

Effects of Fire on the Soil Resource in Arizona Chaparral¹

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Abstract.—Both prescribed burns and wildfires consume aboveground biomass and litter and produce nutrient transformations that affect postfire management. Substantial quantities of important plant nutrients, like nitrogen (N) and phosphorus (P), are lost directly during combustion. Highly available nutrients released during a fire are deposited on the soil surface where they may be immobilized, or lost by erosion. Effect of available nutrients on postfire fertility is discussed. Information on the effect of fire on specific physical, chemical, and biological soil properties is used as a basis for discussing short- and long-term consequences of postfire rehabilitation treatments.

Chaparral covers 1.3-1.5 million hectares as a discontinuous band of vegetation extending across Arizona in a northwest to southeast direction (Hibbert et al. 1974). It is an important vegetation type on both the Prescott and Tonto National Forests and is present, but to a lesser extent, on the Coronado and Kaibab National Forests in Arizona. Wild and prescribed fires occur frequently throughout Arizona chaparral. Fire danger is most severe in spring and early summer until summer rains start, and then again during late fall after the summer monsoon season has ended. Prescribed burning can be done in this type throughout the year, although most burning is done during periods having 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, including soils, while developing burning prescriptions or planning postfire rehabilitation treatments. The objectives of this paper are to (1) describe the chaparral resource, (2) discuss fire behavior in chaparral, (3) outline a general ap-

proach for assessing fire effects on chaparral soils, (4) present a detailed summary of the effects of fire on soil properties that can be expected during prescribed fires, (5) develop an example illustrating a procedure that can be used for assessing fire effects on chaparral soils, and (6) address some concerns arising as part of postfire management of burned areas. This paper focuses mainly on Arizona chaparral although applicable research findings on chaparral soils in California are used when needed to fill knowledge gaps. Detailed comparisons of fire effects and postfire rehabilitation between Arizona and California chaparral are presented elsewhere (DeBano, in press).

The Chaparral Resource

Vegetation and Evolution

The chaparral plant community is characterized by moderate- to deep-rooted evergreen sclerophyllous shrubs. The term "chaparral" is derived from the Spanish word "chaparral" referring to dwarf evergreen oaks (Shantz 1947). These shrubs reach their best development on deep soils or on deeply weathered or broken rock mantles. Arizona chaparral has been classified into several climax vegetation associations: mountainmahogany-mixed shrub, shrub live oak-hairy mountain-

mahogany (*Quercus turbinella*-*Cercocarpus breviflorus*), shrub live oak-birchleaf mountainmahogany (*C. betuloides*), shrub live oak-mixed shrub, Arizona cypress (*Cupressus arizonica*)-shrub live oak, and Arizona oak-yellowleaf silktassel-Emory oak (*Quercus arizonica*-*Garrya flavescens*-*Quercus emoryi*) (Carmichael et al. 1978). Most chaparral shrub species are prolific crown and/or root sprouters and produce few seedlings (Pase 1969); however, the few non-sprouters produce abundant seed. Sprouting species live to a considerable age; Pond (1971) reported little change in individual plants after 47 years.

Arizona chaparral vegetation originated from Madro-Tertiary geoflora during the Cenozoic era (Axelrod 1958) and evolved into its present floristics during the mid-Pliocene Epoch in response to major topographic-climatic changes, which produced its present climate. Arizona chaparral receives about 400-600 mm precipitation annually, distributed bimodally with approximately 55% during the winter from November through April, and the remaining 45% during summer convection storms in July through September (Hibbert et al. 1974). This climatic regime favors a spring and summer growing season for many of the important shrubs.

The adaptation of chaparral vegetation to fire has influenced the evolution of its species since the Miocene

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Era (Axelrod 1958). As a result of natural selection, adaptations have developed that prevent the elimination of chaparral species by fire. These adaptations include (1) seed production at an early age; (2) fire-resistant seeds; (3) seeds depending on fire for germination; (4) production of seeds in such large numbers that some survive even though the heat destroys many; and (5) sprouting from latent buds mainly below-ground (Hanes 1970). The shrub species in this type are well adapted to drought because their well-developed root systems can exploit large volumes of soil for water and nutrients (Davis and Pase 1977, Hellmers et al. 1955b), allowing the stands to regenerate rapidly following fire (Pase and Lindenmuth 1971, Pase and Pond 1964, Pond and Cable 1962). Favorable weather conditions following fire germinate seeds of nonsprouting shrubs, such as ceanothus (*Ceanothus* spp.) and manzanita (*Arctostaphylos* spp.), which, under natural conditions, do not germinate until they are scarified by heat (Pase 1965). Rates of recovery of individual shrub species after fire are dependent on their sprouting ability, ability to establish seedlings, their relative abundance in the prefire stand, and possibly the time of year of the burn (Cable 1975). In some cases, 11 years or more are required for shrubs to reach preburn cover conditions (Hibbert et al. 1974).

Soils and Geology

Soils supporting chaparral are typically deep, coarse textured, and poorly developed. Soil, as used in this discussion, includes all porous material (regolith) in which weathering and roots are active. The distinction between soil depth and solum depth (A and B horizons) is critical in this case, since most of the soil is in the C1 horizon. Consequently, soil surveys that describe soil as shallow generally pertain to solum depth, not

depth of regolith. Usually, the A horizon is only a few inches thick, and the B horizon is commonly absent. Soil texture varies from cobbly and gravelly loamy sand to gravelly loam. The soils belong to several soil suborders, including Ochrepts, Orthents, Ustalfs, Ustolls, and Borolls.

Parent rock materials are made up of deeply weathered and fractured granite, schist, diabase, sandstone, shale, limestone, slate, gneiss, quartzite, and basalt. Granites are found on more than half the total chaparral area, with none of the other types making up more than 10%; schist-derived soils are probably the second most common. Rock types such as basalt, limestone, quartzite, shale, and slate, which weather to fine-textured and shallow regoliths, do not support extensive stands of chaparral, even though rainfall and elevation are often similar. Instead, these soils often support pinyon-juniper woodlands or grass.

Nutrient and Biomass Distribution

When assessing fire effects in chaparral, it is important to estimate biomass and nutrient distributions in

plant and litter biomass because these materials serve as fuels and undergo various degrees of combustion during both prescribed burns and wildfires. Data on biomass and nutrients thus provide a basis for estimating changes in nutrient pools resulting from fire.

Data on plant biomass, litter and nutrient content is limited for Arizona chaparral. Some information is available on plant biomass, litter, and plant nutrients from a recent fire effects study being conducted on the Battle Flat watershed in the Prescott National Forest. Shrub cover on the 50-ha study watershed was determined using 16 30-m-long transects located randomly throughout the watershed. This watershed receives about 65 cm of precipitation annually and supports a dense shrub live oak-mixed shrub community. The area has not been burned for over 80 years (Dieterich and Hibbert, this volume). Weights of leaves, annual growth, small and large stems, and total plant biomass at Battle Flat were estimated using dimensional analyses of the major shrub species on 119 50x100 cm plots (table 1). The amount of biomass would be expected to vary from site to site, as has been reported for California

Table 1.—Biomass and nutrient distribution in a shrub live oak-mixed shrub community at Battle Flat on the Prescott National Forest. Data are means and standard deviations.

Ecosystem component	Biomass ¹ kg/ha	Nutrient			
		Nitrogen		Phosphorus	
		%	kg/ha	%	kg/ha
Leaves	4,060±314	1.82±0.40	74	0.15	6
Annual growth	1,214±139	1.05±0.31	13	0.12	1
Large and small stems	23,793±2090	0.53±0.19	126	0.03	7
Litter	34,000	0.75±0.20	255	0.10	34
Soil					
0-10 cm		0.11±0.04	13000.02±0.009		250
10-20 cm		0.09±0.03	10000.02±0.01		250

¹L. F. DeBano, USDA Forest Service, unpublished data.

²Estimated from P concentrations reported by DeBano and Conrad (1978) for California chaparral.

chaparral (Riggan et al. 1988). However, the total biomass on this Arizona study site, 29,068 kg/ha, compared closely with the 30,394 kg/ha reported for a redshank (*Adenostema sparsifolium*) stand (Riggan et al. 1988), but was greater than the 19,000 kg/ha for scrub oak (*Quercus dumosa*) (Riggan et al. 1988) and 23,000 kg/ha for chamise (*Adenostema fasciculatum*) (Mooney et al. 1977) stands in Southern California. The average amount of litter under the shrub canopy at Battle Flat, about 34,000 kg/ha, was greater than the 16,400 kg/ha reported under oak-mountainmahogany chaparral on a central Arizona site receiving about 46 cm of precipitation annually (Pase 1972). Litter was estimated under shrub canopies on 382 100-cm² plots located randomly throughout the watershed. Compared with California chaparral, this amount of litter was greater than has been reported under chamise (20,500 kg/ha) and hairy ceanothus (*Ceanothus oliganthus*) (28,700 kg/ha) stands, but less than under scrub oak (54,300 kg/ha) and wartystem ceanothus (*Ceanothus crassifolius*) (45,500 kg/ha) stands (Riggan et al. 1988).

Information on plant and litter biomass at Battle Flat was used with nutrient concentration data to calculate total amounts of nutrients contained in different parts of the chaparral ecosystem (table 1). Nutrient estimates were limited to nitrogen (N) and phosphorus (P) because they are considered the two most limiting nutrients (Hellmers et al. 1955a, Vlamis and Gowans 1961). The biomass and nutrient profiles developed for Battle Flat must be used with caution for several reasons. First, data presented in table 1 represent only that area within a watershed covered by a shrub canopy and, as such, do not include the interspaces between individual shrub canopies. Therefore, when the data are used on a watershed basis, they would have to be reduced in direct proportion to percent area present as interspaces. Sec-

ond, density of chaparral stands is known to vary widely and is highly dependent upon local precipitation regimes. Low-precipitation areas (those receiving less than 45 cm annually) will have much sparser stands of shrubs and, consequently, a given area would contain smaller amounts of nutrients than areas supporting dense brush. Third, shrubs are smaller on the more xeric sites and contain less plant biomass and litter than more mesic sites like Battle Flat.

The data in table 1 are, however, useful for illustrating several general characteristics of nutrient distributions in chaparral ecosystems that are important when assessing fire effects. First, a large proportion of the N and P pools is contained in the soil where it can be effectively insulated against heat generated during light-intensity fires. Second, surface litter is an important aboveground storage compartment for biomass and nutrients. Third, the leaves and annual growth contain higher concentrations of N and P than do the larger twigs, which is important, because most of these fine fuels are consumed during all intensities of fire.

Assessing and Predicting Fire Effects

Assessing the effect of prescribed burning, or wildfires, on soil nutrients requires estimating two things: (1) nutrients released, or lost, during combustion of standing plants (both live and dead) and surface litter layer; and (2) changes occurring in the upper mineral soil layers as a result of soil heating. Different techniques are required for assessing fire effects on each (combustion and soil heating effects). However, to understand either of these effects, it is important to be aware of the fire's unique behavior in chaparral.

Although fire behavior can be characterized in several ways, those indices related to rate of combustion

and amount of aboveground biomass and litter consumed during a fire are probably best related to nutrient release from fuels and heating in the underlying soil.

Fire Behavior and Intensity

Large differences in fire behavior commonly observed between prescribed burns and wildfires in forests do not occur in chaparral. In forests, wildfires spread rapidly through the crowns of standing live and dead trees consuming much of the tree canopy (leaves, twigs, and, in some cases, boles) along with substantial amounts of surface needles and litter. Combustion of these woody fuels releases large amounts of thermal energy, which can produce substantial soil heating. On the other hand, prescribed fires in forests burn much less intensely because they are designed to consume only part of the surface needles and litter. These low-intensity fires are often referred to as "cool" fires. In contrast, both wild and prescribed fires in chaparral are carried through the shrub canopy. As a result, differences in fire intensity and soil heating during prescribed burns and wildfires in chaparral are not as great as those experienced in forests. For example, only minimal soil heating occurred during a cool-burning prescribed fire in a mixed conifer forest compared with substantial heating of the upper soil layers even during low-intensity chaparral fire (fig. 1A,B); soil surface temperatures never exceeded 100°C and the soil remained at ambient temperatures 5.0 cm below the soil surface (fig. 1A). In contrast, during a light-intensity fire in chaparral, the soil reached 250°C at the surface, and 100°C 2.5 cm downward in the soil (fig. 1B).

Fire intensities in chaparral can vary widely and, as a result, produce different degrees of soil heating (fig. 1B,C,D). For example, soil surface temperatures can reach 425°C during

moderately intense fires (fig. 1C) and about 700°C during intense fires (fig. 1D). Differences in surface temperatures are reflected in soil temperatures, which can reach 175°C in the 2.5-cm soil layer during a moderately intense fire and over 200°C during an intense fire.

Managers can reduce fire intensities when using prescribed fire in chaparral by specifying marginal burning conditions in their burn plan. If properly carried out, these less intense fires will consume only part of the shrub canopy and leave substantial amounts of unburned litter on the soil surface. However, although the entire canopy may not be consumed during a low-intensity fire, the remaining shrubs usually die and can contribute dead fuel for future fires. Recently developed aerial ignition techniques have also increased the chances of conducting prescribed burning during marginal, and safer, burning conditions. A better understanding of fire effects, combined with modern ignition techniques, allow managers to design burning prescriptions that can minimize fire intensities, and thereby reduce the impact on the soil resource.

Changes in Plant and Litter Nutrients During Combustion

Fire acts as a rapid mineralizing agent that releases plant nutrients from fuels (standing live and dead plants and surface litter) during combustion and deposits them in a highly available form on the soil surface (St. John and Rundel 1976, Vlamis and Gowans 1961). Substantial amounts of some nutrients, such as N, sulfur (S), and P, are lost into the atmosphere during combustion because the temperatures at which they volatilize are lower than the flaming temperature of woody fuels (1100°C) and, except for P, lower than glowing combustion temperature (650°C) (table 2). Nitrogen losses start at 200°C when organic matter is

initially altered (Hosking 1938), S starts changing at 375°C (Tiedemann 1987), and P must reach 774°C before being lost (Raison et al. 1985). Loss of N is important because it is usually the most limiting plant nutrient in forest ecosystems (Maars et al. 1983), including California chaparral (Hellmers et al. 1955a, Vlamis and Gowans 1961). Phosphorus has also been reported to be limiting in forest ecosystems, particularly on areas where P-fixing soils are present (Vlamis et al. 1955). Results of controlled burning experiments show that the amount of total N volatilized during a fire is in direct proportion

to the amount of organic matter combusted (Raison et al. 1985). In contrast, only about 60% of the total P is lost by non-particulate transfer when fuels are totally combusted. Percentage loss of S by volatilization is intermediate to that of N and P (Tiedemann 1987). Of the cations, potassium (K) is vaporized at the lowest temperature (774°C) (Raison et al. 1985); a measurable amount of K was reported lost during a prescribed fire in California chaparral (DeBano and Conrad 1978). Calcium, magnesium, and sodium are not vaporized until they reach temperatures of 1484°C (table 2) so most of these cations re-

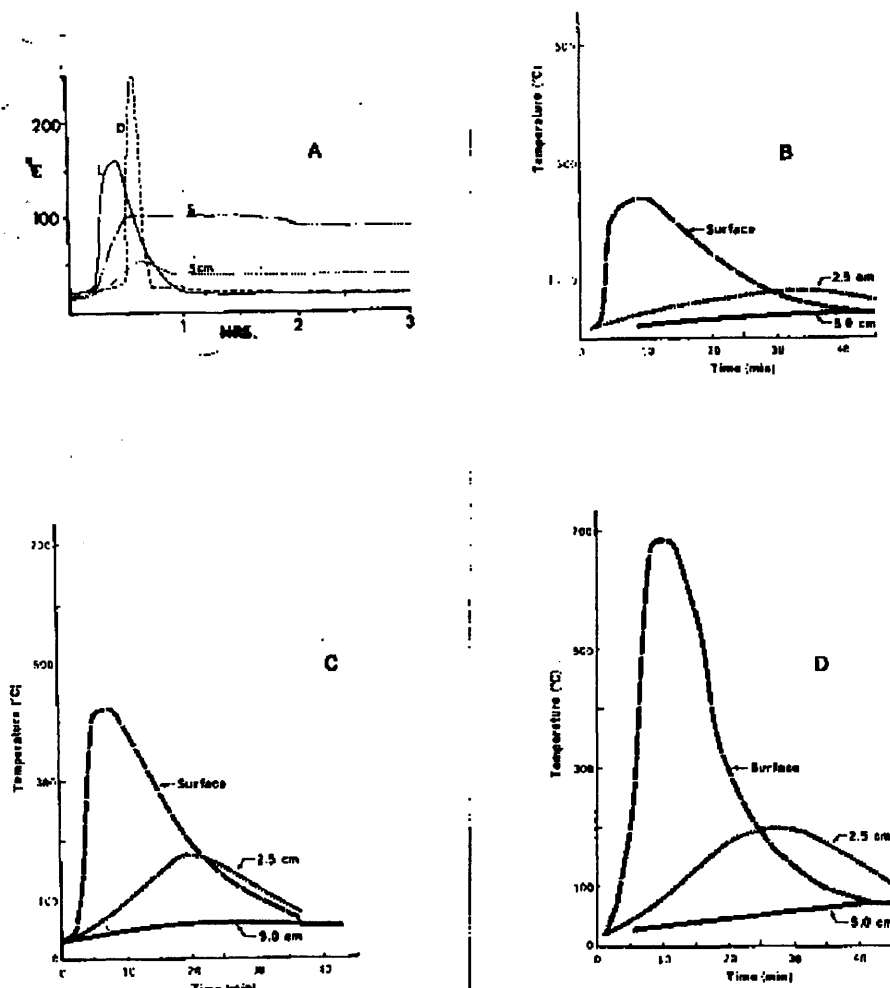


Figure 1.—Soil and litter temperatures during (A) a cool-burning prescribed fire in a mixed conifer forest (Agee 1973), (B) a light-intensity prescribed fire in chaparral, (C) a moderately intense fire in chaparral, and (D) an intense prescribed fire approaching wildfire conditions in chaparral (DeBano et al. 1979b). (L is litter temperature, D is duff temperature, surface is the temperature at the soil surface, 2.5 and 5.0 are soil temperatures 2.5 and 5.0 cm below the soil surface.)

leased during fire are deposited in the ash on the soil surface, except for small amounts that are transferred off-site in smoke (Clayton 1976).

A large body of information has been summarized on fire effects on soils (Wells et al. 1979) and fuels (Martin et al. 1979). Likewise, summary papers quantifying fire intensities are also available (Albini 1976, Rothermel and Deeming 1980). Unfortunately, because fire behavior is complex, a reliable mathematical model has not been developed that relates fire intensity measurements directly to soil heating, although some simplified models have been proposed for describing heat transfer in bare soils (Aston and Gill 1976) and for smothering litter (Albini 1975). Because adequate theoretical models are lacking, qualitative techniques have been used for character-

izing fire intensity so its effect on soil properties can be evaluated. One such semi-quantitative method involves classifying fire intensity as light, moderate, or intense based on the visual appearance of burned brush and litter (Wells et al. 1979). This method is based on the assumption that soil surface conditions following burning are indicative of soil heating. A light burn occurs when the litter is singed and less than 40% of the brush canopy is burned. Irregular and spotty burning occurs and some leaves and small twigs remain on the plants either unburned or slightly singed. After a moderately intense burn surface litter is charred but not ashed. Between 40 and 80% of the plant canopy is burned by the fire and the remaining charred twigs are greater than 0.6-1.3 cm in diameter. After a severe fire only ashes re-

main on the soil surface and the area is completely burned. Plant stems remaining are 1.3 cm or greater in diameter. In many cases only charred remains of large plant stems are left on the burned area.

Fire Effects on Mineral Soil

Developing guidelines for assessing fire effects on mineral soils can be visualized as a three-stage procedure, namely: (1) characterizing fire intensity; (2) relating fire intensity to fuel consumption, nutrient loss from fuels, and soil heating; and (3) finally predicting changes in chemical, physical, and biological soil properties resulting from nutrient input by ash deposition and soil heating of the mineral soil.

Once a burn has been classified as to its intensity class, soil heating can be estimated from curves developed by DeBano et al. (1979b) (fig. 1B, C, D). Temperatures in the soil can then be used for predicting changes from known responses (table 2) of soil properties to different soil heating regimes (DeBano 1979). Although these soil heating relationships were originally developed for California chaparral, they can serve equally well for Arizona because similar fuel loadings and fire behavior are found in both Arizona and California chaparral.

Fire effects on mineral soil can best be illustrated by using a conceptual model depicting an idealized soil profile that is exposed to surface heating by energy radiated downward during the combustion of plants and litter. Although most of the energy released during combustion is lost upward into the atmosphere, a small, but significant, quantity is absorbed by the soil surface and transmitted downward into the soil. It has been estimated only 8% of the total energy released during combustion of chaparral fuels is transmitted into the underlying soil (DeBano 1974). If heat radiates directly on a

Table 2.—Threshold temperatures (°C (°F)) for insensitive, moderately sensitive, and sensitive soil properties.

Soil property		Threshold temperature ¹	
Relatively insensitive			
Potassium and Phosphorus		774	(1425)
Calcium		1484	(3150)
Manganese		1962	(3564)
Clay destruction		980	(1796)
Moderately sensitive			
Organic matter		100	(212)
Nitrogen		200	(392)
Sulfur		375	(707)
Soil structure		300	(572)
Soil wettability		250	(482)
Sensitive			
Bacteria	—Wet	110	(230)
	—Dry	210	(410)
<i>Nitrosomas</i> bacteria	—Wet	75	(167)
	—Dry	140	(284)
Fungi	—Wet	100	(212)
	—Dry	155	(311)
VAM		94	(201)
Glowing combustion		650	(1202)
Flame temperatures		1100	(3542)

¹Temperature at which detectable changes of a soil property begin in response to

bare, dry soil, it will be transmitted slowly into the soil with a minimum of soil heating because dry soil is a poor conductor of heat. Dry soil heats slowly because heat transfer is limited to particle-to-particle conduction and convection through soil pores. In contrast, wet soil conducts heat faster because it is also transferred rapidly by vaporization and condensation. There are also some differences in heat capacity of dry and wet soils, with wet soils absorbing greater quantities of heat per degree rise in temperature than dry soils because of the high specific heat capacity of water compared with mineral soil particles. Where thick litter layers are present, secondary combustion of litter occurs, further contributing to soil heating (Albini 1975). Conduction of radiated heat into the soil produces heating, which in turn affects the chemical, physical, and biological properties of the underlying soil.

Their spatial distribution in a typical soil profile expose some soil properties more directly to surface heating than others. For example, living organisms and soil organic matter concentrated on, or near, the soil surface are most affected. This strategic 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 by radiated energy than other soil properties, such as clay content, which is concentrated in subsurface layers where it is insulated from 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). Cation exchange ca-

capacity of a soil depends not only on humus, but also on clay colloids. Humus is concentrated at, or near, the soil surface and thus is directly exposed to radiated heat. In contrast, clay formed by pedogenic processes is usually concentrated deeper in the soil profile, although clays can sometimes be 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 (e.g., water repellency, etc.). Soil chemical properties most readily affected are total and available forms of N, P, and S; and cation exchange capacity. Microbiological properties regulating input, loss, and availability of nutrients may also be significantly changed by soil heating.

Plant Nutrients

Although large amounts of total N and P are lost during the combustion of plants and litter, available ammonium-N and P are increased in the ash and upper soil layers during a fire (DeBano et al. 1979a). Ammonium-N is highest immediately after

burning. Following burning, ammonium-N decreases and nitrate-N increases as nitrification occurs. The increased levels of available P produced during a fire slowly decrease and reach prefire levels within about one year. Highly available N and P provide a postfire fertility effect for newly established plant communities on burned sites. For example, a prescribed fire in Arizona increased ammonium-N concentrations in the surface 0-2 cm layer from 6 to 60 $\mu\text{g/g}$ (which is an increase of about 15 kg/ha), did not affect nitrate-N concentrations of about 2 $\mu\text{g/g}$, and increased available P from 6 to 16 $\mu\text{g/g}^3$.

Soil Physical Properties

Soil physical properties dependent upon organic matter (e.g., soil structure and infiltration) are also affected directly by fire. An important hydrologic property affected by burning is soil wettability (DeBano 1981). During fires, organic matter in the litter and upper mineral soil layers is volatilized (fig. 2A). Most of the volatilized organic matter is lost upward in the smoke, but a small amount

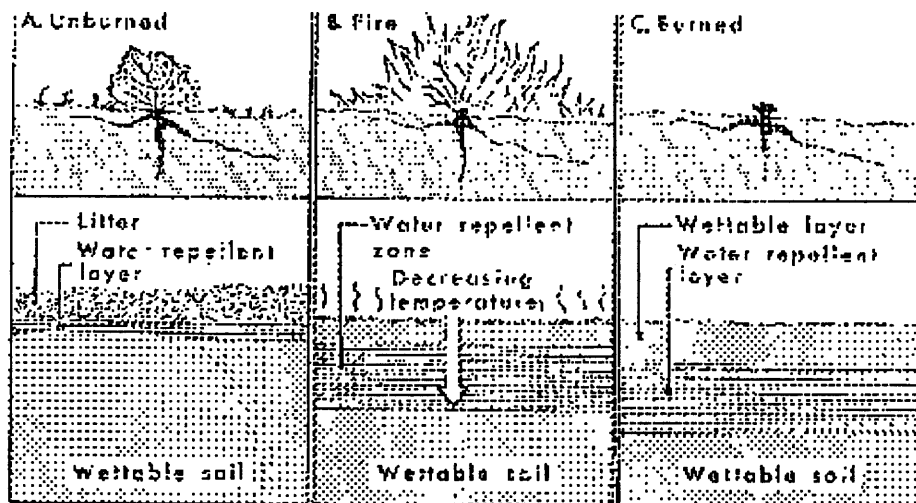


Figure 2.—Soil water repellency as altered by fire: (A) before fire, hydrophobic substances accumulate in the litter layer and mineral soil immediately beneath; (B) fire burns the vegetation and litter layer, causing hydrophobic substances to move downward along temperature gradients; (C) after fire, a water-repellent layer is present below and parallel to the soil surface on the burned area (DeBano 1969).

moves downward along steep temperature gradients in the upper 5 cm of the soil and condenses to form a water-repellent layer that impedes infiltration (fig. 2B, C) (DeBano et al. 1976).

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 fine-textured clay soils. The formation of this water-repellent layer, along with the loss of protective plant cover, increases surface runoff and erosion during the first rains following burning (DeBano and Conrad 1976). A reduction in infiltration by a water-repellent layer can lead to extensive rill erosion on burned watersheds (Wells 1981).

Soil Microbiology

Soil heating affects microorganisms either by killing them directly or altering their reproductive capabilities. Indirectly, soil heating alters organic matter, increasing nutrient availability and stimulating microbial growth. Although complex interrelationships exist between soil heating and microbial populations in soils, it appears that duration of heating, maximum temperatures, and soil wa-

ter 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). Lethal temperature for bacteria was found to be 210°C in dry and 110°C in wet soil (table 2). Fungi tolerate temperatures of only 155°C in dry soil and 100°C in wet chaparral soils. Nitrifying bacteria appear to be particularly sensitive to soil heating, and even the most resistant *Nitrosomonas* bacteria can be killed in dry soil at 140°C and in wet soil at 75°C (Dunn et al. 1979). Physiologically active populations of microorganisms in moist soil are significantly more sensitive than dormant populations in dry soil (Dunn et al. 1985). Mineralization of killed microbial biomass may release readily available plant nutrients in addition to those produced directly by combustion of fuels.

Seed Mortality

Heat radiated during a fire also affects postfire germination of seeds occupying the litter and upper soil layers. Germination of seeds produced by some chaparral brush species is stimulated with exposure to elevated temperatures during a fire (Keeley 1987). Both maximum tem-

peratures reached and time of exposure affect survival and germination of seeds. As with microorganisms, lethal temperatures for seeds are reached at lower temperatures in moist soils compared with dry.

Example of Assessing Fire Effects

The information given on nutrient losses during combustion of plants and litter along with estimates of soil heating can be used for assessing the impact of light, moderate, and intense fires on chaparral soils. The chaparral stand described for the Battle Flat watershed will be used for illustration.

According to the criteria cited, a light intensity fire leaves about 60% of the canopy unburned and only an irregular spotty burning of the surface litter occurs (Wells et al. 1979). Under these burning conditions it is reasonable to assume that only 10-15% of the litter will be lost. Assuming a 40% canopy reduction in canopy biomass, the shrub stand at Battle Flat would lose 11,628 kg/ha of canopy materials (table 3), of which 4,060 1,214, and 6,354 kg/ha would be lost from leaves, current growth, and large and small stems, respectively. This estimate is based on the complete combustion of leaves and current growth along with partial combustion of large and small stems. Associated with the combustion of 11,628 kg/ha of canopy biomass would be a loss of about 121 kg/ha of N (assuming N loss is in direct proportion to biomass combustion), and 5 kg/ha of P (assuming only a 60% loss of P upon total combustion).

In addition to the N lost from the standing plants, an additional 15% of the litter N (38 kg/ha) and about 9% (0.60 X 15%) of the litter P (3 kg/ha) would be lost. Maximum soil temperatures would be about 275°C at the surface and 100°C at 2.5 cm in the soil (fig. 1B). Soil temperatures 5.0 cm deep in the soil would remain at

Table 3.—Loss¹ of biomass, nitrogen, and phosphorus from vegetation, litter, and soil (in kg/ha) during light, moderate, and severe fires in Arizona chaparral.

Ecosystem component	Nutrient								
	Lgt	Biomass Mod	Int	Nitrogen			Phosphorus		
				Lgt	Mod	Int	Lgt	Mod	Int
Vegetation	11,628	17,440	26,160	121	151	188	5	8	9
Litter	5,100	17,000	30,600	38	128	230	3	10	18
Soil				0	65	130	0	0	2
Total				159	344	548	8	18	29

¹The estimates of nutrient losses are based on data from under plant canopies (100% canopy cover) and therefore must be reduced in direct proportion to amount of interspace area present between shrubs.

ambient temperature. No additional losses of N and P would be expected from the soil at these temperatures.

During a moderately intense burn most of the litter is charred, but not ashed. Between 40% and 80% of the plant canopy is consumed by the fire and the remaining charred twigs are greater than 0.6-1.3 cm in diameter (Wells et al. 1979). Under these conditions it is assumed the plant canopy is reduced 60% (17,440 kg/ha) and litter 50% (17,000 kg/ha) (table 3). Associated with a 60% combustion of canopy would be a loss of about 151 kg/ha of N and 8 kg/ha of P. An additional 128 kg/ha of N and 10 kg/ha of P would be lost during the combustion of 50% of the surface litter. Soil heating would reach about 425°C at the surface and be 175°C at 2.5 cm downward in the soil (fig. 1C). Moderately sensitive soil properties, including organic matter, N, S, soil structure, and soil wettability, would all be affected near the soil surface (table 2).

Substantial losses of N from soil organic matter could also occur. It is estimated 5% of the 1,300 kg/ha of N in the upper soil layer (65 kg/ha) could be lost (table 3). Soil P would not be expected to be lost because the surface maximum surface temperature (425°C) is below the threshold temperature for P (774°C) (table 2). However, at 2.5 cm only microbiological properties would be affected. Deeper at 5-cm in the soil, temperatures would only reach 75°C and have little, or no, effect on soil chemical, physical, and biological properties.

After a severe fire only ash remains on the soil surface and the only plant stems remaining are 1.3 cm or greater in diameter (Wells et al. 1979). In many cases only charred remains of large plant stems remain after the fire. Under these intense burning conditions it is assumed that at least 90% of both the plant canopy and surface litter are combusted. Large losses of N (188 kg/ha) and P (9 kg/ha) from the plants would oc-

cur along with greater losses from the litter (230 kg/ha of N and 18 kg/ha of P). Soil heating would be equally severe, reaching 700°C at the soil surface, 200°C at 2.5 cm, and 140°C at 5.0 cm. Near the soil surface severe damage would occur to all soil properties except K, P, calcium, manganese, and soil clays. Large amounts of soil N, perhaps 10% (130 kg/ha), and small amounts of P could be lost. The soil surface would most likely be sterilized, with no viable microorganisms or seeds surviving.

Using the above calculations it is estimated that the total N lost from plants and litter during light, moderate, and intense burns could be at least 159, 344, and 548 kg/ha, respectively. Additional losses of soil N may also occur with moderate and intense fires. Phosphorus losses from the plants and litter would be 8, 18 and 29 kg/ha during light, moderate, and intense fires, respectively. These calculations are in line with losses measured experimentally during chaparral fires in California where 149 kg/ha of N was lost during a prescribed fire when about 30% of the plants was consumed (a light-intensity fire). Amounts of N and P lost during burning will vary depending upon the amount of above-ground biomass, litter, and soil organic matter combusted during a fire.

It is important to remember that the above calculations represent only changes under the plant canopy and therefore must be reduced in direct proportion to the amount of interspace area between shrubs when estimating total nutrient losses on an areal basis. However, the above calculations of N and P losses do illustrate the importance of burning chaparral as coolly as possible in order to reduce consumption of surface litter and soil heating. It is also important to be aware of these nutrient losses in order to insure that N-restoration to the site is included as part of postfire management.

Management Implications

The preceding discussion on fire behavior and fire effects on soils provides information that can be used when designing burning prescriptions or developing post-wildfire rehabilitation treatments.

Designing Burning Prescriptions

All available information on fire effects indicate it is desirable to burn as coolly as possible because this reduces litter combustion and soil heating. Although it is never possible to achieve the cool burning conditions prevailing during prescribed burning in forests, the intensity of chaparral fires can be mitigated to some extent. This requires burning under marginal burning conditions. Fire intensity in chaparral can be decreased to some extent by burning when (1) cooler air temperatures and higher humidities prevail, (2) live and dead fuel moistures are high, and (3) wind speeds are low. Fortunately modern ignition techniques make it easier to conduct successful prescribed burns under marginal burning conditions.

However, it must be kept in mind that even when marginal burning conditions prevail, localized sites within a prescribed burn area will burn intensely because "fire storms" are invariably generated by local wind convection patterns produced by the fire itself. Burning during marginal burning conditions is also more likely to produce a mosaic pattern of burned areas intermingled with unburned islands of vegetation. This mosaic pattern is less susceptible to postfire erosion than are large continuous areas. Also, reducing fire intensity reduces litter combustion, which, in turn, reduces total N and P losses from the site. Cooler burning conditions also reduce litter and soil surface temperatures, which lessen the chances of a water-repellent soil layer being formed. Reduced litter loss by combustion also protects the

soil surface from erosion by raindrop impact following burning.

Some studies suggest that burning over wet soils may not be beneficial to microorganisms and seeds because heating is more likely to be lethal in wet soils than in dry soils. However, it is not completely known what effect these changes in microbial populations have on nutrient cycling, decomposition, and site productivity. Nor is the effect that season of burning has on soils and nutrient cycling known. However, it is known that nutrient content of plants change throughout the year. Higher concentrations of N and P are present in the leaves and small fuels during active growing seasons. Burning during periods of active growth would potentially expose larger quantities of N and P to combustion losses.

Although managers are not always able to burn under marginal burning conditions, they still need to be able to assess changes in nutrient relationships, erosion, and site productivity resulting from prescribed fires. Sufficient research information is currently available for making reasonable estimates of the changes that can be expected to result from different burning prescriptions.

Postfire Rehabilitation

Postfire rehabilitation plans must consider both short- and long-term fire effects. Some important considerations are losses of total nutrients (particularly N), changes in nutrient availability, decreased infiltration rates, and subsequent erosion on burned areas.

Nutrient Loss and Replenishment

Although several plant nutrients are lost directly by combustion during fire and by erosion following fire, N is the most important nutrient because it is lost in the largest quanti-

ties and is likely to be the most limiting nutrient in chaparral ecosystems (Hellmers et al. 1955a). Postfire rehabilitation plans must consider natural mechanisms available for replenishing N in order to assure long-term productivity of these chaparral ecosystems.

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 25-35 years (Ellis et al. 1983). However, the annual input of N may be substantially greater in localized areas having large amounts of airborne N pollutants present (e.g., Los Angeles Basin). Riggan and co-workers (1985) found annual inputs of 23.3 and 8.2 kg/ha of N as canopy throughfall and bulk precipitation, respectively. It is unlikely that significant atmospheric input of N occurs in Arizona chaparral ecosystems because most of the areas supporting this shrubby vegetation are far removed from metropolitan centers.

An important source of N replenishment appears to be by N-fixing organisms. Nitrogen fixation by short-lived legumes is important in postfire management in California chaparral, but is absent in Arizona. Nitrogen fixation by asymbiotic organisms is also low, amounting to about 1 kg/ha annually. It now appears the most likely source of ecosystem N is biological N-fixation by actinomycete nodulated shrubs such as *Cercocarpus betuloides*. Therefore, it becomes important in postfire planning to manage for the reestablishment of these N-fixing shrubs, which can effectively fix N after the "flush" of available N produced by the fire has been immobilized. Both ammonium- and nitrate-N generally drop to prefire levels within a year after fire.

Another postfire rehabilitation treatment that affects N-fixation is

competition between introduced plants used for erosion control and the reestablishment of native plants. Although dense stands of seeded grasses can become established following fire, it is the exception, rather than the rule, because postfire grass reseeding is unpredictable. However, when dense stands of grass become established they can effectively compete with shrubs for moisture and nutrients. For example, it was found in California that reseeded annual ryegrasses competed with seedling establishment of N-fixing shrubs (e.g., *Cercocarpus* sp. and *Ceanothus* sp.), and even with sprouting species (Conrad and DeBano 1974). Therefore, it is recommended that management plans concerned with rehabilitating burned areas address the establishment and perpetuation of N-fixing shrubs during the postfire plant reestablishment period.

Postfire Fertilization

The question frequently arises whether there is a need to fertilize as part of postfire rehabilitation. Fertility trials have generally shown that burned soils have a greater supply of available N than unburned soils (Vlams et al. 1955). Likewise, N fertilizer responses were not detectable on field plots immediately following a chaparral fire in southern California (DeBano and Conrad 1974). Postfire responses to P fertilizers are more variable because some soils can rapidly fix available P produced during burning (DeBano and Klopatek 1988, Vlams et al. 1955). The preponderance of research findings indicate 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 increase denitrification. The advisability of P fer-

tilization is less clear but it may be of little advantage in those soils that fix available P. In summary, it appears that fertilizing in the "ash" is not a recommended postfire treatment for at least one year following burning.

Postfire Erosion

There are limited opportunities for preventing, or reducing, erosion on chaparral soils burned under wildfire conditions. Grass reseeding has been widely used as a postfire rehabilitation treatment. The usefulness of grass reseeding for reducing postfire erosion has not been clearly established because grasses have only a limited opportunity to become established before active erosion occurs during the first rainy season 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). Grass competition may also indirectly interfere with the establishment of native plants following fire and, as a result, increase 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 reburn.

The judicious use of prescribed fire provides a potential technique for minimizing large erosional losses following wildfires. In southern California prescribed fire is being advocated as a tool for reducing wildfire severity by creating uneven-age stands that break up continuous fuel loads necessary for sustaining large-scale wildfires (Florence 1987). Reducing the probability of intense, widespread wildfires by cooler burning prescribed fires would be expected to reduce fire impacts on soil properties and postfire erosion. This management concept is also compatible with the concept of developing

brush-grass mosaics for water augmentation in Arizona chaparral (Boulanger 1982).

Concluding Comments

Both wild and prescribed fires occur frequently in Arizona chaparral. These fires affect physical, chemical, and biological soil properties of soils. Prescribed fires in chaparral are generally more intense than those in forests because fire is carried primarily through the shrub canopy. Therefore, more subtle differences in fire behavior exist between wildfires and prescribed burns in chaparral, although burning prescriptions in chaparral can be designed to reduce total fuel consumption, thereby minimizing soil heating and associated fire effects.

Soil chemical, physical, and microbiological properties most strongly interrelated with 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. Fire also acts as a rapid mineralizing agent; it releases plant nutrients from fuels which are then deposited on the soil surface in a highly available form. During combustion, however, substantial amounts of N, S, and P can be lost to the atmosphere. Replenishment of N losses should be included in postfire rehabilitation plans. Treatments interfering with the establishment of postfire N-fixing plants should be avoided. A particularly important concern is the possible competition between reseeded grasses and native N-fixing plants.

Burning increases the availability of most plant nutrients. Although total N is lost, available ammonium-N and P increase substantially during burning. The presence of high concentrations of available plant nu-

trients on the soil surface immediately following fire negates the advantage of fertilizing for at least one year after burning.

In the final analysis, the judicious use of prescribed fire has an important role in managing chaparral ecosystems in Arizona. Prescribed fire can be used as a technique for reducing potentially catastrophic wildfires. Improved wildlife habitat, better access, and increased water production also result from well-planned prescribed burning programs. However, certain precautions must be taken when planning postfire treatments to assure the continued long-term productivity of this unique ecosystem.

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