrosomonas* bacteria can be killed in dry soil at 140° C and in wet soil at 75° C (Dunn and others 1979). Physiologically active populations of microorganisms in moist soil are more sensitive than dormant populations in dry soil.

Soil heating during a fire affects postfire germination of seeds in the litter and upper soil layers. Germination of seeds produced by some chaparral brush species is stimulated by elevated temperatures during fire (Keeley 1987). Both maximum temperatures and time of exposure affect survival and germination of ceanothus seeds (Barro and Poth 1988). As for microorganisms, lethal temperatures for seeds are lower in moist soils than in dry.

MANAGEMENT IMPLICATIONS

Postfire rehabilitation needs to address both short- and long-term fire effects on total nutrient losses (particularly N), changes in nutrient availability, decreased infiltration rates, and erosion.

Nutrient Losses

Although several plant nutrients are lost directly during combustion and by erosion following fire, N is most important because larger amounts are lost, and it is the most limiting nutrient in chaparral ecosystems (Hellmers et al. 1955). Therefore, postfire rehabilitation planning must consider mechanisms available for replenishing N to assure long-term productivity.

The amount of N lost during burning will vary depending upon the amount of aboveground biomass, litter, and soil organic matter pyrolyzed during a fire. Studies in California chaparral showed that 150 kg/ha of N were lost by volatilization and an additional 15 kg/ha by erosion after fire (DeBano and Conrad 1976, 1978). This loss represented about 11 percent of the N in plants, litter, and upper 10 cm of soil before burning. If this amount had been lost from the site during each fire over the many millennia during which chaparral vegetation has been evolving, and no mechanism existed for replenishing it, then the site would be completely devoid of N.

Several mechanisms are available for restoring N lost during a fire. These include input by bulk precipitation and N-fixing plants and microorganisms. Bulk precipitation is estimated to restore about 1.5 kg/ha annually, which is not sufficient to restore the N lost if it is assumed chaparral burns every 25 to 35 years (Ellis and others 1983). The annual input of N may be substantially greater in localized areas having large amounts of airborne N pollutants present such as the Los Angeles Basin. For example, Riggan and others (1985) found annual inputs of 23.3 and 8.2 kg/ha of N as canopy throughfall and bulk precipitation, respectively.

An important source of N replenishment appears to be by N-fixing microorganisms. It was initially thought that short-lived, nodulated legumes--deervetches and lupines--may replace a large amount of N lost during fire (DeBano and Conrad 1978). However, recent estimates of N-input by these legumes was only about one-half that gained from precipitation (Poth and others 1988). Nitrogen fixation by asymbiotic organisms is also low, amounting to about 1 kg/ha annually. It now appears that the most likely source of ecosystem N is biological N-fixation by actinomycete-nodulated shrubs such as birchleaf mountainmahogany and perhaps ceanothus (*Ceanothus leucodermis*). However, a paradox still exists regarding N loss during a fire, production of highly available N, and the role of N-fixing legumes in restoring N after fire. Although large amounts of total N are lost, high concentrations of available N are present on the soil surface immediately following burning. The problem is further complicated because N-fixation by legumes is suppressed by high concentrations of available N. Furthermore, poorly aerated soil may lead to denitrification, which further increases N losses resulting from fire. Therefore, it becomes important in postfire planning to favor establishment of N-fixing shrubs, which can effectively fix N after the high levels of available N released during the fire have been immobilized. Both ammonium-N and nitrate-N generally drop to prefire levels within a year following fire.

Another postfire rehabilitation treatment that can affect N-fixation is competition among introduced plants used for erosion control, and native plants. For example, reseeding annual grasses may compete with either short-lived legumes immediately after fire or, more importantly, with seedling establishment of longer term N-fixers--mountainmahogany and ceanothus--or even sprouting species (Conrad and DeBano 1974). Undesirable competition by reseeded grasses after fire would probably affect N replenishment in California chaparral more adversely than in Arizona because short-lived legumes are absent immediately after fire in Arizona. Longer term effects of grass on shrubs should be similar in the two ecosystems because both ecosystems contain both mountainmahogany and ceanothus.

Nutrient Availability

The question frequently arises whether there is a need to fertilize as part of postfire rehabilitation. Fertility assessment trials show burned soils have a greater available N supply than unburned soils (Vlamis and others 1955). Similarly, N fertilizer responses were not detectable on field plots immediately following fire (DeBano and Conrad 1974). Postfire responses to P fertilizers are more variable because some soils can rapidly fix available P produced during burning (Vlamis and others 1955; DeBano and Klopatek 1988). The preponderance of research results seems to indicate that fertilization is probably not a desirable treatment immediately following burning. In fact, fertilization may have a depressing effect on N fixation because additional amounts of highly available N are added to already high levels produced by burning. Also, the high levels of available N following fire could lead to increased denitrification in poorly aerated soils. The advisability of P fertilization is less clear but it may, be of little advantage in those soils that irreversibly fix available P. In summary, fertilizing in the "ash" is not a recommended postfire treatment, and fertilizers should not be applied for at least 1 year following burning.

Erosion

There are limited opportunities for preventing, or reducing, erosion on chaparral soils burned during wildfire conditions. Grass reseeding has been widely used in postfire rehabilitation. The usefulness of ryegrass reseeding for postfire erosion reduction has not been clearly established because of the limited opportunities for grass to become established before active erosion occurs during the first year following fire. It is also extremely difficult to design studies clarifying the relationship between grass establishment and erosion because of the high variation encountered under field conditions (Barro and Conard 1987). Ryegrass competition may also indirectly interfere with establishing native plants following fire and, as a result, contribute to long-term erosion. Establishment of a dense grass cover on burned sites may also increase the volume of fine dead fuels by the end of the first growing season, thereby making these areas more susceptible to ignition and early reburns.

The judicious use of prescribed fire could potentially provide a viable technique for minimizing erosion resulting from wildfires. Prescribed fire is being advocated as a tool in southern California for reducing wildfire severity by creating uneven-age stands that break up continuous fuel loads necessary for sustaining large-scale wildfires (Florence 1987). Replacing intense, widespread wildfires with cooler burning prescribed fires would reduce fire impacts on soils. Not only would plant nutrient loss be reduced, but burning under cooler conditions and over moist soils would reduce the severity of water repellency and postfire erosion (DeBano 1981). This management concept is also consistent with developing brush-grass mosaics for water augmentation in Arizona chaparral (Bolander 1982).

CONCLUDING COMMENTS

Both wild and prescribed fires occur frequently in Arizona and California chaparral. Although these two ecosystems evolved into different floristic entities, they share many common attributes in their response to fire. From limited comparative data for Arizona and California, it appears that fire has a similar effect on physical, chemical, and biological soil properties in both ecosystems.

Soil chemical, physical, and microbiological properties most strongly interrelated with organic matter are most susceptible to being changed by soil heating. Soil structure, cation exchange capacity, available nutrients, and microbial activity are all highly dependent upon organic matter, which is completely destroyed at 450° C. Fire also acts as a rapid mineralizing agent releasing plant nutrients from organic fuels during combustion and depositing them in a highly available form on the soil surface. Substantial amounts of N, S, and P can be lost during combustion. Replenishment of N losses is an important part of postfire rehabilitation planning. Treatments interfering with postfire establishment of N-fixing plants should be avoided; particularly important is the competition between reseeded grasses and naturally occurring N-fixing plants.

Burning increases the availability of most plant nutrients. Although total N is lost, available ammonium-N and P increase substantially as a result of burning. High levels of available plant nutrients immediately after burning make fertilizing for at least 1 year following fire impractical.

In the final analysis, the judicious use of prescribed fire has an important role in managing chaparral ecosystems in both Arizona and California. Prescribed fire can be used as a technique for reducing the probability of catastrophic wildfires. Improved wildlife habitat, better access, and increased water production also result from well-planned prescribed burning programs. Certain precautions must be taken during postfire treatments, however, to assure the continued long-term productivity of these ecosystems.

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