Effects of Fire on Soil

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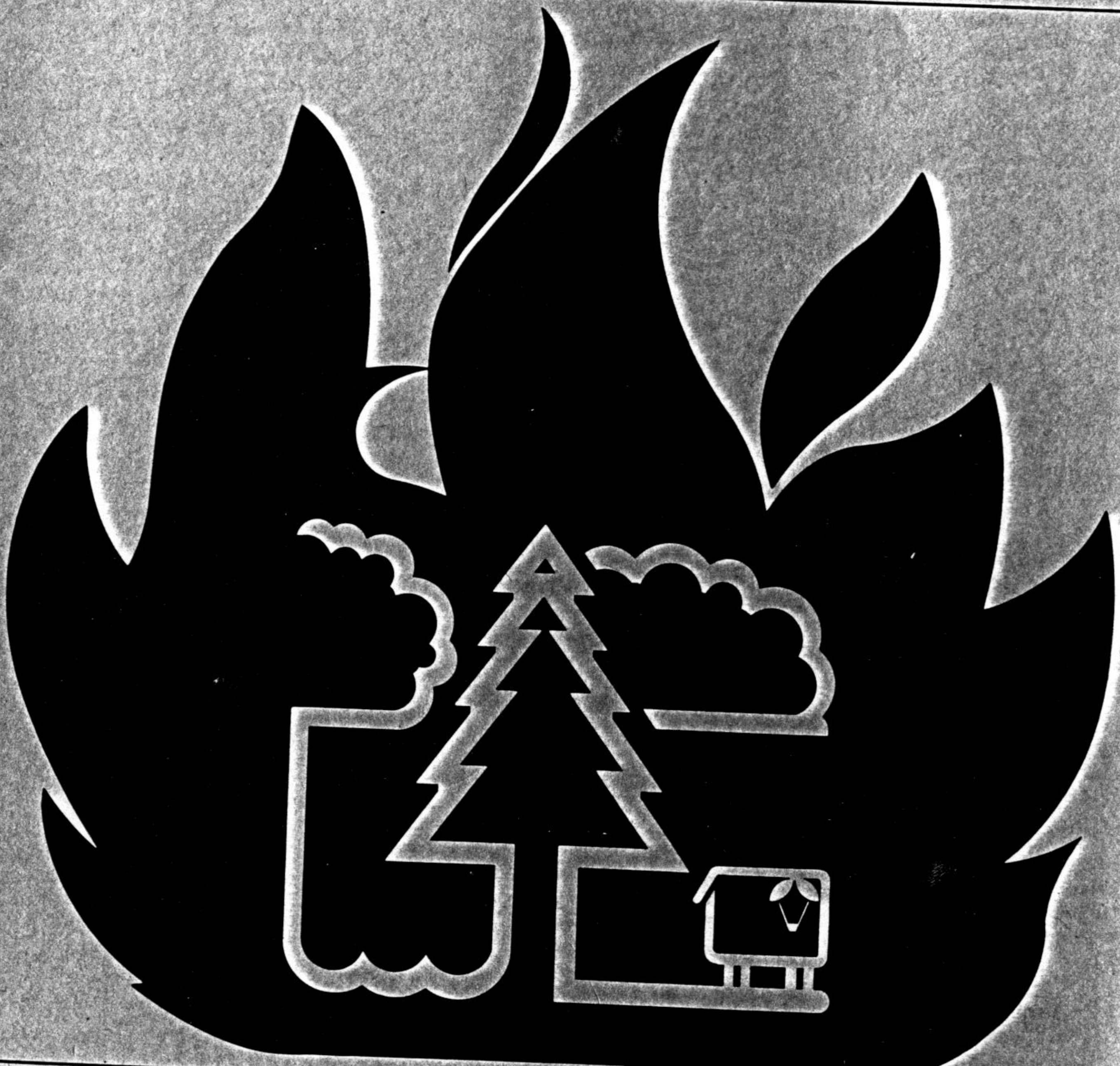
A State-of-Knowledge Review
National Fire Effects Workshop
Denver, Colorado
April 10-14, 1978



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EFFECTS OF FIRE ON SOIL

A State-of-Knowledge Review

Prepared for the Forest Service National Fire Effects Workshop, Denver, Colo., April 10-14, 1978

by

Carol G. Wells
Project Leader, Research Triangle Park, N.C.

Ralph E. Campbell
Soil Scientist, Flagstaff, Ariz.

Leonard F. DeBano
Project Leader, Tempe, Ariz.

Clifford E. Lewis
Range Scientist, Marianna, Fla.

Richard L. Fredriksen
Soil Scientist, Corvallis, Oreg.

E. Carlyle Franklin
Program Manager, Charleston, S.C.

Ronald C. Froelich
Plant Pathologist, Gulfport, Miss.

Paul H. Dunn
Microbiologist, Glendora, Calif.

(All with the Forest Service, U.S. Department of Agriculture.)

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PREFACE

Recent changes in Forest Service fire management policy make it clear that resource managers today need a great deal more information on the physical, biological, and ecological effects of fire. They will need information on fire behavior and fire effects as a basis for analyzing the benefits, damages, and values of various fire management alternatives. Managers must be able to place a value on all resources if they are going to incorporate fire and its effects into land management plans. The Forest Service is committed to the concept that fire management planning has to be a fundamental part of all our planning.

Recent laws and regulations also give additional guidance for the Forest Service to use in developing land management plans for each unit of the National Forest System. These plans must coordinate outdoor recreation, range, timber, watershed, wildlife and fish, and wilderness resources. Interdisciplinary planning is vital, and research must cover the same universe as our planning—therefore interdisciplinary research is a must.

The effects of fire have been studied since the beginning of organized Forest Service research, but the results are scattered over a wide range of outlets. In addition, research is conducted on the effects of fire under several appropriation line items, and in some instances lacks the interdisciplinary approach needed to make the results as useful as possible to land managers.

The National Fire Effects Workshop was held April 10 through 14, 1978, as a first step in responding to the most recent changes in policies, laws, regulations, and initiatives. One of the major Workshop objectives was to prepare a report indicating the current state-of-knowledge about effects of fire on various resources. These reports formed the basis for pinpointing knowledge gaps. Using this information and input from land managers, priorities for research needed on the effects of fire were established.

Six work groups were established to prepare the state-of-knowledge reports on the following subjects: soil, water, air,. flora, fauna, and fuels. Work group members were mainly Forest Service research scientists, but individuals from National Forest Systems, Bureau of Land Management, National Park Service, Fish and Wildlife Service, and Bureau of Indian Affairs also participated.

We hope these state-of-knowledge reports will prove useful to researchers and research planners as well as land and fire management planners. Each report will be published as an individual document. A separate bibliography also will be included in this series in an effort to provide a source document for most of the literature dealing with the effects of fire.

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A State-of-Knowledge Review

INTRODUCTION

It is important to understand the effects of fire on forest and range soils. This knowledge provides a basis for developing guides to the effective use of prescribed fire and for determining the situations where wildfires can be minimized or prevented by using prescribed fires.

The catastrophic effects of uncontrolled fires on the soil have been observed frequently following wildfires. There is a need for evaluating those burning situations where fire effects are less dramatic than during wildfires so the tradeoffs between prescribed burning and/or other means of vegetation manipulation can be compared. For example, burning volatilizes nitrogen, an essential element for plant growth; however, the loss of some nitrogen by burning might become a more acceptable alternative than large soil losses occurring after the use of heavy mechanical equipment. Likewise, several light or moderately controlled burns possibly have less impact on the soil than a single severe wildfire that may result from a large fuel accumulation.

Fire destroys soil organic matter, or residues that eventually become soil organic matter. The amount and location of the organic matter lost depends on the intensity[1] of the prescribed fire. Burning the surface organic matter removes or decreases the protective forest floor, volatilizes large amounts of nitrogen and smaller amounts of other elements, and transforms less volatile elements to soluble mineral forms that are more easily absorbed by plants or are lost by leaching. Heating the underlying soil layers also alters the physical, chemical, and biological properties of the soil dependent upon soil organic matter. These general relationships would lead one to believe the effects of burning are predictable; however, to the contrary, the effects reported in the literature are highly variable. These variations are attributed to fire intensity, temperature, vegetation type and amount, soil, moisture, and other speculative factors. In spite of the seemingly drastic changes associated with fire, most of the effects on the soil are relatively minor. It is the purpose of this report to summarize the information available in the literature about the effects of fire on soil properties and provide more specific data for certain important forests, brush, and range types. This information will provide the basis for evaluating alterations in fire management.

[1]Fire intensity is defined as the rate of heat release per unit of ground surface area and is proportional to flame height and rate of spread.

SOIL TEMPERATURE AND HEATING

Many of the changes in soil chemical, physical, and biological properties that occur during a fire are related to the degree and duration of soil heating. Most of the energy released by the combustion of plant biomass and forest floor during a prescribed burn or wildfire is lost upward. However, the energy transmitted downward heats and alters the underlying litter and mineral soil. If the surface organic layer is moist and thick such as occurs in some forests, little soil heating occurs (Agee 1973). However, if the litter layer is dry and partially or wholly consumed in the fire, or if the litter layer is thin as in chapparal, the underlying soil can be heated substantially and large temperatures are generated in the underlying soil. Ignition of the surface litter and heating of the underlying mineral soil alters all soil physical, chemical, and biological properties dependent on soil organic matter.

The degree of soil heating during any particular fire is highly variable and depends upon the type of fuel (grass, brush, trees), fire intensity (wildfire, prescribed burns, etc.), nature of the litter layer (thickness, packing, moisture content, etc.), and the soil properties (organic matter, soil water, texture, etc.). This section summarizes our knowledge of soil heating in relation to various fire, soil, and fuel parameters. It also reviews basic heat transfer in soils along with a discussion of the various methods of characterizing soil temperatures and fire intensity as related to soil heating and mineral soil exposure.

Characterizing Soil Heating, Soil Temperature, and Fire Intensity

Before considering the various factors affecting soil heating we need to review (1) the nature of the heat flow in soils during fire, (2) the methods of characterizing soil temperatures, and (3) the attempts that have been made to characterize fire intensity in terms of soil heating.

Soil heating and heat flow processes.—Characterizing thermal conductivity and heat transfer in soils during wildfires and prescribed burns is difficult and complex because high temperatures and large temperature gradients prevail. Under these conditions, traditional diffusion type equations, used to describe heat flow in dry soils at ambient temperatures, are invalid because convection and gaseous exchange of heat occur. Heat transfer becomes even more complex when water is present because coupled soil moisture, heat, and vapor transport occur. When water is present in the soil, the temperature at any particular depth does not exceed 100° C (212° F) until the water has evaporated or moved into lower layers (Scotter 1970, DeBano *et al.* 1976). Heating moist soil under grass has been analyzed by the diffusion equation although heat transfer by moisture fluxes were not considered (Scotter 1970). However, later Scotter's data along with additional laboratory data were used to develop a more sophisticated model coupling the transfer of water, heat, and water vapor (Aston and Gill 1976). Although this later model successfully predicted soil temperature profiles, moisture profiles, ground heat flux, and evaporation under simulated surface fire conditions in grasslands, it has not been tested for forests and brushlands. Also, the soil surface temperature data, required as input data for this model, have not been related directly to fire intensity as defined in terms of traditional fire intensity such as rate of spread or energy released per unit area.

Measuring soil temperatures.—Soil temperatures are commonly reported in the literature in two ways—maximum or continuous. Maximum temperatures are measured with heat sensitive materials (paints, tablets, etc.) that melt at known temperatures (DeBano and Conrad in press, Bentley and Fenner 1958, Tothill and Shaw 1968, DeBano *et al.* in press). Temperatures can be measured at both the soil surface and downward in the soil by placing these materials at the desired depths. Maximum temperatures can also be measured with high temperature maximum thermometers.

Continuous soil temperature data are more meaningful because they provide information on the duration of heating. These types of measurements are obtained by attaching a recording instrument to a suitable heat sensor (thermocouple, thermistor). Soil heating has been measured with some version of this system under grass (Tothill and Shaw 1968), windrows of piled eucalyptus logs (Cromer and Vines 1966), prescribed burns and wildfires in chapparal (DeBano *et al.* in press), and prescribed burns in forests (Agee 1973).

Characterizing fire intensity.—Fire intensity has been characterized at various levels of sophistication. Sometimes only subjective visual estimates (Tarrant 1956, Bentley and Fenner 1958) have been made because measurements have not been taken during the fire or the sites have not been examined until after the fire has burned over the area (e.g., after wildfires). In other cases fire has been characterized by measuring heat fluxes (Beaufait 1966) or amount and rate of fuel consumption (Albini 1976).

Visual Characterization

The intensity of a fire can be classified subjectively by using the appearance of the litter and soil after burning, and referred to in relation to soil as fire severity. Tarrant (1956) described light and severe burns for the Pacific Northwest. In most forest and range prescribed burns and in many wildfires, the fire is limited to the litter layer and other fine materials near the ground. In this case, both the vertical and horizontal dimensions of a fire are used to classify the severity of burn. The authors developed a system that seemingly corresponds to descriptions in the literature for light, moderate, and severe burns of forest and range soils. According to this system any particular spot of a fire is classified as being **lightly burned** if the litter and duff or layer are scorched but not altered over the entire depth. **Moderate burns** char the litter and duff but do not visibly alter the underlying mineral soil. On **severely burned** spots all the organic layer is consumed and the mineral soil structure and color are visibly altered. This criteria is then extended horizontally to classify larger areas or even an entire fire. This is done by determining the percentage of the total area severely, moderately, and lightly burned. An area is considered **severely burned** if more than 10 percent of the area has spots that are severely burned (as defined above), more than 80 percent moderately or severely burned, and the rest lightly burned. In a **moderately burned** area, less than 10 percent of the area is severely burned but over 15 percent is moderately burned. A **lightly burned** area would have less than 2 percent severely burned, less than 15 percent moderately burned, and the rest lightly burned or nonburned.

This same type of visual estimation has been used to classify burn intensity after chaparral fires in southern California. Here the appearance of the seedbed has been related to the soil temperatures generated during a fire (Bentley and Fenner 1958). The lightly burned condition is characterized by charred leaf litter produced when the poorly aerated litter layer is not totally incinerated by the heat radiated downward by burning brush. Some greyish ash is present immediately after the fire but soon becomes inconspicuous. The maximum temperatures in the soil during a burn producing "black ash" conditions were 177° C (350° F) at the soil surface and 121° C (250° F) at 0.3 in (0.76 cm) downward in the soil. When a more intense or moderate burn occurred, a "bare-soil" seedbed was produced. The bare-soil condition occurred when the fire was hot enough to consume the leaf litter and fine woody material on the ground surface. Some charred material remained but was very sparse. Immediately after the fire the ash from the incinerated litter and branches was inconspicuous and soon disappeared. The maximum temperatures at the mineral surfaces were 399° C (750° F) and at 0.3 in (0.76 cm) 288° C (550° F). The most severely burned areas were characterized by a "white ash" seedbed. This was identified by a fluffy ash layer where large branches or main stems of trees or shrubs had burned. The white ash layers were most extensive where dense stands of heavy brush had been burned to stubs. Temperatures at the surface exceeded 510° C (950° F) and 399° C (750° F) at 0.3 in (0.76 cm).

Although soil surface conditions after a fire are partly indicative of the soil heating, the appearance of the remaining brush plants should also be used to estimate fire intensity. At present we believe a **light burn** occurs when the litter is singed and less than 40 percent of the brush canopy remains. Irregular and spotty burning occurs and some leaves and small twigs remain on the plants either unharmed or slightly singed. After a **moderately intense burn** most of the litter is charred, but not ashed. Between 40 and 80 percent of the plant canopy is burned by the fire and the remaining charred twigs are greater than 0.25-0.50 in (0.6-1.3 cm) in diameter. After a **severe fire** only ashes remain on the soil surface. The area is completely burned and the plant stems remaining are 0.5 in (1.3 cm) or greater in diameter. In many cases only charred remains of the large stubs of the main plant stems are left.

Heat Flux Integrators

An integrating device made from 1-gallon cans painted black over their entire exterior surface has been used to characterize the downward flux of heat during a fire (Beaufait 1966). Before the fire those cans were filled with 3 liters of water and placed in contact with the upper surface of the mineral soil. After the area had burned, the measured water loss was used to calculate the heat load reaching the soil surface. Follow-up studies showed the heat load delivered to the surface, as measured by this device, was strongly correlated to the upper duff moisture content and to a fuel buildup index (George 1969).

Correlative Parameters

Several fire intensity parameters have been proposed as possible "correlative parameters" which may be useful for relating soil heating to fire behavior and intensity (Albini 1975). The parameters recommended included: unit area energy release (EA), residence time (both surface area (T_o) and loading (T_w) weighted), intensity reaction (IR), and total energy release. Future evaluations are necessary before these parameters can be correlated with soil heating.

Eventually, a purely physical model describing heat flux downward to the litter and underlying soil must be formulated before soil heat flow models such as proposed by Aston and Gill (1976) can be fully utilized. At present no satisfactory model has been developed to account for the effect of the litter layer because neither the duff consumption model (Van Wagner 1972) nor the duff burnout model (Albini 1975) has been useful for predicting slash burn heat release (Albini 1975).

Soil Temperatures During Grass, Brush, and Forest Fires

Generally, lower soil temperatures have been reported under burning grass than under brush or trees. Lower temperatures under grass result from less fuel. A heavy stand of grass probably contains less than 2.5 tons of mulch per acre (Heady 1956). In contrast a mature chaparral brush stand contains between 15 and 50 tons per acre of standing plant biomass (DeBano *et al.* 1977). Soil heating during brush fires is usually more severe than prescribed burns in forests for several reasons. Fire generally is carried by the canopy and standing dead stems. This leads to rapid and intense combustion even during cooler burning prescribed fires in brush. In contrast, prescribed fires used in forests are designed to minimize damage to standing trees (Biswell 1975). Prescribed burning in forests is also done during moister conditions since dead fuels are the only components burned. Chaparral fires usually will only burn under drier conditions since live fuels are also consumed during burning. A thinner litter layer is also present in chaparral and thus the soil is not well insulated against heat radiated downward during a fire compared to the forest floor where a thick layer of duff and litter is normally present. Consequently, temperatures at the soil surface and in the soil during chaparral fires generally are higher than those reported during prescribed fires in forests (DeBano and Rice 1971).

Soil temperatures reported under **grass** in different parts of the world seem surprisingly similar. For example, in southeast Queensland, the maximum surface temperature under burning speargrass (*Hetropogon contortus*) was 245° C (473° F) (Tothill and Shaw 1968). At 0.5 in (1.3 cm) below the surface, the soil temperature never exceeded 65-68° C (149-154° F). A fire in an annual grassland in California produced a maximum surface temperature of 177° C (350° F); maximum temperature at 0.5 in (1.3 cm) was only 93° C (200° F) (Bentley and Fenner 1958).

The maximum temperatures under burning **brush** can be high, although they vary widely—depending on the weather and plant conditions existing during and before a fire. Portable recording pyrometers buried ahead of a rapidly burning wildfire in southern California indicated a maximum temperature of 716° C (1320° F) at the soil surface (DeBano and Rice 1971). The highest temperature was recorded when the fire was burning rapidly upslope in the late afternoon. At 1 in (2.5 cm) below the soil surface, the maximum soil temperature recorded was 166° C (330° F) and at 2 in (5.0 cm) it was only 66° C (150° F). At other places covered by the same fire, much lower temperatures were recorded. For example, on a site where the fire was burning slowly across a level area in early evening, the maximum surface temperature was only 316° C (600° F). The temperature at the 1 in (2.5 cm) depth was 66° C (150° F) and at 3 in (7.6 cm) was 43° C (110° F). Most likely the largest amount of acreage is burned during a wildfire when the humidity is low and a fire is burning actively through dry brush. This means a relatively high average maximum surface temperature would be expected on a large percentage of the area burned by wildfires. Data from several prescribed burns in chaparral show the maximum temperature recorded in one-half inch of litter under burning chamise was 538° C (1000° F) (Sampson 1944). At 1-1.2 in (3.8 cm), the maximum soil temperature recorded was 149° C (300° F). Bentley and Fenner (1958) reported the maximum temperature at the 0.5 in (1.3 cm) layer was 454° C (850° F) when the fire was hot enough to produce a white ash condition.

Recent publications (DeBano *et al.* 1977, DeBano *et al.* in press) have summarized all the soil heating data in the literature along with numerous soil temperature data collected during the last 10 years in southern California chaparral on prescribed burns and wildfires. This information was used to construct stylized soil heating curves for light, moderate, and intense chaparral fires. These curves show the maximum temperatures at the surface are about 700° C (1,291° F) during an intense burn, 425° C (797° F) under a moderate burn, and only about 250° C (482° F) under a light burn. At 1 in (2.5 cm) downward in the soil the maximum temperatures do not exceed 200° C (392° F) even under an intense chaparral fire.

The soil temperatures generated during a **forest** fire probably also vary widely—depending upon whether they are produced during a wildfire or a prescribed burn. No direct soil temperature measurements have been reported for wildfire conditions. The available information on temperatures in the soil during prescribed burning in forests is that soil temperatures were intermediate on brush and grass fires. The maximum temperature recorded at 1 in (2.5 cm) below the surface during an extreme fire burning for 8 hours in an eucalyptus forest was about 275° C (527° F) (Beadle 1940). In a less intense fire where the eucalyptus trees were burned, the maximum temperature at 1 in (2.5 cm) was 175° C (347° F). In longleaf pine stands, in Southeastern United States, fires tend to remain as surface fires while moving through the understory and usually do not burn the trees (Heyward 1938). Under these conditions, the temperatures in the 0.12-0.25 in (0.32-0.64 cm) layer did not exceed 135° C (275° F). Likewise, relatively cool burning fires have been reported in the duff, litter, and soil during a cool burning prescribed fire in ponderosa pine and incense cedar in California (Agee 1973). During these fires the maximum temperatures of the duff never exceeded 260° C (500° F) and the maximum temperatures of the litter never exceeded 154° C (310° F). The soil surface temperature only reached about 93° C (200° F) and at 2 in (5 cm) the temperature rose only slightly. When fuels are windrowed or piled and burned, more soil heating can be expected. For example, temperature measurements under burning windrows of eucalyptus slash and logs revealed peak temperatures of 666° C (1,231° F) just below the soil surface to 112° C (233° F) at a depth of 8-1/2 in (22 cm) (Cromer 1967, Cromer and Vines 1966, Humphreys and Lambert 1965, Robert 1965).

Soil and Litter Properties Affecting Soil Heating

Fuel loading, fuel moisture, meteorological conditions, and several other variables also affect fire behavior and burning intensity. Although little quantitative data are available on heat fluxes emanating downward from a burning plant canopy, it has been estimated that only about 8 percent of the energy released by the burning chaparral canopy is absorbed at the soil surface and transmitted downward in the soil (DeBano 1974). Downward heat transfer is further complicated by ignition and combustion of organic matter on the soil surface and in the upper layers of mineral soil. This is particularly true in forests where thick and moist litter and duff layers are present (Van Wagner 1972). Qualitatively, heat originating in the burning canopy or aboveground fuels impinges first on the litter layer, which may be totally or partially consumed. The litter layer can provide an insulating effect on soil heating even if it is reduced to an ash layer (Scholl 1975). Upon reaching the mineral soil surface, heat is transferred downward through the soil by conduction, convection, and vapor flux (Aston and Gill 1976).

Although several soil properties affect the rate of heat transfer in soils, soil water is most important. Because water has a high heat capacity, moist soil usually does not rise to about 100° C (212° F) until the water in any one layer has evaporated (DeBano *et al.* 1976). Water moves out of the soil relatively slowly and, consequently, soil heating is reduced. Other soil physical properties, such as texture, also affect heat transfer. For example, thermal diffusivity of quartz is about three times that of clay minerals. Organic matter has a lower thermal diffusivity than soil minerals but when ignited also heats the upper mineral soil layers.

Indirect Effects of Fire

Removing the plant canopy and/or the soil litter layer can affect the diurnal temperature regime because the shading and insulating effects of these covers have been lost. For example, the temperature differentials between burned sites and undisturbed forested sites were about 10° C (18° F) at 3.0 in (7.6 cm) depth; however, the difference was only 2° C (3.6° F) where the burned site was shaded (Beaton 1959a, 1959b). At 2.0 in (5 cm) depth the average weekly temperature was as much as 11° C (20° F) greater where slash was burned on the south slope and 8° C (15° F) greater on the north slope (Neal *et al.* 1965).

Consistent responses have been measured for increases in soil temperature of range soil after burning (Ehrenreich 1959, Greene 1935, Hervey 1949, Hulbert 1969, Kucera and Ehrenreich 1962, Scotter 1964, Sharrow and Wright 1977a, and Tothill 1969).

Permafrost melting and deepening is closely related to the insulation provided by vegetation—the thickness of the moss-lichen mat (Viereck 1973). Permafrost remains stable as long as the mat is undisturbed. Removal by burning causes melt and recession of the ice surface, but the mat re-forms in a few years, and the ice returns to its previous position.

CHEMICAL PROPERTIES AND NUTRIENT CYCLING

Burning affects the chemical properties of soils by ashing the organic materials contained in the aboveground vegetation, including organic residues. The ash on the soil surface further affects various soil chemical properties, including pH and concentration of soluble elements. Precipitation carries the ash into the soil and the elements react with the soil and/or are dissolved in the soil solution. Variable amounts of ash are lost from the site aerially in overland flow, and as soluble ions moving into the ground water (Clayton 1976, Harwood and Jackson 1975). In a discussion of the indirect effects of fire, Wright and Heinselman (1973) stated that "Fires may indirectly release... mineral elements through increased decomposition rates of remaining organic layers and other remains, leaching or erosion of mineral soils, physical spalling of rocks, and the subsequent breakdown of rock fragments, etc. The exfoliation of granite boulders and rock outcrops heated intensively by the burning of moss and lichens and other fuels, as manifested in the Little Sioux fire of 1971 in northern Minnesota, may be by far the most important rock-weathering process in the region."

Organic Matter

The soil organic matter consists of the surface layers referred to as the O horizon, forest floor, litter or duff, and organic matter mixed with or combined with mineral soil. Physically, the surface organic matter is a protective layer and the organic matter in the mineral soil improves water relations. Organic matter both above and within the mineral soil provides and holds nutrients. When the organic matter is burned or heated a chain of events is initiated.

Generally the more intense the fire the greater the change in organic matter and thus in plant nutrients (DeBano and Conrad, in press). For example, during an intense chaparral fire, surface temperatures of 690° C (1,275° F) were high enough to destroy all the surface litter whereas the temperatures at 1 in (2.5 cm) in the soil, estimated to be 200° C (392° F), were only high enough to destructively distill the organic matter (DeBano *et al.* in press). This same type of analysis showed about 85 percent of the litter could be destroyed during a light intensity burn and only the humic acids are destroyed at 1 in (2.5 cm) downward in the soil. Measurements taken during a prescribed burn in chaparral showed about 45 percent of the organic matter in the litter, 19 percent of the organic matter in the 0.-0.5 in (0-1 cm) soil depth, and 9 percent of the organic matter in the 0.5-1 in (1-2 cm) soil depth were lost when two-thirds of the plant canopy was consumed (DeBano and Conrad, in press).

In the South, the surface of annually burned plots was covered with charred branches and needles. For periodic prescribed fires at a 4- or 5-year interval, except for the first year or two after burning, there was little visible change in the forest floor (Wells 1971). Forest floor samples collected immediately after a periodic winter burn showed a loss of 6,500 lb of the 24,000 lb/acre (7,300 and 26 900 kg/ha) of the forest floor initially present. After 20 years, annual summer and annual winter burns reduced the forest floor to 7,000 and 13,000 lb/acre (7,800 and 14 600 kg/ha), respectively. Several studies in the South show that prescribed burning in pine stands does not remove all of the forest floor, and that under some conditions, a single burn may remove only a small percentage of it (Brender and Cooper 1968, Moehring *et al.* 1966, Romancier 1960).

In the 20-year burning study in South Carolina (Wells 1971), burning increased organic matter in the 0-2 in (0.5 cm) layer of mineral soil but had no effect in the 2-4 in

(5-10 cm) layer. When the influence of fire on organic matter in both the forest floor and the 0-4 in (0-10 cm) of mineral soil was taken into account, the effect of burning was redistribution of organic matter within the profile but no reduction of organic matter.

For range soils, organic matter in the mineral soil was increased by fire according to Greene (1935b), Owensby and Wyrill (1973), and Wahlenberg (1935), but according to Scotter (1964) organic matter in the soil was decreased. Hervey (1949), Reynolds and Bohing (1956), and Suman and Carter (1954) measured no change. The contradicting results could be explained by the type of burning as reported by Blaisdell (1953) where an intense fire decreased the organic matter while light and moderate fires produced no changes. Hooker (1972) reported that approximately 70 percent of the surface litter remained after a low intensity spring burn. Therefore, the intensity of burning seems to be a primary factor in organic matter destruction. Studying the rate of mulch recovery, Dix (1960) found that a stand of *Stipa comata* had completely recovered in 4 years, but that a stand of *Agropyron smithii* recovered at a somewhat slower rate.

Reductions of organic matter are greatest on unproductive and submarginal forests where the organic matter is not incorporated into the soil or where there is only a thin layer of organic matter over parent material. Hayes (1970) recounts an example from New Hampshire where deliberate burning of the forests of Mt. Monadnok, which harbored wolves, destroyed the organic soils, and to this day the upper third of the mountain is bare rock. Another example was observed by Fredriksen on one site on Vancouver Island, British Columbia, Canada, where the boulders and talus, once covered by organic soils, supported marginal forests of Douglas-fir and western hemlock. Broadcast burning set the site back to primary succession at the moss-lichen level. High intensity wildfires could be as destructive. Although these forests have little commercial value, they do have value for animal habitat, streamflow regulation, and wilderness recreation.

Broadcast burning on productive Douglas-fir sites in the Pacific Northwest reduces the organic matter of the surface soil (A horizon) by intense burning under heavy concentrations of logging residue. Dyrness and Youngberg (1957) found that the organic matter content of the surface 2 in (5 cm) of soil was reduced from 11 to 4 percent on 8 percent of the area of clearcuts in the Coastal Range of Oregon. There was no change or only slight increases in organic matter content where the surface litter was charred by fire but not removed. Thirty percent of the area remained unburned. Possible effects of burning on soil productivity are confined to a small percentage of the area that is severely burned. Improved utilization in recent years has undoubtedly reduced the proportion of the area severely burned.

Nutrient Changes

Although there is no model to quantitatively predict the transformations of elements and subsequent soil chemical changes from fire, consideration of the chemical properties of and amounts of ignited material helps explain varying results. Burning materials high in a mineral element increases the concentration of that element in the soil. Conversely, burning the same amount of material low in that element may not measureably change the element in the soil. An excess of basic ions ($K+$, $Ca++$, $Mg++$) over anions (PO_4, SO_4) in the ash neutralizes soil acidity. An immediate flush of elements is followed by a slower release. Burning, which releases a relatively large amount of a basic element, changes the acidity of a highly buffered clay soil high in organic matter less than if the elements were released in a sandy soil low in organic matter. Soils are highly variable in chemical properties and the release of relatively large amounts of basic elements by fire would not significantly change the soil if the soil were already rich in those elements. These general considerations are applicable for mineral elements, but fire effects on volatile elements, especially nitrogen, are less predictable. Some of these general principles are illustrated in results from Burns

1952, Heyward 1936, Heyward and Barnette 1934, Lunt 1950, Moehring *et al.* 1966, Suman and Carter 1954, Wahlenberg 1935, Wahlenger *et al.* 1939, Wells 1971. There are usually trends toward higher concentrations of N, P, K, Ca, and Mg in the upper few inches of mineral soil and a decrease in these elements in the forest floor.

The effect of residual charcoal with its low bulk density and a high adsorptive capacity for mineral nutrients will influence the response of soil properties to burning. The effect on chemical properties was greater on sandy soils than on clay soils (Tryon 1948); however, there is no method to quantify the charcoal effect. The changes in soil resulting from shifts in microbe or higher plant populations contribute to the complexity of fire effects predictions. For example, biological N-fixation following fire may in some cases balance the N loss caused by fire.

Chemical properties of range soils have shown considerable variation in response to fires. Nitrogen content has been improved according to Christensen (1976), Hooker (1972), Vlamis and Gowans (1961), Wahlenberg (1935), and Greene (1935a) while it has been decreased according to Blaisdell (1953) and Owensby and Wyrill (1973). That both results may be real can be seen from results obtained by other scientists. White *et al.* (1973) found that intense fires caused a decrease in N while less intense fires caused no change. Kenworthy (1963) reported significant losses of N in smoke at fire temperatures above 400° C. Also, season of burning can alter N response to fire (Owensby and Wyrill 1973). Sharrow and Wright (1977a) found that both burning and clipping to remove plant material resulted in increased N mineralization. As an example of the effect of species, Reynolds and Bohning (1956) reported that as a result of burning, N increased under large mesquite and dense black grama but showed no change under heavy stands of burro-weed. Scotter (1964) found no changes in N levels in response to burning. On tobosagrass ranges of west Texas, Sharrow and Wright (1977b) determined that after 3 years standing old-growth-N and after 5 years litter-N on the soil surface returned to prefire levels.

Phosphorus levels in the soil were found to increase with burning by Vlamis and Gowans (1961) and White *et al.* (1973). Decreases in soil P have been reported by Scotter (1964), while no differences were reported by Christensen (1976), Pellant and Nicholson (1976), and Suman and Carter (1954). Other nutrients responded in similar ways. Calcium contents increased according to Christensen (1976), Scotter (1964), and Wahlenberg (1935). Potassium levels increased according to Christensen (1976), Owensby and Wyrill (1973), and White *et al.* (1973); decreased according to Reynolds and Bohning (1956); and were unchanged according to Scotter (1964), Suman and Carter (1954), and Vlamis and Gowans (1961). Magnesium increased or remained unchanged according to Christensen (1976) and Scotter (1964), respectively. These conflicting changes appear to result from widely varying fuel characteristics and loading and fire intensity.

Soil Reaction

Soil acidity in the surface layers is reduced by burning as a result of the basic cations released by combustion of organic matter and the chemical effects of heating on organic matter and minerals. Soil pH is raised temporarily depending upon the amount of ash released, original soil pH, the chemical composition of the ash, and wetness of the climate (Grier 1975, DeByle 1976, Metz *et al.* 1961, Wells 1971, Lutz 1956). Twenty years of annual and periodic burning in loblolly pine on a poorly drained soil in South Carolina changed the pH from 3.5 to 4.0 in the F layer and from 4.2 to 4.6 in the 0-2 in (0-5 cm) mineral soil layer. Most of this effect occurred during the first 10 years. Burning every 4 or 5 years failed to influence the acidity of the mineral soil and annual burns did not change pH in the 2-4 in (5-10 cm) depth. Fourteen years of annual burning of red pine and white pine stands in Connecticut increased pH of the 0-1 in (0-2.5 cm) mineral soil from about 4.3 to 5.0 (Lunt 1950). The 1-8 in (2.5-20 cm) soil layer was not changed. In Minnesota, annual, biennial, and periodic burns of a red pine plantation increased the forest floor pH from 4.9 to about 5.9 and the 0-4 in (0-10 cm) layer of mineral soil from 5.3 to 5.5 (Alban 1977).

Slash burning as practiced in the West has a greater effect on soil pH than silvicultural burning in the South. Light and severe burn increased pH from about 5 to about 7 following clearcutting Douglas-fir at three locations (Tarrant 1956). Three and 4 years after the burn soil pH decreased more rapidly on a light burn than on a severe burn. An intense slash burn in Douglas-fir increased pH from 5.0 to 7.6 in the duff, from 5.0 to 6.2 at 0-3 in (0-7.5 cm) depth, and from 4.8 to 5.5 at the 3-6 in (7.5-15 cm) depth (Isaac and Hopkins 1937). There was no effect below the 6 in (15 cm) depth. For range soils where small amounts of organic matter are burned, the soil reaction changed only slightly. Soil pH was unchanged according to Blaisdell (1953), Reynolds and Bohning (1956), and Suman and Carter (1954). However, an increase in pH was reported by Owensby and Wyrill (1973) and a decrease by Scotter (1964). The reason was not found for this unusual decrease in pH. Tarrant (1953) showed in the laboratory that heating soils at 315° C (600° F) for 90 minutes changed pH more than heating for 15 minutes. The change was also greater for an Olympic loam with an original pH of 5.5 than for an Astoria clay loam with an original pH of 4.5. This occurred because pH is expressed in terms of the negative logarithmn of the hydrogen ion concentration and therefore a given incremental change in hydrogen ion concentration has a much greater effect on the expressed pH in high pH soil than in a low pH soil. Also, the finer textured soil was influenced less because the cation exchange capacity was greater.

The quantity of basic metal ions in ash after burning is small in terms of lime equivalents or neutralization effects. For the loblolly pine stand in South Carolina the sum of Ca, Mg, and K in the unburned forest floor was about 180 lb/acre (200 kg/ha), which would have a very small liming effect if all these ions were converted to oxide in the residual ash from burning. Burning slash of species higher in basic cations would have a greater liming effect. Reports from the literature indicate that heat may have as great or greater effect on soil pH than the oxides in the ashes.

Nutrient Availability By Seedling Studies and Pot Experiments

Fire has variable effects on nutrient availability in soils—sometimes mobilizing nutrients, inducing deficiency or causing no discernible effect. Although changes in availability have often been demonstrated, the underlying causes have seldom been identified as will be evident from the following literature. Nutrient availability is often evaluated by pot experiments, whereby growth or nutrient content of indicator plants is compared for soils from burned and unburned areas. The lack of knowledge about the form of nitrogen residues after burning makes this type of experiment particularly adaptable to nitrogen investigations, but they have been used successfully for P, K, Ca, and Mg.

On ponderosa pine in the Coastal Range of northern California, Vlamis *et al.* (1955) found burning treatments increased the N- and P-supply power of the soil to indicator lettuce and barley plants. The increase was considerably greater when tests were made 1 year after burning than it was after 2 years. In a second pot experiment, Vlamis and Gowans (1961) found that brush burning increased the N, P, and S supply to plants on soils acutely deficient in these elements. Availability of N, as shown by short-term uptake by barley, was significantly higher from burned than unburned areas 10 months after burning chaparral (Mayland 1967). Wahlenberg (1935) reported an increase in available N, exchangeable Ca, and organic matter after burning and in green house tests; slash pine grew better on the burned soil. Loblolly pine in pots of soil from plots annually burned for 20 years contained more phosphorus and potassium than seedlings in soil from nonburned plots (Wells 1971). Responses to the mineral elements released in burning are expected when supplies of the elements are limited.

In contrast to this increased growth on the burned soil, spruce seedlings in pots of soils from repeatedly burned hardwood stands had poorer growth (Lunt 1941). Vlamis *et al.* (1955) demonstrated intense P deficiency to lettuce plants on Holland soils in the Coast Range of northern California after burning. Although they did not identify the mechanism, it is probable that the fire changed the chemical forms of the iron and aluminum with which phosphorus is associated. In a cutover cedar-hemlock forest, seedling growth on unburned soil was superior to that on lightly or heavily burned soil (Baker 1968). Poorest growth was associated with the heavily burned soils. Mixing the unconsumed litter with the underlying mineral soil mitigated the adverse effects of burning on mineral soil. The reasons for the adverse effects were not determined.

Douglas-fir needle samples from trees sampled 4 years after planting on slash-burned and nonburned soil were not significantly different in N, P, K, Ca, and Mg (Knight 1968). Improved growth (Thielges *et al.* 1974) frequently observed in ash beds, "the ash-bed effect," is generally attributed to less competition and more nutrients (Applequist 1960). The ash-bed effect has been investigated by transferring the ashes to nonburned soil and observing plant growth with and without ashes on burned and unburned soil. Superior tree growth was obtained where ashes had been removed and the ashes had no effect on nonburned soil, thus indicating an effect of heat on the soil (Bruce 1950, Renbuss *et al.* 1973).

Results from the cited studies and others, as expected, show that plants responded to mineral elements released in burning. Apparently a soil sterilization factor also increases N availability in some conditions and volitalization or chemical transformations of N may decrease availability in other cases.

Nutrient Losses

Several mechanisms are responsible for increased nutrient losses from burned sites. Nutrients in soil may be lost by wind and water erosion, leaching, or volatilization. Volatile elements (N, S, P. Cl) are lost when burning temperatures exceed the temperature of volatilization. Nitrogen and S are most important because they are limiting in many ecosystems and also because they have a low volatilization temperature. Nitrogen volatilization will be discussed more thoroughly later. Erosion losses will depend on the erosion mechanism. Surface erosion removes those nutrients (N, P, and S) closely associated with organic matter, while mass erosion will remove the entire soil with its incorporated nutrient capital to the depth of the failure. Greater nutrient depletion will result from surface erosion than from mass erosion because of the greater area affected. Leaching losses of cations depend upon the generation of mobile anions HCO_3, NO_3, SO_4, and organic acids in solution. Since the ionic charge of anions and cations must be equal in soil solution, then increased concentrations of anions will displace greater quantities of cations from the ion exchange complex in the soil to streams (McColl and Cole 1968). Losses of mobile anions are important when they are essential nutrients (NO_3 and SO_4). Cation losses will remain elevated until anion concentrations are abated by physical and biological processes on site. Cation losses into stream may not increase if cations released by burning can be stored in the soil.

Broadcast burning has had variable effects on water quality at one site in western Oregon. Frederiksen (unpublished)[2] found nitrate outflow to be elevated on clearcut sites compared to an adjacent undisturbed forest. Furthermore, the level varied depending upon whether the slash was burned or not burned. Outflows were 2.2 lb/acre (2.49 kg/ha) after clearcutting, 0.82 lb/acre (0.92 kg/ha) by broadcast burning after clearcutting on an adjacent watershed and 0.04 lb/acre (0.05 kg/ha) from the undisturbed forest. Presumably, the difference in nitrate outflow on the clearcut sites was due to differences in the availability of N caused by the volatilization of N by burning. There were no cation responses to burning on this site, but on another site cation outflows were increased for the year following burning by the following percentages: Ca 34, Mg 25, K 21, and Na 14 (Fredriksen 1971). The differences in cation response between the two sites were attributed to the base saturation of the soils, but possible differences in

[2]Progress report: Changes in streamflow and water quality from clearcutting with and without slash burning on the Fox Creek Watersheds—Bull Run Watershed. March 1978, 13 p., + illus., Forestry Sciences Laboratory, Corvallis, Oreg.

the cation content of the residue are unknown. The effect of fire on solution transport of nutrients was reviewed by Tiedemann *et al.*[3] (1978).

Nutrient losses from the site are important only if they cannot be resupplied to the ecosystem to meet the requirements for optimum growth within the limits of climate and soil. For ecosystems in warm, temperate climates on soil derived from basic igneous parent materials or from sediments derived from these basic materials, earth-derived elements are in abundant supply, but N and possibly also S may limit growth. In soils derived from acid igneous rocks and from old highly weathered sediments, P, K, and trace elements may also be limiting. Only in rare instances have site specific studies of this type been undertaken. Stark (1977), on one site in the Intermountain Region, estimated that nutrients removed by harvest, erosion, and leaching should not limit productivity for several tens of thousands of years. Other reports of fertilization research and nutrient cycling indicate nutrient deficiencies exist and will be intensified by excessive nutrient movement from the system by fire or other means (Boyle 1976, Jorgensen *et al.* 1975, Penning de Vries *et al.* 1975, Switzer and Nelson 1973, and Waide and Swank 1975).

Nitrogen Volitalization and Additions

Nitrogen is the main nutrient lost during fire and if a replacement mechanism were not present, site quality would decrease in areas subjected to repeated fires.

In a laboratory study, N was lost from the samples of ponderosa pine forest when the samples were heated in excess of 200° C (392° F), (White *et al.* 1973). During the fires in chaparral, a large portion of the N in the plants, litter, and upper soil layers is lost by volatilization or is changed into a readily available form. It has been estimated that 10 percent of the total N in a chaparral ecosystem can be lost during a prescribed burn (DeBano and Conrad, in press), 125 lb N/acre (140 kg N/ha) were lost in a prescribed burn of ponderosa pine (Klemmedson *et al.* 1962), and 100 lb/acre (112 kg/ha) were lost in a prescribed burn in loblolly pine (Wells 1971). In what may possibly be a extreme case, 20 percent of the ecosystem N was lost from a wildfire in ponderosa pine (Welch and Klemmendson 1975). Other large N loss estimates are found for the Northwest. In a severe wildfire in a conifer forest in Washington, 809 lb N/acre (907 kg/ha) were lost (Grier 1975) and 669 lb/acre (750 kg/ha) were lost from Douglas-fir slash burning (Zavitkovski and Newton 1968, and Youngberg and Wollum 1976).

Most of the N lost from chaparral was from the standing brush and litter although 12 percent of the nitrogen in the 0-0.4 in soil layer and 9.4 percent of the nitrogen in the 0-0.8 in (1-2 cm) soil layer were lost. A portion of the nitrogen not volatilized is available as ammonium N near the soil surface (Christensen and Muller 1975, Dunn and DeBano 1977). One of the authors (Dunn) sensed a large concentration of ammonia by smell and eye irritation immediately after burning chaparral. DeBell and Ralson (1970), however, trapped extremely small quantities of ammonia from burning pine in laboratory studies. Up to 21 lb/acre (24 kg/ha) of ammonium nitrogen have been produced directly in the soil by a prescribed fire during the winter (DeBano *et al.*, in press). Little changes in nitrate nitrogen occur during burning but nitrate increases during subsequent mineralization (Dunn and DeBano 1977, Lewis 1974) probably as a result of decreased acidity of the humus layer and increased ammonification (Viro 1974).

The general results of repeated annual or perennial prescribed burns of pine forests have shown that burns of 4- or 5-year intervals have little effect on the forest floor or mineral soil (Alban 1977, Burns 1952, Metz *et al.* 1961, Moehring *et al.* 1966, and Wells 1971). Annual burning for long periods reduced the forest floor and nutrient pool therein, and increased the nutrients and organic matter in the upper A horizon. Even though nitrogen is volatilized during burning, an actual decrease in the site N was not shown.

Viro (1974) discussed the effects of N loss from slash by volitalization and concluded

[3]State of Knowledge Report presented at the National Fire Effects Workshop, Denver, Colo., April 10-14, 1978.

that even though substantial N is lost when logging slash is burned, this loss is unimportant because it is unavailable to plants. This statement requires qualification with regard to the type of slash burned, the possibility of burning the forest floor, and whether climatic factors will allow for decomposition and mineralization of essential nutrients from the forest floor and foliage residue.

The productivity of areas frequently burned testifies to the effectiveness of the N additions by N fixation processes. Atmospheric deposition of from 1-10 lb/acre (1-12 kg/ha) is insufficient to balance N losses from burning and other mechanisms. In addition to the uptake and nutrient cycling function, certain species of vegetation in fire-adapted ecosystems supply N to the site by symbiotic fixation. Species of *Alnus, Ceanothus, myrica,* most species of the *Leguminosae,* and some tropical grasses are known N fixers. One or more of these species is commonly found as part of the shrub-herb flora dominant on the site during the regeneration stage. Several native legumes occurring in rangelands and forests known to fix nitrogen are *Cassia fasciculata, Lespedeza capitata, Schrankia unicinata, Amorpha canescens,* and *Psoralea argophylla* (Becker and Crockett 1976). The populations of some of these plants are greatly increased by wildfires or prescribed burning (Chen *et al.* 1975, Cushwa and Reed 1966, Cushwa and Martin 1969, Youngberg and Wollum 1976). Several reports also indicate more N is fixed by nonsymbiotic microrganisms following burning (Jorgensen and Wells 1971, Lutz 1956, and Vlamis and Gowans 1961).

Ceanothus (snowbrush) species are nodulated and effectively fix N. They are common invaders after fire or logging in the Western United States. Youngberg and Wollum (1976) found that snowbrush fixed 636 lb N/acre (715 kg/ha) in a pine stand in 10 years after a wildfire and 964 lb/acre (1081 kg/ha) in a fir stand in 10 years after harvest, slash burning, and planting. Fixation after 15 years was 714 and 1,143 lb N/acre (800 and 1 281 kg/ha) respectively, in the pine and fir stands (A. G. Wollum, personal communication). If 669 lb N/acre (750 kg/ha) is volatilized due to slash burning, preburn N levels will thus be restored in approximately 7 years. Zavitkovski and Newton (1968) reported much lower levels of N fixation for snowbrush and estimated that 35 years would be required to restore the N to its preburn level.

The symbiotic replacement of N after fire is rapid (Paul Dunn, unpublished data[4]) in chaparral when the N-fixation system is not severely disrupted. The combination of fire intensity and soil conditions at which the soil N fixation mechanisms would be disrupted is not known. Data on the death of *Lotus* and *Lupinus* species seeds after fire in southern California chaparral show that *Lotus* species produce two types of seeds, those resistant to heating and those that are not. The resistant seeds show a fire survival similar to that of fungi but at a slightly lower temperature (Laura Westermeier, California State University, Fullerton, personal communication). The *Lupinus* sp. tested are killed by 90° C (194° F) in dry or wet soil.

Restoration of N through symbiotic fixation may not be sufficiently rapid or great enough to balance losses from fires in some ecosystems (Jones and Richards 1977). Nitrogen-fixation estimates have not been made for the numerous N-fixing plants that reproduce following fires in the Eastern United States; however, their biomass is much less than for snowbrush and their N-fixing rate is expected to be relatively small when shaded in established stands or competing during regeneration of trees. Seeding leguminous plants is considered a possible means of adding N to the soil. Research is underway to find adaptable species and to develop successful methods (Jorgensen 1978).

[4]Data available from author. U.S. Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station, Glendora, Calif.

SOIL MICROFLORA

Forest productivity is dependent on interrelationships between climate and physical, chemical, and microbiological properties of soil. Since soil microorganisms are strongly influenced by aeration, pH, water, temperature, and available food (Cramer 1974) any disturbance affecting these properties will likewise affect the microorganisms and thus will affect soil fertility and forest yield.

The effects of fire on soil microorganisms have been studied by several investigators. Ahlgren's (1974a) review article, "The effect of fire on soil organisms," provides a relatively complete, up-to-date summary of most pertinent literature.

As one might expect, the effects of burning on soil microorganisms have been variable, depending on the local site, intensity of fires, and sampling method. Intense fires affected microorganisms most dramatically. Hot fires as reported by Renbuss *et al.* (1973) and Ahlgren and Ahlgren (1965) temporarily sterilize the soil. Renbuss concluded that accelerated growth of plants established in ashbeds of burned windrows resulted from reduced competition between plants and microorganisms for available soil nutrients. A direct chemical stimulus was discounted because the addition of ash to unburned sites usually had no stimulating effect on plant growth.

Less intensive fires, as typified by prescribed burning in the Southern United States, usually have little documentable effect on soil fungi, actinomycetes, and bacteria because only minor changes in soil properties are wrought by fire. For example, Berry (1970) reported that in Louisiana plots which were burned annually in winter for about 50 years showed only minor increases in soil pH, moisture, and temperature and no changes in soil microorganisms. Jorgensen and Hodges (1970) found few indications that a program of annual or periodic burning had "altered the composition of saprophytic, sporeforming microfungi or reduced the number of bacteria and actinomycetes to the extent that soil metabolic processes were impaired."

Qualitative information of the effects of fire on fungi is limited because many species cannot be successfully isolated from soil and because some fungi are prolific sporulators that can be readily isolated so they may be given undue attention. Nevertheless, qualitative differences in fungi have been clearly attributed to burning as summarized by Ahlgren (1974a).

Jorgensen and Hodges (1970) conjectured that prescribed burning may alter host-parasite relationships of important soil-inhabiting pathogens. A *Rhizinia undulata* root rot is made more severe by fire (Ahlgren 1974b). However, in a recent report, Froelich *et al.*, (in press) state that prethinning burning of southern pine plantations often helps to prevent serious losses from annosus root rot caused by the fungus *Heterobasidion annosum (Fomes annosus)*. This pathogen is not free-living in soil, but is confined to the surface or interior of roots. The mechanism of control provided by burning is therefore difficult to resolve because the effect may involve changes in host resistance or changes in the competitive abilities between the pathogen and microorganisms that are free-living in soil. The authors could not demonstrate that burning altered pH or chemistry of the soil which had been previously cultivated. Although total numbers of bacteria, actinomycetes, and fungi, or rate of respiration of soil organisms were unaffected by fire, significant changes did occur in numbers of *Trichoderma* spp. These species are often regarded as fungal competitors of the pathogen.

Tarrant (1956) studied natural Douglas-fir seedlings growing on slash-burned areas and critically examined the seedling roots for mycorrhizae. One year after the burn, 65 percent of 1-year-old seedlings on unburned soil had external mycorrhizae. On burned soil, however, only 40 percent of 1-year-old seedlings were mycorrhizal. The second year after burning, 100 percent of 2-year-old seedlings on unburned soil had mycorrhizae compared to only 79 percent of those on burned soil. Mycorrhizae were deeper in the burned soil on 1-year-old seedlings, but on 2-year-old seedlings he found no differences in depth of mycorrhizae between burned and unburned soils.

Results of recent studies show complex interrelationships between soil heating and microbial populations in chaparral soils (Dunn and DeBano 1977). Similar complexities are assumed in other soils. Duration of heating, maximum temperatures, and soil water content appear to be the most important factors affecting microbial responses to soil heating. Generally, bacteria are more resistant than fungi to heating in both wet and dry soil. Lethal temperature for bacteria was found to be 210° C (410° F) in dry soil and 110° C (230° F) in wet soil. Similar lethal temperatures have been reported in forest soils by Ahlgren and Ahlgren (1965) who found bacterial numbers were reduced significantly by heating to 200° C (392° F) for 25 minutes. Fungi in chaparral soils have been found to tolerate temperatures of only 155° C (311° F) in dry soil and 100° C (212° F) in wet soil (Dunn and DeBano 1977). Additionally, some fungi species are more sensitive than others to temperature increases. For example, up to 120° C (248° F) in dry soil and 60° C (140° F) in wet soil, normal saprophytic fungi prevail; above these temperatures "heat shock" fungi began appearing. These "heat shock" fungi persist until they are finally killed at 155° C (311° F) in dry soil and 100° C (212° F) in wet.

Nitrifying bacteria influence the availability of N for plants and leaching. This group of bacteria appears to be particularly sensitive to soil heating. *Nitrosomonas* group bacteria can be killed in dry soil at temperatures of 140° C (284° F) and in wet soil at 75° C (167° F) (Dunn and DeBano 1977). Nitrobacter group bacteria are even more sensitive and are killed at 100° C (212° F) in dry soil and 50° C (122° F) in wet soil. The sensitivity of nitrifying bacteria to heating has important implications concerning plant nutrition because N is frequently a limiting nutrient in chaparral soils (Hellmers *et al.* 1955) and forest soils generally in the Northwest and South. In unburned stands high levels of the total N are present as organic N, and relatively low levels of inorganic mineral N are present (ammonium and nitrate nitrogen). Christensen (1973) hypothesized that this occurred in unburned stands because heterotrophic microrganisms responsible for mineralization were inhibited by alleleopathic substances present in chaparral soils or because the high lignin content of chaparral plant leaves resisted decomposition and subsequent mineralization of N. These hypotheses are applicable to other forest types. However, higher concentrations of ammonium and nitrate N are generally present after a fire, (Sampson 1944b, Christensen and Muller 1975, Lewis 1974). Recently, detailed studies of these inorganic N compounds before and after burning revealed ammonium and nitrate N are formed by different processes in response to a fire. Apparently, large amounts of ammonium N are produced chemically by soil heating during a fire and also microbially shortly after burning. In contrast, nitrates are not produced directly by heating during a fire but are formed during subsequent mineralization and nitrification. Surprisingly, post-fire nitrification does not appear to be carried out by the classical nitrifying bacteria (*Nitrosomonas* and *Nitrobacter* group bacteria), probably because these bacteria are extremely sensitive to heating and other disturbances and consequently are absent or at extremely low levels for several months following burning (Jones and Richards 1977; Dunn, DeBano, and Eberlein, in preparation[5]). Results from this study suggest nitrification in burned chaparral soils was heterotrophic nitrification, possibly by fungi.

Any management plan involving winter and summer burning must balance the tradeoffs between soil microorganisms and N (Dunn and DeBano 1977). Prescribed burns during the winter over moist soil will be cool

[5]Available from author, U.S. Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station, Glendora, Calif.

and volatilize the least amount of N from a site. However, microorganisms are more sensitive to heating in a wet soil than in a dry soil. Results of experiments conducted thus far show winter burns are cooler and the effects on microbes are about equal to that of most hot dry summer burns (Dunn and DeBano 1977). However, it is possible to produce an extremely hot fire over wet soil if a large amount of either crushed or standing dead fuel is burned on dry days during the winter. Under these extreme burning conditions microbial numbers could be reduced to such low levels that recovery would be hampered. These tradeoffs between microorganisms and N must also be considered in terms of both short- and long-term effects on chaparral succession and site productivity.

This interaction of soil moisture and burning temperature should be considered when interpreting effects and planning burning programs in other forest types. In soil conditions where nitrification is limited by acidity, the influence of soil moisture and burning temperature on nitrifiers or N availability would be small. Furthermore, reduction in nitrification is an advantage in soils where N losses by leaching carry excessive nitrate or nitrite into streams or groundwater.

SOIL PHYSICAL PROPERTIES

Fire influences soil physical properties and erosion to a degree depending upon intensity of the fire, the proportion of the overstory and understory vegetation destroyed, forest floor consumed, heating of the soil, proportion of the area burned, and frequency of fire occurrence. Ahlgren and Ahlgren (1960) in an extensive review point out that the role of fire in increasing erosion and surface runoff, and in changing soil-moisture characteristics, has been a subject of much concern in studies of the effects of burning on soils. It is logical to assume that, since fire often changes the vegetation and forest floor suddenly and drastically, it also would change the reaction of the forest area to rainfall. However, the changes wrought vary greatly with the conditions of the soil, forest floor, topography, and climate.

Soil Porosity and Structure

The majority of studies indicate that fires were not intense enough to produce direct effects upon the structure of the soils, except where complete removal of duff and litter and subsequent exposure of mineral soil to rain result in puddling and baking of the surface (Dyrness and Youngberg 1957, Isaac and Hopkins 1937, Kittredge 1938, Lutz 1956, Sampson 1944, Trimble and Tripp 1949). Garren (1943), however, reported burned soil in Southern States to have a more massive structure and to be less permeable to water. Similarly, Wahlenberg *et al.* (1939) reported that burned soil was up to five times harder than unburned soil. Heyward (1937) found excluding fire for as little as 10 years in the longleaf pine forests resulted in a more porous, penetrable soil. Soils of sandy loam or heavier texture may exhibit fine crumb structure, and the humus layer will become mull-like. Kittredge (1938) believed soil porosity was greatly reduced because fire destroys insects and other macro-organisms which channel in the soil. Edwards (1930) reported better tilth in soils in India as a result of high temperatures during slash burning, and Ehrenberg (1922) ascribed similar findings to the fact that the heat of fire could make clay more friable. Screenivasan and Aurangabadkar (1940) reported lumping and hardening of clay soils after burning, the result of colloidal aggregation. In the Northwest, Dyrness and Youngberg (1957) reported that only severely burned soils were significantly changed in particle size distribution, soil structure, and organic matter.

The effects of fire moderate with time. The duration of effects ranges from a single season to many decades, depending on the extent of the fire itself and the rate of recovery as influenced by natural conditions, post fire use, and remedial measures applied by man. In the East, recovery from fires, usually surface fires, may be rapid (Bower 1966). However, in high elevation areas of the Northwest, or in more arid areas of the Southwest, regrowth after severe burning can be very slow (Anderson 1976).

Water Storage and Infiltration

Where much of the overstory foliage is destroyed, interception and evapotranspiration will be reduced resulting in increased soil water for storage (Anderson 1976, Campbell *et al.* 1977). Where organic layers of the forest floor are consumed and mineral soil exposed, infiltration and soil water storage capacity may be immediately reduced. Accelerated oxidation of soil organic matter from greater radiation can further decrease infiltration and water storage.

Erosion and runoff are often the result of lower infiltration rates and decreased water absorption particularly in regions receiving high intensity summer storms. In a study of infiltration rates on seven types of soil in Missouri, Arend (1941) found that burning reduced infiltration rates 38 percent, compared to an 18 percent reduction when litter was removed by raking. Similarly, Kittredge (1938) found infiltration rate on land burned annually was one-fourth the rate on unburned land. Meginnis (1935) reported lower water absorption for burned oak forests in Mississippi. Reduced water absorption caused by burning has also been reported by others (Austin and Baisinger 1955, Auten 1934, Musgrave and Free 1936, Pearse 1943, Wahlenberg 1935, Zwolinski 1971). Conversely, Veihmeyer and Johnson (1944) found no change in infiltration rates following brushland burning in California. Ferrell and Olson (1952) reported varying effects on infiltration following burning in the western white pine area.

Water infiltration rate is generally decreased by fire on range soils (Buckhouse and Gifford 1976, McMurphy and Anderson 1965, Suman and Halls 1955, and Wahlenberg 1935). However, an increased infiltration rate was reported by Scotter (1964) while Duvall and Linnartz (1967) and Linnartz *et al.* (1966) reported no change. Percolation rate was decreased according to Suman and Halls (1955) while Linnartz *et al.* (1966) found no change.

Intense surface fire reduced water storage capacity in the upper 2 in (5 cm) of soil by about one-fourth inch (Dyrness *et al.* 1957). If the overlying 2-in (5 cm) layer of humus was destroyed, the reduction totaled 1 in (2.5 cm).

A diminution of the actual moisture content of the upper layer of soil following fire is reported for different regions (Beadle 1940, Blaisdell 1953, Haines 1926, Heyward 1936, 1939, and Sampson 1944a). Conversely, Blaisdell (1953), studying burning of sagebrush and grasslands in the West, found that any reduction in moisture content was only temporary. No differences in moisture content between burned and unburned plots were reported on various vegetation types (Greene 1935b, Wahlenberg 1935, Wahlenberg *et al.* 1939, Wicht 1948).

Soil moisture in burned range soil was found to be higher by some authors (Hulbert 1969, Sharrow and Wright 1977a, Trlica and Schuster 1969) and lower by others (Anderson 1965, Anderson *et al.* 1970, McMurphy and Anderson 1965). No changes in soil moisture were reported by Hervey (1949), Larson and Duncan (1978), and Pellant and Nicholson (1976). However, Blaisdell (1953) found that intense fires decreased soil moisture while light and moderate fires had no effect.

Soil water storage may be reduced by fire-induced repellency in the surface soil (DeBano 1968, DeBano and Rice 1971). If mineral soil is exposed, aggregates are dispersed by raindrop impact and pores become clogged with fine particles, decreases in macropore space, and infiltration and aeration can be expected (Arend 1941, Auten 1934, Beaton 1959a, Sampson 1944, Vogl and Ryder 1969). When surface organic horizons are not completely burned, changes in pore space and infiltration may be too small to be detected (Metz *et al.* 1961, Moehring *et al.* 1966). The effect of fire on range soil porosity varies as for forest soils and the same explanation seems applicable. No changes in pore space were reported by Duvall and Linnartz (1967) and Linnartz *et al.* (1966). Bulk density was unchanged according to Duvall and Linnartz (1967), Linnartz *et al.* (1966), and Owensby and Wyrill (1973), and increased bulk density was reported by

Suman and Halls (1955) and Wahlenberg (1935). The importance of moisture-holding capacity in determining survival of forest trees was stressed by Kell (1938) and Daubenmire (1936). Although Austin and Baisinger (1955) reported that after burning the moisture-holding capacity in the top one-half in (1.2 cm) of soil was reduced 33.7 percent, many investigators agree that the moisture holding capacity is seldom affected by burning (Beadle 1940, Heyward 1939, Lunt 1950, Tarrant 1956). In the Douglas-fir region, the field capacity of the duff and top 0.3 in (1 cm) of soil was decreased with burning, but no change was noted below that depth (Isaac and Hopkins 1937). The presence of charcoal in sandy soil increased moisture-capacity, while in clay soil charcoal may have decreased it (Lowdermilk 1930, McCulooch 1944).

The effect of these various changes in soil moisture relations upon the water table apparently vary greatly with different site conditions. Lutz (1956) cited references (Buhler 1918, Gulisashvili and Stratonovitch 1935, Wiedmann 1925) to indicate that where the ground water is close to the surface, destruction of the forest by fire or other agencies will cause a rise in the water table resulting in the production of swamp conditions, at least in Alaska. In Finland, Kolchmainen (1951), however, did not believe that this occurred. He felt that transpiration from the larger number of plants developed after burning kept the water table normal. He further reported that in Sweden burning lowered the water table in some previously wet sites because the unburned areas with a thick moss cover did not freeze completely in the winter. Consequently, the spring surface thaw was absorbed into the ground and the water table was kept too high. When these areas were burned, however, they froze in winter, the surface water ran off, and the water table was thus lowered to a more desirable level.

Water Repellency

Water repellency has been observed as an important fire effect, particularly in the Southwest. It received initial and primary attention in association with chaparral fires where runoff and erosion are greatly increased by the phenomenon (DeBano *et al.* 1967). Following burning, the ash dust layer is resistant to wetting, thus causing runoff and erosion DeBano *et al.* 1967). On other areas the soil at or near the surface may be wettable but a layer beneath it repeals water. This layered arrangement allows incoming rainfall to infiltrate only to a limited depth before the wetting front reaches the water repellent layer. When the thin mantle above the water repellent layer becomes saturated, it along with some of the underlying water repellent layer may be carried off by surface runoff.

The water repellent layer described above is formed when litter and organic matter accumulate at or near the soil surface during the years between fires. When fire occurs the surface litter layer is heated sufficiently to volatilize and/or decompose the organic matter. A large percent (over 90 percent) of the decomposed organic matter is lost as smoke or ash (DeBano 1974). However, a small but significant amount is distilled downward in the soil along temperature gradients until it condenses in the cooler underlying layers (DeBano 1966). After condensing it may be further fixed in place by subsequent heating (Savage 1974). The thickness of the water repellent layer depends on the intensity of the fire, the soil water content, and the soil physical properties. If the surface temperatures are not hot, water repellency may be near the surface; but when the soil is heated to higher temperatures, water repellency is present in the deeper layers and the surface may be wettable (Scholl 1975). When the soils are dry, the water repellent layer is thicker and more severe than when the soil is wet (DeBano *et al.* 1976). Also, coarse textured soils are more likely to become highly water repellent than fine textured clay soils (DeBano *et al.* 1967). The organic substances responsible for water repellency are believed to be long chain aliphatic hydrocarbons (Savage *et al.* 1972). These substances are destroyed when heated much over 280° C (536° F) (Scholl 1975, Savage 1974, DeBano and Krammes 1966).

Fire-induced water repellency is not restricted to chaparral soils in California but is also found in Arizona chaparral (Scholl 1975) as well as in other vegetation types and burning situations. During a wildfire in a lodgepole pine forest in Oregon, a water repellent layer 1-9 in (2.5-23 cm) thick was formed on severely burned sites. This water repellent layer persisted for 5 years (Dyrness 1976). The broadcast burning of logging residue in Montana did not produce appreciable water repellency over medium-to-fine textured soils (DeByle and Packer 1976). However, when slash was piled and burned over coarse textured soils it presented wettability problems, particularly when the soil was dry. Water repellency has also been reported formed by prescribed burning in sagebrush (Salih *et al.* 1973) and during wildfires in ponderosa pine in Arizona (Campbell *et al.* 1977). However, in three studies on four watersheds in the Pacific Northwest, water repellency was not found (Harr *et al.* 1975). Instead, streamflow differences noted were attributed to soil compaction or snow accumulation and melt.

EROSION

Few investigators disagree with the idea that intensive burning increases erosion on many sites. In Oklahoma, Ewell *et al.* (1941) reported that over a 9-year period, soil loss was 31 times as great on burned as on unburned woodlots. In the pine region of the Sierras, erosion was 2 to 239 times as great on burned areas (Haig 1938). Increased erosion of wooded land has also been reported by many others (Anderson 1949, Connaughton 1935, Hendricks and Johnson 1944, Kolock 1931, Lowdermilk 1930, Lutz 1934, McLeod 1953, Morris 1935, Thompson 1935, Trimble and Tripp 1949). Erodibility of range soils would be affected by fires if all vegetation and mulch were burned. Wind erosion as the result of burning has been reported by Blaisdell (1953) and Hinds (1976) before recovery of vegetal cover. Water erosion and sediment production were not affected by burning in studies by Buckhouse and Gifford (1976) and Duvall and Linnartz (1967). On certain types of sites, burning does not increase erosion. Some studies in California indicated burning of brush and woodland grazing lands apparently had no effect on runoff and erosion (Adams *et al.* 1947, Biswell and Shultz 1957, Veihmeyer and Johnson 1944).

Other studies of burned brush and grassland, however, have revealed increased erosion (Brown 1943, Eaton 1932, Forsling 1931, Musgrave 1935, Musgrave and Free 1936, Sampson 1944). Horton and Kraebel (1955) reported increased erosion in brush plots in California following burning, but stated that it stopped when the proper prefire species reinvaded the burned land. Tedrow (1952), while studying burning in the New Jersey pine barrens, emphasized that when the land was flat and the soil sandy, runoff was negligible. In this same area, Burns (1952) also found no effect of fire on the physical properties of the soil.

The importance of forest floors in regulating runoff and controlling erosion was investigated intensively by Lowdermilk (1930). He concluded (1) forest litter greatly reduced runoff, especially in finer textured soils; (2) destruction of litter and exposure of bare soil greatly increased soil erosion and reduced the water absorption rate; (3) sealing of pores by particles in runoff caused marked differences in infiltration between bare and litter covered soils; and (4) water absorption capacity of litter is insignificant in comparison with its role in protecting maximum percolating capacity of soils.

Ralston and Hatchell (1971) reported estimates of soil losses caused by burning in the South (Table 1). Only the Piedmont North Carolina site showed erosion greatly exceeding the 1.8 inch (3 cm) per 1,000 years estimated by Judson (1968) as the erosion rate of the Central United States before man interceded on a large scale. Although the scrub oak site in north Mississippi slightly exceeded this rate, it was stabilized by the end of the third growing season.

Campbell *et al.* (1977) estimated that as a result of abnormally heavy rains 13.8 tons/acre (30.9 t/ha) of sediment was lost from a 10 acre (24.5 ha) ponderosa pine watershed in the 6 months following an intense wildfire. However, erosion decreased to an insignificant level the following year as ground cover was reestablished. Adequate ground cover to protect the soil surface appears to be the critical factor in avoiding unacceptable erosion rates following fire.

Megahan and Molitor (1975) described effects of the Pine Creek fire on the Boise National Forest. Fire burned the forested watershed and the clearcut watershed where only logging slash remained. Burning intensity on the clearcut with 90 tons/acre (200 t/ha) of slash was much greater compared to 10 tons/acre (22.4 t/ha) of down material in the adjacent uncut watershed. All organic matter was consumed on the clearcut and rill erosion began immediately.

Table 1.—Soil losses from burned and protected woodlands[1]

Investigator	Location	Forest cover	Years of record	Annual PPt Inches	Soil loss Tons/ acre/ year	Erosion Inches/ 1,000 yrs.
Meginnis (1935)	Holly Springs, Miss.	Scrub oak, burned	2	63.8	0.33	1.968
		oak forest, protected	2	67.1	.025	.157
Daniel *et al.* (1943)	Guthrie, Okla.	Woodland burned annually	10	30.6	.11	.669
		Virgin woodland	10	30.6	.01	.059
Copley *et al.* (1944)	Statesville, N.C.	Hardwood, burned semi-annually	9	46.9	3.08	18.504
		Hardwood, protected	9	46.9	.002	.012
Pope *et al.* (1946)	Tyler, Tex.	Woodland, burned annually	9	40.9	.36	2.165
		Woodland, protected	9	40.9	.05	.315
Ferguson (1957)	East Texas	Shortleaf-loblolly, single burn	1.5	--	.21	1.299
		Shortleaf-loblolly, protected	1.5	--	.10	.590
Ursic (1970)	North Mississippi	Scrub oak, burned and deadened	1st	65.1	.51	3.071
			2d	40.5	.20	1.220
			3d	50.5	.05	.315
		Scrub oak, protected	1st	65.1	.21	1.220
			2d	40.5	.09	.551
			3d	50.5	.03	.177

[1]Adapted from Ralston and Hatchell 1971.

Soil formed from granite eroded in proportion to the intensity of burn. Soil loss measured from the clearcut was nearly 13 ft^3/acre (0.15 m^3/ha), whereas no soil was lost from the uncut watershed. This study illustrates the sensitivity of such soils formed from acid igneous parent material to surface erosion and how the erosion rate is controlled by fire intensity.

Soils in the Pacific Northwest are generally strongly aggregated because of favorable climate and the preponderance of basic igneous parent materials. Surface erosion, even on steep slopes, is quickly controlled by invading annual vegetation (Mersereau and Dyrness 1972). Dyrness *et al.* (1957) listed three of several factors that tend to minimize the danger of erosion when slash is burned after clearcutting Douglas-fir.

1. Often a crust was present on the soil surface of the severely burned areas. It appeared that this crust provided some protection against soil movement.

2. The severely burned soil condition occurred almost entirely in small scattered areas. This tended to reduce the importance of the increased erodibility.

3. Very few severely burned areas were located on steep slopes where erosion would be more apt to occur. Most were found on gentle slopes and benches where topography was more conducive to slash accumulation.

Aggregation of the soils of interior Alaska is not so well achieved, but summer precipitation intensities are low and snow accumulations light. Therefore, surface erosion from burned areas is low.

Chaparral areas in both California and Arizona are relatively stable when fully vegetated and have not been burned for several years. However, the relative stability of these areas is changed dramatically by wildfires. Both runoff and debris production greatly increase after fire (Krammes 1965, Sinclair 1954, Row 1941, Hibbert *et al.* 1974).

Debris production from chaparral seems to be a two-phased process. Although erosion from sideslopes after wildfires is primarily by gravity activated landslides and dry ravel, some debris is delivered by overland flow. The increased overland flow after fire occurs because the soil surface is exposed to raindrop splash and a water repellent layer may be formed.

On steep slopes, dry ravel may occur during and immediately after fire even before the rainy season commences. Dry ravel from steep unburned chaparral slopes can amount to about 200-3,800 lbs/acre (224-4,300 kg/ha) (Anderson *et al.* 1959). The first year after being burned by a wildfire this rate can increase ninefold (Krammes 1960). Eighty-nine percent of this erosion occurred during the first 88 days after fire. Since dry ravel occurs in the absence of streamflow, debris routinely accumulates in deposits at the base of steep slopes. These deposits along with untransported remnants of landslide debris supply readily transportable sediment to the downstream areas when high discharges occur.

Only a limited amount of information is available on erosion following prescribed burning in chaparral (DeBano and Conrad 1976). However, these studies indicate slope is important. The first year after a prescribed burn 2.6 times more surface erosion occurred on the 50 percent slope than on the 20 percent slope. On the 50 percent slope about 35 times as much erosion occurred on the burned area as on the similar unburned site. The erosion rates for the burned and unburned sites were 6,500 and 186 lbs/acre (7,300 and 210 kg/ha), respectively. Chaparral in Arizona was strip burned after treatment with a herbicide (Pase and Lindermuth 1971). Erosion was greatest on steep slopes adjacent to main channels; however, lightly burned areas retaining 70 percent or more litter residue eroded but little, while areas with less than 60 percent litter remaining eroded moderately during periods of high precipitation.

Erosion following prescribed burning of Ashe Juniper (*Juniperus ashei*) also is affected by slope (Wright *et al.* 1976). On 45-53 percent slopes 5.9-7.9 tons/acre (13.2-17.7 t/ha) of sediment were lost before the slopes stabilized 15 to 18 months after burning. The gentler slopes (15-20 percent) yielded only 0.19-1.07 tons/acre (0.43-2.4 t/ha) before becoming stabilized 9-15 months after burning.

Reestablishment of ground cover naturally or by seeding is the most effective erosion control following fire. After investigating a fire that killed a ponderosa pine forest in South Dakota, Orr (1970) concluded that total ground cover of native and seeded vegetation must equal or exceed 60 percent density for minimum tolerable control of runoff and erosion. Ralston and Hatchell (1971) considered the question of acceptable erosion and concluded available reserve soil depth was a critical planning factor for fire use and suppression.

Fire has not been recognized as an important factor in mass erosion. Geologic structure and the nature of parent materials—their cohesive properties, the strength of bedrock, together with the duration of precipitation and snow melting, control the occurrence and rate of mass erosion. The major inputs of mass erosion have been road construction and clearcutting (Swanston and Swanson 1976). If there are fire effects, they can be expected to act indirectly on mass erosion as vegetation controls the water balance on the burned site. Work currently underway has shown the importance of root strength as a natural agent of control of shallow failures (debris avalanches) where the shear zone is often within the soil mantle (Ziemer and Swanston 1977). It is possible broadcast burning may slow the growth of shrub and herb vegetation and increase the extent and occurrence of debris avalanches.

EFFECT OF FIRE ON RANGE SOIL

There seems to be little consistency in research reports on burning ranges. This is probably because so many widely divergent ecosystems can be classified as range. Weather conditions can vary from very dry to very wet, from very hot to very cold, and from sea level to high altitudes. Also, the response to fire varies according to soil types (Brogg and Hulbert 1976). The responses vary according to season burned (Owensby and Wyrill 1973), whether the burning was prescribed or a wildfire, which usually reflects fire intensity (Blaisdell 1953, Hooker 1972, Kenworthy 1963, and White *et al.* 1973). The purpose for prescribed burning will no doubt affect the soil responses since different techniques or seasons would be used when burning for grass production (Anderson *et al.* 1970, Sharrow and Wright 1977a), manipulation of species (Owensby and Launchbaugh 1977, Tothill 1969), sagebrush control (Blaisdell 1953), tree and shrub invasion (Brogg and Hulbert 1976), or debris removal (Buckhouse and Gifford 1976). To date, fire has been studied in too few of the range ecosystems to summarize on a regional or other meaningful basis. Compounding the problem is that most of the fire research has not included measurements of soil parameters.

KNOWLEDGE GAPS, RESEARCH SCOPE, AND PRIORITIES

There are gaps in knowledge and in application of information of fire effects on soil. The following is a list of some of the more important research subjects, their scope and priority.

Subject		Priority	Remarks
Soil temperature and heating			
Determine quantitatively the relationships between fire intensity and soil heating	National	H	Related to prediction of surface erosion, soil physical properties, and nutrient losses
Refine heat flow models in soil	National	H	Related to prediction of nutrient transformation and wettability
Effect of fire on radiant heating and changes in maximum soil temperature	West and interior Alaska	M	Plant succession is often related to radiation and soil temperature. In Alaska depth to permafrost is influenced
Physical properties and erosion			
Effect of burning intensity on aggregate stability and soil erosion and its relation to soils from various parent materials	National	H	General processes are well known, but need specific information for prediction purposes

Factors affecting reestablishment of plants on soils after fires	National	M	Research application
Fire-related factors that affect infiltration, soil moisture, bulk density, hydraulic conductivity, and wettability	National	M	Considerable information is available that can be applied after more development research
Effect of soil microbes on stability of disturbed soils	National	H	Basic to understanding effects and recovery from fire
Soil chemical and microbiological properties and processes			
Nutrient cycling concepts and nutrient availability	National	H	General knowledge is lacking for range and for organic soils
Nitrogen cycle N volatilization N fixation Mineralization Leaching and surface losses	National	H	Most important nutrient when maximum fiber and energy production are desired from forest and range
Sulfur cycle Volatilization Transformations Plant use from Atmosphere	National	H	There are some indications in the Western U.S. that sulfur is limiting tree growth. More important in the East is the effect of fire on soil acidification from atmospheric deposition of sulfur.
Cation transformation and mobilization	National	L	Improved knowledge of basic processes is needed to predict long-term effects of fire
Mycorrhizae	National	M	Fire effects are though to be minimal, but little information is available
Methods of survey, classification and mapping of soils			
In relation to their potential damage by fires of various intensities	National	H	Organic soils and highly erodible soils should be identified and mapped
In relation to damage from fire suppression efforts	National	H	Methodology is required to enable managers to rapidly make decisions

CONCLUSIONS

The one finding that emerges from the literature on the effects of fire on soils is that fire intensity and the resulting degree of exposure of mineral soil to heat govern the degree of response of all soil properties investigated.

Land productivity and soil stability are both adversely affected by excessive heat. These vitally important attributes are unaffected or may even be substantially enhanced if the aboveground fuels are burned at sufficiently low intensity so that soil temperature is not greatly increased. Low intensity fire facilitates cycling of some nutrients, may help control plant pathogens, and generally does not increase soil erosion. On the other hand, intense fire volatilizes excessive amounts of nitrogen and other essential nutrients, destroys organic matter, disrupts soil structure, and may induce water repellency. These effects all combine to subject the soil to excessive erosion and lost productivity potential. Soils from acid igneous parent materials are more prone to surface erosion than those from basic igneous materials and therefore the former soils require more conservative prescriptions for burning than would be necessary for the latter.

Frequency of burning and the mitigating effects of management during the recovery time between fires are important considerations when evaluating longterm effects of fire on a site and prescribing fire management. Characteristics of soil cover and soil physical, chemical, and microbiological properties all must be considered when interpreting fire effects and when projecting effects for making fire management plans.

SUMMARY

Information is needed on fire effects to develop guides for effectively using prescribed burning, and for determining the situations where wildfires can be minimized or prevented by using prescribed fires.

Fire destroys protective organic matter, volatilizes some elements, transforms elements to soluble forms, and alters the physical, chemical, and biological properties of soil.

Soil Temperature

Under well developed forest floor conditions and prescribed burns, the mineral soil surface temperature is usually less than 100°C and at 5 cm the temperature is increased only slightly.

Stylized soil heating curves have been made for light, moderate, and intense chaparral fires. At 2.5 cm soil temperatures do not exceed 200° C when the surface was 700° C in a severe burn.

The temperature differential between burned and nonburned sites is about 10° C at 5 cm in depth, but this differential decreases rapidly when vegetation is restored.

Chemical Properties and Nutrient Cycling

Soil pH, P and exchangeable K, Ca, and Mg increase immediately after burning.

Nitrogen is lost by volatilization. Some loss estimates are 112 kg/ha in loblolly pine, 10 and 20 percent of system total for chaparral and ponderosa pine.

Soil Temperature

Nitrogen fixation, both symbiotic and nonsymbiotic, is more active following fires and in some ecosystems N fixation may restore the lost N.

Some studies show no net change in N (sum of forest floor and mineral soil) after 10 to 20 years of annual or periodic burning.

Pot experiments generally show increased availability of P, K, Ca, Mg, and no change or decrease for N availability.

Nutrient losses by leaching and runoff have been small for prescribed burns, but may be large for intense wildfires.

Soil Microflora

Heat from fires has a temporary sterilizing effect that may improve plant growth.

Prescribed burning annually for 20 years alters microorganism populations but essential soil processes are not impaired.

Two cases are cited where host parasite relationships were altered—one negatively (*Rhizina undulata*) and one positively (*Fomes annosus*).

Fungi are more easily destroyed by heat than are bacteria, while both groups are affected more at a given temperature in wet soil than in dry soil.

Nitrifying bacteria are killed at low temperatures, e.g., nitrobactor at 100° C in dry soil and at 50° C in wet soil.

Fungi possibly oxidize ammonium in burned soil.

Physical Properties

In exposed mineral soil, aggregates are dispersed by raindrop impact, pores become clogged, and macropore space, infiltration, and aeration are decreased.

When surface organic matter is not completely burned, changes in pore space and infiltration are extremely small.

Fires cause soils to be water repellent at the surface or as much as 20 cm below, and the condition is worse on dry coarse soils than on wet finer soils.

Erodibility

Soil losses caused by burning may be considerably above acceptable rates or no greater than controls, depending on soil, slope, and fire intensity.

Dry ravel accumulates after fires in chapparral and is later transported by water.

Slope and fire intensity are extremely important variables controlling erosion.

Range Soil

Qualitative response to fire has been similar for range soil and forest soil. Quantitative results are highly variable because range ecosystems differ, wildfire is more intense than prescribed burns, and the purposes for burning vary.

Wind erosion has been reported for range and is possibly a more important consideration than in forests.

Conclusions

Frequency of burning and the mitigating effects of management during the recovery time between fires are important considerations when prescribing fire management and when evaluating long-term effects of fire on a site.

Characteristics of soil cover and soil physical, chemical, and microbiological properties all must be considered when interpreting fire effects and when projecting effects for making fire management plans.

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