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Soil Heating in Chaparral Fires: effects on soil properties, plant nutrients, erosion, and runoff

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CONTENTS

Page

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IN BRIEF . . .

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The Revised Fire Management Policy, adopted by the Forest Service, U.S. Department of Agriculture, in 1977, "encourages land managers to make more use of prescription fire to protect, maintain, and enhance the natural resource values and aesthetics within approved areas on the National Forest." Prescribed fire would be one approach to reducing fuel hazard in chaparral brushlands in southern California. These brushlands burn as often as every 30 years, and resulting fires can threaten urban as well as rural areas.

Prescribed fire would be used to burn small areas of chaparral at different times to create a patchwork of brush stands of varying age. Such a mosaic would pose less of a hazard than would large continuous stands now commonly found throughout southern California. Renewed interest in fuel modification using fire, however, has raised questions of the effects of fire on the environment.

This paper is a state-of-the-art report on what is known about the effects of fire on chaparral in southern California, including effects on soil, plants, micro-organisms, erosion, and hydrology. It summarizes data on soil heating collected by other investigators, and more recent data recorded during prescribed burns and a wildfire in southern California. These data were recorded from 1968 to 1975 by self-contained pyrometers buried on the site being burned. These instruments recorded soil temperatures continuously at 2.5-cm intervals downward in the soil. Among the fires studied, wide differences in soil heating were measured because of variations in fuel loading, weather conditions, and soil-water content.

Soil heating data were summarized, analyzed, and used to construct three stylized temperature curves of soil heating during light, moderate, and intense fires. These stylized curves were used to predict the effects of burning intensity on the physical, chemical, and biological properties of soils. Soil nitrogen losses based on fire intensity were estimated from the stylized curves. Less volatile nutrients were found to be released as highly mobile ions to be metabolized by plants or micro-organisms, or were lost from the site by erosion and runoff. Micro-organisms were affected lethally at much lower temperatures than those necessary to change nonliving organic matter.

Light intensity burns on chaparral brushlands released smaller amounts of plant nutrients and, therefore, smaller erosional losses occurred than after wildfires. Site differences—slope steepness, kind of soil, amount of rainfall—resulted in different rates of erosion. Despite site differences, a higher degree of soil heating during a wildfire would be expected to do more damage than would a cooler, prescribed burn.

Chaparral brushlands in southern California burn as often as every 30 years (Muller and others 1968). Since 1945, the State's Public Resources Code has set forth fuel hazard reduction as a primary goal in the management of public lands.[1] A variety of techniques are available in attempts to reduce fuel hazard. One of these techniques—prescribed burning—has received increasing attention in recent years. The Revised Fire Management Policy adopted by the Forest Service, U.S. Department of Agriculture (1977) "encourages land managers to make more use of prescription fire to protect, maintain, and enhance the natural resource values and aesthetics within approved areas on the National Forest."

In the chaparral areas of southern California, prescribed fire would be used to burn small areas of brushland at different times to create a patchwork of brush stands of varying age. Such a mosaic would pose less of a hazard than would large continuous stands of brush now commonly found throughout southern California. But renewed interest in fuel modification using fire raises questions of the effects of fire on the environment and specifically on how fire affects soils, plants, micro-organisms, erosion, and hydrology.

Information on fire in chaparral areas of California has been collected since the 1930's by several investigators (Bentley and Fenner 1958, Lawrence 1966, Sampson 1944). However, much of this soil heating data presents only the maximum temperatures reached and only a limited amount of continuous temperature data. To supplement this data, we collected additional soil temperature data during several prescribed burns and one wildfire in southern California between 1968 and 1975. Most of the data were collected with recording pyrometers, although tempil tablets were used to measure maximum temperatures on some fires. Only recording pyrometer data are reported in this paper. The recording pyrometers consisted of battery-operated recorders connected to either chromel-alumel or iron-constantan thermocouples. These instruments could measure temperatures up to 1315°C. The recorders were enclosed in an insulated metal box and buried in the soil to prevent damage during the fire. Temperatures were measured at the surface, 2.5 cm, 5.0 cm, and 10 cm in the soil during the earlier studies, but were changed to the surface, 1, 2, and 4 cm in 1970. At some sites, only surface temperatures were measured.

Descriptive information on vegetation and soils was also collected. During the earlier studies done in 1968, only observational data were taken on vegetation and soils because most of our effort was directed toward installing instruments for measuring soil temperatures. By 1973, however, detailed site measurements were taken and, on a prescribed burn at the Paradise Valley site near Santa Maria, California, nutrients in the plants, litter, and soils, along with soil water at several depths, were measured before and after burning (DeBano and Conrad 1978).

A summary table of pertinent vegetation and soils data collected between 1968 and 1975 showing maximum temperatures is provided *(Appendix, table 1)*. Continuous temperature data for some individual fires are given in detail, as necessary, to illustrate the effect of vegetation pretreatment, soil water, or other environmental parameters on soil heating. Data on differences in soil heating during wildfires and prescribed burns are also discussed. Finally, these data were summarized and used to produce stylized soil heating curves which represent light, moderate, and intense burning intensities.

The stylized heating curves were used along with published information to estimate: (1) the direct effects of fire on plants, litter, and soil; and (2) the long-term effects on erosion, surface runoff, and hydrology. As such, this paper constitutes a state-of-the-art report on what is known about fire and its effects on the chaparral environment in southern California.

[1] Public Resources Code Section 4491-94, 1945.

SOIL HEATING

Nature of Soil Heating

Soil heating and fire temperatures vary widely among fires and within any particular fire. Maximum temperatures at the surface and downward differ from site to site within a fire and also between fires *(Appendix, table 1)*. Large temperature gradients develop between the surface and underlying soil layers because soil is a poor conductor of heat and only a small portion of the energy released during burning is transferred downward into the soil (DeBano 1974).

Although maximum temperatures can be measured easily and inexpensively, they do not adequately characterize the dynamic relationship between time and temperature—heat pulses—as they develop in litter and soil during a fire. Separate fires may have similar maximum temperatures but different durations of heating. The duration of soil heating is important because it affects the degree of change in soil properties. Heating of longer duration is more damaging than is heating of shorter duration. Longer heating destroys more organic matter and this affects many physical and chemical soil properties. Of particular importance is the effect of soil heating on nitrogen and soil microorganisms contained in the litter and soil.

The effects of different durations of heating are illustrated by a fire at Lone Pine Canyon *(Appendix, table 1)* which had the same maximum temperatures (716°C) at Sites 4 and 6, but the duration of heating was shorter at Site 4 *(fig. 1)* than at Site 6 *(fig. 2)*. The different durations of surface heating were reflected in the maximum temperatures of the 2.5-cm and 5.0-cm soil layers. At the 2.5-cm depth, the temperature on Site 6 was 124°C as compared to 91°C on Site 4. At the 5.0-cm depth, slightly more soil heating was apparent on Site 6 than on Site 4 *(Appendix, table 1)*.

The nature of soil heating with its variations between fires and within a fire, its temperature gradients, heat pulses, and duration is such that the kinetics of fire must be understood if we are to assess accurately the effects of soil heating.

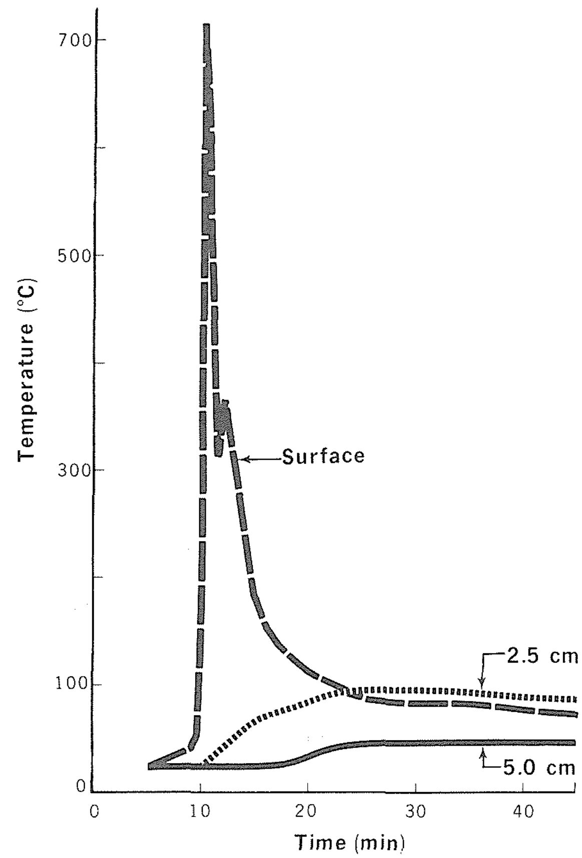

Figure 1—A short duration of heating in the soil and at the soil surface on Site 4 during the Lone Pine Canyon fire in southern California, September, 1968.

Differences in Heating, by Fire Types

Soil Temperatures During Wildfires and Prescribed Burns

Soil heating during wildfires and prescribed burns may not differ substantially if the soil is dry, large accumulations of dead flammable fuel are present, or the climatic conditions (humidity, air temperatures, and wind) are conducive to rapid burning. The differences between prescribed burning and wildfires are not as great in chaparral as in forests. In chaparral, the brush canopy is generally consumed and fire may burn briskly even at the lower intensities when continuous spread occurs. This type of fire behavior is considerably different than that during prescribed burns in forests where the fire moves through the litter layer without damaging the overstory of tree canopies. Fire behavior during chaparral fires can vary widely and produce large differences in soil heating *(Appendix, table 1)*. These differences must be considered by land managers, if the effects of prescribed fires on the chaparral ecosystem are to be minimized.

Although our information on wildfires is limited, the one wildfire measured (Lone Pine Canyon, *Appendix, table 1*) showed that maximum temperatures in litter and soil vary widely. On six sites studied during this wildfire, maximum temperatures measured in the afternoon (Sites 1, 4, 5, and 6) were much higher and

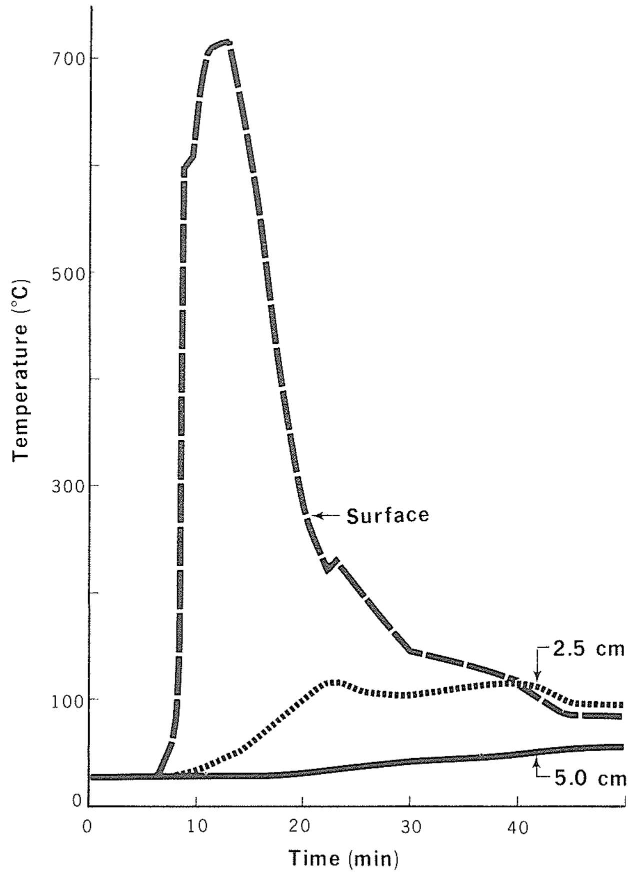

Figure 2—A long duration heat pulse in the soil and at the soil surface on Site 6 during the Lone Pine Canyon fire in southern California, September, 1968.

burning was more severe than during late evening (Sites 2 and 3) *(Appendix, table 1)*. Although meteorological measurements during this wildfire were not available, humidities were lower and burning conditions better during the afternoon compared to the evening. Soil heating during wildfires over larger areas is probably much more severe than during prescribed burning. Uncontrollable wildfires occur when weather conditions are optimum for burning and may sweep over large areas in a short time. Most of the area is burned under conditions of high-fire intensity. Maximum temperatures in the soil and litter during these extreme burning conditions are probably represented by those measured at Lone Pine Canyon on Sites 1, 4, 5, and 6. At Sites 4 and 6, the maximum surface temperature was 716°C, and at Site 5, the 2.5-cm soil layer reached 174°C. Prescribed burning—by design—is carried out under marginal burning conditions. Soil heating is less severe and is probably represented by some of the maximum temperatures measured during the prescribed burns at Mission Viejo. During this fire, surface temperatures at the six sites measured never exceeded 538°C. The temperatures generated during the late evening at Lone Pine Canyon (Sites 2 and 3) were cooler, and correspond to those produced during a prescribed burn of lower intensity.

High maximum temperatures were recorded at other prescribed burn sites, further illustrating the narrow margin between prescribed burning and wildfires. The highest maximum temperatures of any fires studied were recorded during an experimental burn on Site 2 at North Mountain *(Appendix, table 1)* (Dunn and others 1977). Heavy, dry, dead fuel, desiccated prior to the fire, was present on this experimental site and contributed to the severe fire behavior (Green 1970). At Cameron and Palomar, where standing brush was present, fires were also intense *(Appendix, table 1)*.

Although large differences in soil and litter temperatures may not exist between prescribed burns and wildfires, it is possible to predict that some of the conditions will produce less severe fire behavior and thereby minimize soil heating and damage. Burning over a wet or moist soil undoubtedly reduces the impact of fire on litter and soil. Under moist conditons, the canopy may burn briskly with a minimum of heating in the underlying litter and soil.

Prescribed Burns in Chaparral and in Forests

Although considerable data are available on temperatures developed at the surface and in the soil during prescribed fires in forested areas, these data are not useful for predicting soil temperatures during chaparral fires. Soil heating is different during a prescribed fire in chaparral than in a forest in the following ways:

Chaparral	*Forests*
• Flames move through canopy where they destroy variable amounts of the standing vegetation.	• Fires are designed to minimize damage to the larger standing trees (Biswell 1975).
• Fire will burn only under dry conditions because live fuels are consumed during burning.	• Burn is done under moist conditions because dead fuels are the only components burned.
• A thinner litter layer does not insulate the soil against heat radiated downward during a fire.	• A thick layer of duff and litter offer good insulation against heat radiated downward during a fire.
• Temperatures at the soil surface and in the soil are generally higher than those in forests.	• Temperatures at the soil surface and in the soil are generally lower than those in chaparral.

Chaparral Fires

Information on flame temperatures during chaparral fires is scant, and the only data reported has been on a prescribed burn in mixed chaparral (Green 1970). During this burn, the brush was dry and desiccated, and flame temperatures, measured 188 cm above the soil surface, reached 677°C before going off scale on a recording instrument (Green 1970). Green (1970) speculated the flame temperatures on this fire may have reached 1093°C, a level reported earlier by Countryman (1964) in burning piles of brush and trees.

Soil heating during wildfires in chaparral has not been previously measured although soil temperature data has been collected during several prescribed burns. In one such study, Lawrence (1966) studied the ecology of vertebrate animals during fire and reported surface temperatures in dry humus and grass, under a dead log at 5 cm in the soil, and 15 cm in a rodent burrow. Surface temperatures beneath the burning log were highest, reaching a maximum temperature of 560°C and remaining at 482°C for over an hour. The maximum temperature at 5 cm in the soil was 69°C, and was reached during the first 50 minutes of burning. The maximum temperature at 15 cm in the rodent burrow was 72°C. Sampson (1944) measured temperatures under 1.3 cm of litter, 1.9 cm of soil, and 3.8 cm of soil during several controlled burns on chaparral areas in northern California. Maximum temperatures in the top 1.3 cm of soil varied widely from a high of 649°C under chamise litter, to a low of 97°C at the same depth under a wedgeleaf ceanothus with scattered grasses. At 3.8 cm in the soil, the highest maximum temperature recorded was 332°C and the lowest 102°C, with the average temperature of from 110°C to 116°C. Bentley and Fenner (1958) measured maximum temperatures in brush fires resulting in different ash conditions. A maximum temperature of 538°C was measured at the soil surface when white ash was produced, and 177°C when black ash occurred.

Effects of Soil Water on Heating

Soil water is an important consideration during prescribed fire because when the soil and litter are moist, less soil heating occurs. Data collected during the Palomar Fire *(Appendix, table 1)* illustrates the moderating effect of water on soil heating during a fire. Samples of litter and soil contained from 16 to 20 percent water on an oven-dry basis before the fire *(table 1)*. After the fire, much less water was present in the surface ash layer and the 0-1-cm soil layer *(table 1)*.

Table 1—*Water content (by weight) of soil and litter before and after a prescribed burn of a scrub oak stand near Palomar, California*

Depth	Before fire	After fire
	Percent	
$A_{00} + A_0$[1]	16.3	[2]0.8
Cm		
0 to 1	20.1	4.1
1 to 2	16.0	14.2
2 to 3	16.1	19.3
3 to 4	13.9	17.5
4 to 6	15.2	15.4

[1] The A_{00} horizon consists of loose leaves and organic debris, largely decomposed; the A_0 horizon consists of organic debris, partially decomposed, or matted.

[2] Water content of the surface ash dust layer after the fire.

Some water was apparently translocated downward during the fire because water in the 2- to 3-cm and 3- to 4-cm soil layers increased. The presence of water reduced soil heating significantly at depths of 1 cm or more *(fig. 3)*. Although the surface temperature reached about 538°C, maximum temperature of the 1-cm soil layer was only 82°C. At 3 cm, the temperature increased slightly *(Appendix, table 1, fig. 3)*. This pattern of heating is consistent with results of other studies which have shown that the temperature of a wet soil layer does not increase above the boiling point of water until the water evaporates or is moved into a deeper layer (Aston and Gill 1976, DeBano and others 1976, Scotter 1970). During this vaporization and condensation process, heat, water and organic hydrophobic substances can be transferred simultaneously downward in the soil.

Soil chemical and physical properties undergo less change and any adverse impact of prescribed burning on soil properties is minimized when less soil heating occurs. Soil water can be measured before a burn and, if burning cannot be done over a moist soil, the impact on nutrient loss (e.g., nitrogen) can be weighed against the advantages of burning under less than optimum soil moisture conditions.

Variability of Surface Temperatures

Maximum surface temperatures measured at several locations at a site can vary over short distances *(Ap-*

pendix, table 1). Temperature measurements taken within 90 cm of each other at the Cameron, Palomar, and Paradise Valley prescribed burns provided data on this variation. At Cameron, among the four recorders, maximum temperatures ranged from 632°C to 749°C, with a mean of 682°C, and a standard deviation of 37°C. At Palomar, the maximum temperatures ranged from 416°C to 732°C, with a mean of 567°C, and a standard deviation of 97°C. During the Paradise Valley burn, the average maximum surface temperature on the eight locations monitored was 634°C, with a standard deviation of 68°C, and a range of from 516°C to 782°C.

In addition to the variation in maximum temperatures, large differences in the duration of heating were observed *(fig. 4)*. During the Palomar Fire, one site had a heat pulse reaching a maximum of 599°C for a short duration and another nearby site had a maximum temperature of 549°C for a much longer time *(fig. 4)*.

Predictions of Heat Effects

Renewed interest in prescribed burning has raised many questions including what soil and litter temperatures can be expected during a typical chaparral fire. Also, temperature data are needed for simulating chaparral fires during laboratory experiments which realistically characterize soil heating during prescribed burns in the field.

Because soil heating varies considerably over short distances *(fig. 4)*, we will characterize soil and litter temperatures for only light, moderate, and intense burning. The range of our data *(Appendix, table 1)* represents a gradual transition from very light to extremely intense soil heating, so we selected fires with temperatures representative of different degrees of soil heating that were comparable to previously reported maximum temperatures (Bentley and Fenner 1958, Sampson 1944).

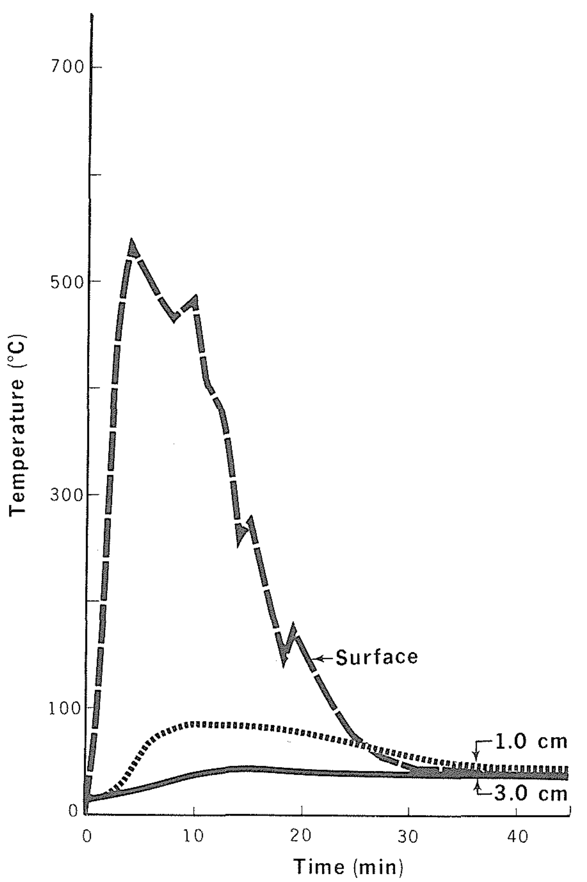

Figure 3—Soil heating at the surface and downward in the soil at Site 1 during a prescribed fire at Mt. Palomar, May, 1973.

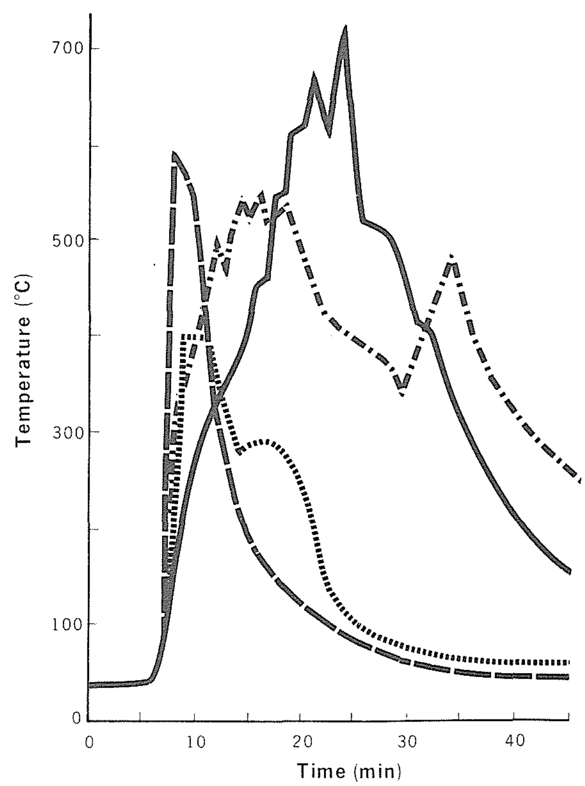

Figure 4—The variation in surface temperatures at four locations within 90 cm of each other at Site 2 during a prescribed burn at Mt. Palomar, May, 1973.

Although light, moderate, and intense burning conditions were not specified by Sampson (1944), or Bentley and Fenner (1958), the maximum temperatures they reported can be related to burning intensity. For example, intense burning appears to correspond well to the "white ash" condition described by Bentley and Fenner (1958). A "white ash" is present after litter and heavy fuels have been completely consumed and a thick ash deposit remains on the soil surface. Although Sampson (1944) did not refer to either an intense burn or a "white ash" condition, he provided data for a fire in a chamise stand with a scattered herb understory where the litter temperature exceeded 649°C. The temperature at 3.8 cm in the soil was 243°C. The soil temperatures present during a moderately intense burn may produce a "bare" condition (Bentley and Fenner 1958) when all litter has been burned and no ash remains. Surface temperatures at 399°C were present when this condition developed (Bentley and Fenner 1958). At the 2.5-cm soil depth, the maximum temperature was 177°C. Sampson (1944) described a fire in wedgeleaf ceanothus with an annual grass understory which corresponded closely to the maximum temperatures reported by Bentley and Fenner for a "bare" condition. Light burning was characterized by a "black ash" condition where the surface was covered by charred litter fragments (Bentley and Fenner 1958). When the "black ash" condition was produced, the maximum litter temperature was 177°C, and the temperature at 2.5 cm was 71°C. A low intensity fire described by Sampson (1944) in wedgeleaf ceanothus with scattered grass produced a maximum temperature of 149°C in the 1.27 cm of litter, and 93°C at 1.27 cm in the soil.

This published information gave us some guidance in selecting fire data which represented three burning intensities. Temperature data from three sites (Site 1 at Paradise Valley, and Sites 5 and 6 at Lone Pine Canyon) were combined to represent the temperature regimes existing in the soil and litter during an intense fire. These data were used to construct a stylized curve describing soil and litter heating during an intense fire

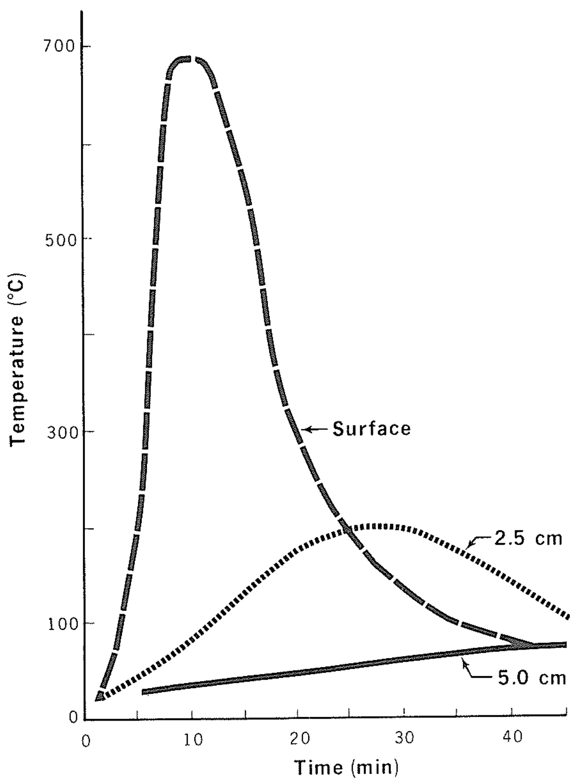

Figure 5—Soil and litter temperatures during an intense chaparral fire.

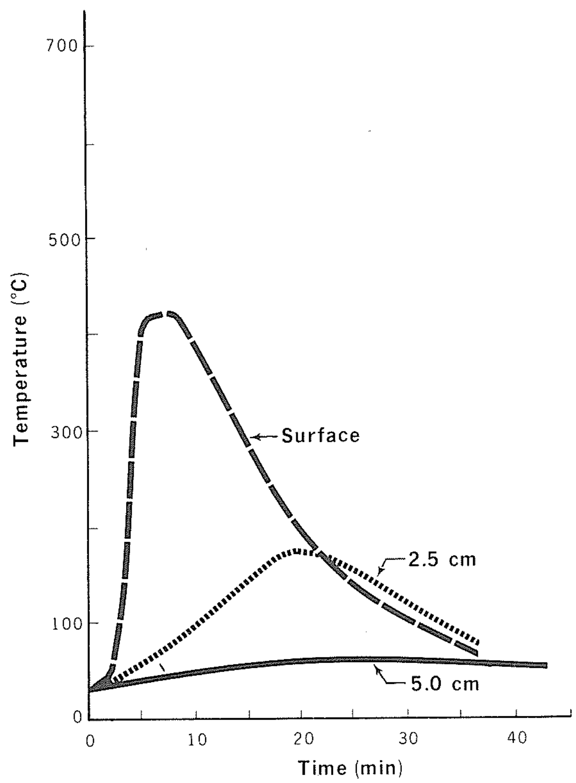

Figure 6—Soil and litter temperatures during a moderately intense chaparral fire.

(fig. 5). The maximum temperature developing at the surface as shown on this curve was slightly higher than that reported by Sampson (1944) and Bentley and Fenner (1958); the maximum temperature at the 2.5-cm depth was 199°C and lower than reported by Sampson (1944) and Bentley and Fenner (1958) *(table 2).* Data from an additional three fires were used to construct temperature curves representing a moderately intense burn *(fig. 6).* Data from Sites 1 and 6 at Mission Viejo and Site 4 at North Mountain represent a moderately intense burn. The maximum temperatures of our stylized curve compared very closely with those soil and litter temperatures reported by Sampson (1944) and Bentley and Fenner (1958) *(table 2).* Only data from Site 8 at Mission Viejo and Site 2 at Lone Pine Canyon were found suitable for developing curves to represent a low intensity burn *(fig. 7).* The surface temperatures for our stylized curves for the light intensity burn were slightly higher than those reported by Sampson (1944) and Bentley and Fenner (1958), but the soil temperatures were comparable *(table 2).*

The value of these stylized curves is that the information they provide can be used to predict the degree of soil heating in a given fire situation. Knowing the degree of heating—light, moderate, or intense—and knowing the effects of this degree of heating on soil, plant nutrients, micro-organisms, soil wettability, erosion, and runoff provides the facts necessary to assess correctly the advantages and disadvantages of a burn.

EFFECTS OF FIRE ON CHAPARRAL ECOSYSTEMS

Temperature regimes during light, moderate, and intense soil heating each affect the chaparral ecosystem differently. This section summarizes available information on the effects of fire on chaparral ecosystems. Included is information on soils, plant nutrients, soil wettability, infiltration, runoff, and erosion. When relationships were lacking for chaparral, they were supplemented with appropriate information taken from other vegetation types (e.g., grasslands, forests).

Soils

Information on the physical, chemical, and biological properties of chaparral soils is scant and even less is known about the effects of fire on chaparral soils (DeBano 1974). Most information on soils has been taken incidental to other studies and, although numerous studies have been done on plant succession after chaparral fires, little data has been collected on soil changes. Only a publication by Christensen and Muller (1975) considers detailed changes in soil properties resulting from chaparral fires. This meager "state-of-the-art" on chaparral soils is in sharp contrast to the volumes of published information on the physical, chemical, and biological changes occurring in forest and grassland soils during fire. Many fire-related changes in forest soils are of limited value in chaparral

Table 2—*A comparison of maximum surface, litter, and soil temperatures during intense, moderate, and light burns*

Intensity	Typical maximum temperatures [1]		Data from Sampson (1944)[2]		Data from Bentley and Fenner (1958)	
	Surface	2.5 cm	Litter	Soil	Surface	2.5 cm
	°C					
Intense	691	199	649	243	>538	288
Moderate	427	166	429	202	399	177
Light	249	88	149	93	177	71

[1] Maximum temperatures taken from three stylized curves representing light, moderate, and intense burning conditions.

[2] Temperatures were taken at: 1.3 cm in the litter and 3.8 cm in the soil for the intense burn; 1.3 cm in the litter and 4.5 cm in the soil for the moderate burn; and 1.3 cm in the litter and 1.3 cm in the soil for the light burn. From the author's description, it could not be determined whether the sensor in 1.3 cm of litter was at the soil surface, although the temperatures seemed reasonable for this position.

areas. The sketchy understanding of chaparral soils makes it difficult to apply relationships developed in forest soils to brushland soils, and fire behavior is different in chaparral than in forests.

Although specific information on many heat-induced changes is lacking for chaparral soils, some basic relationships are obvious. First, organic matter in the soil, litter, or standing brush will ignite when heated to 427°C (Gaylor 1974). These temperatures exist at the soil surface during most chaparral fires. Second, when organic matter is destroyed, the physical, chemical, and biological soil properties related to organic matter are also changed. The magnitude of change is directly related to the quantity of organic matter destroyed.

Typically, the soil surface in a chaparral stand is covered with varying amounts of litter, depending upon the species occupying the site and the time since the last fire. The average annual accumulation varies from 1994 to 3942 kg per ha in southern California (Kittredge 1955). Downward in the soil, plant material is in various stages of decomposition and eventually, at some depth, organic matter is no longer discernible as plant material but, instead, imparts only a darkish color to the mineral soil. Although organic matter decreases with depth, substantial amounts can be present in deeper soil layers as plant roots. The root distribution of chaparral brush species may vary from the deep penetrating roots of chamise to the more extensive lateral system under bigberry manzanita where the roots are confined to the upper 0.6 m of soil (Hellmers and others 1955b).

Soil Physical Properties

Soil physical properties change when organic matter is destroyed during burning. Organic matter improves soil aggregation and structure by binding individual soil particles together and creating large pores which allow better water penetration and aeration. When organic matter is destroyed by fire, soil structure also deteriorates. A study by Hosking (1938) showed that humic acids in organic matter can be lost at temperatures below 100°C. About 35 percent of the organic carbon in the soil was contained in the humic acid fraction. At temperatures between 100°C and 200°C, nondestructive distillation of volatile organic substances occurred, while temperatures between 200°C and 300°C removed 85 percent of the organic substances by destructive distillation. At temperatures of 300°C, ignition of carboneous residues commenced, and above 450°C, carboneous residues were completely consumed (Hosking 1938). If we apply these relationships to chaparral soils, we find that an intense burn *(fig. 5)* completely destroys organic matter at the soil surface. Maximum temperatures at the 2.5-cm depth during an intense burn are hot enough to destructively distill a large percent of the organic matter. During moderate burns *(fig. 6),* surface heating to 432°C is sufficient to destroy most of the litter. A low intensity fire can remove 85 percent of the litter on the soil surface by destructive distillation *(fig. 7),* but only the humic acids would be altered at 2.5 cm.

Not all studies have shown a deterioration in soil structure by heating. Laboratory experiments using a Hugo and Aiken soil, for example, showed aggregation was increased in the upper 0- to 0.64-cm layer by burning (Scott and Burgy 1956). Temperature of the 0.16- to 0.32-cm layer was over 450°C for more than 30 minutes and should have destroyed the organic matter in this layer. This was confirmed in a separate study where the same investigators found lower bulk densities on burned soils (1.0 gm/cm^3) than on unburned soils (1.4 gm/cm^3) (Burgy and Scott 1953).

Soil Chemical Properties

Fire affects both soil chemical properties and nutrient availability. Soil properties most affected by burning are organic matter, pH, cation exchange capacity, nitrogen, sulfur, divalent cations, and potassium. When organic matter is destroyed by fire, plant nutrients are released and become highly available for plant growth, or loss by erosion.

Cation exchange capacity can be decreased by burning and may remain low for at least 1 year (Christensen and Muller 1975) because exchange sites on organic matter are destroyed. Plant nutrients in the organic matter released by burning are deposited and concentrated on the soil surface. A study on burned and unburned soil under chamise showed the concentrations of acetate-soluble sulfate, potassium, phosphate, total nitrogen, ammonia nitrogen, and nitrate nitrogen were higher in burned soils (Christensen and Muller 1975). Increased solubility of cations after fire is responsible for the commonly observed increase in pH following fire, particularly in the upper soil and ash layers (Christensen and Muller 1975, Sampson 1944, Vogl and Schorr 1972). Usually, however, pH increases only slightly and probably does not significantly affect plant growth (Sampson 1944).

Nitrogen cycling occupies a special role in chaparral ecosystems. It is the nutrient most likely to limit plant growth in chaparral (Hellmers and others 1955a). It is also easily volatilized by heating during a fire. At temperatures above 500°C, 100 percent of the nitrogen in plant and litter material can be lost (White and others 1973). Between 400°C and 500°C, from 75 to 100 percent of the nitrogen is lost; between 300°C and 400°C, from 50 to 75 percent is lost. Between 200°C and 300°C, up to 50 percent of the nitrogen may be lost. Below 200°C, no measurable amounts of nitrogen are lost. These reported losses can be used to estimate nitrogen losses during fires producing different degrees of soil heating. If these nitrogen losses are superimposed over the soil heating graphs used to represent light, moderate, and intense burning *(figs. 5, 6, 7)*, nitrogen losses at the surface and downward in the soil can be estimated. During an intense fire, for example, the surface temperature exceeds 500°C and all the nitrogen in the litter is probably volatilized *(fig. 8)*. At the 2.5-cm depth, temperatures are not high enough to volatilize nitrogen. However, some nitrogen is undoubtedly volatilized in the upper 1.3 to 1.9 cm, and the closer to the surface, the greater the loss. The amount of nitrogen contained in the litter layer varies depending on the quantities of litter present. Measurements taken before a prescribed burn in chaparral near Santa Maria showed that about 150 kg per ha of nitrogen were contained in the litter (DeBano and Conrad 1978). Most of this nitrogen would be volatilized during an intense fire. Nitrogen lost during a fire of moderate intensity is less, although about 75 percent of that in the litter may be lost *(fig. 9)*. In the upper inch of soil only small amounts of nitrogen would be lost. During light intensity fires, less than 50 percent of the nitrogen at the soil surface is lost *(fig. 10)*. Although the soil temperatures in *figs. 7* and *10* were classified as light intensity burns, surface temperatures at some sites never exceeded 149°C *(Appendix, table 1)*. Under these conditions, little or no nitrogen should be lost at this level.

Nitrogen loss not only occurs from the litter and soil during a fire but most of it in the brush plants is also volatilized. The plant canopy probably ignites at about 427°C (Gaylor 1974), and once ignited, the temperature may rise to 1093°C (Green 1970). Temperatures of this magnitude can volatilize large amounts of nitrogen in small live and dead stems. About 134 to 142 kg per ha of nitrogen can be contained in the aboveground biomass of a chaparral stand (DeBano and others 1977, Specht 1969).

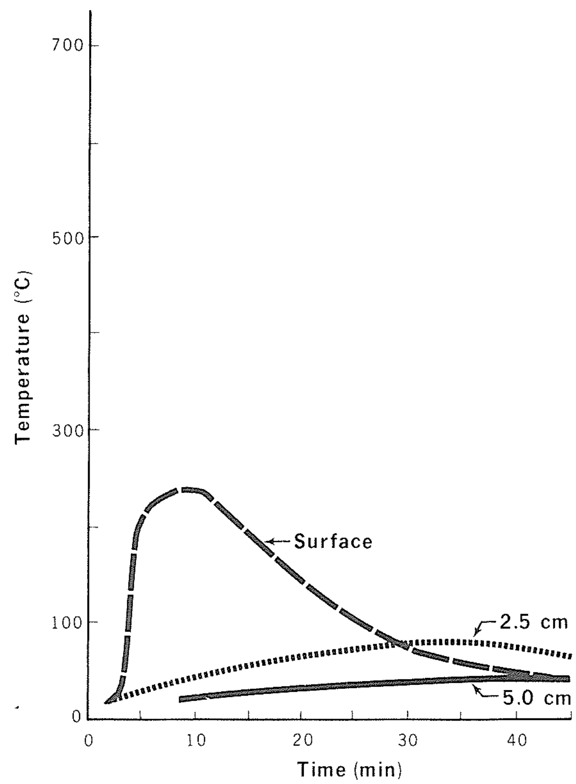

Figure 7—Soil and litter temperatures during a light intensity chaparral fire.

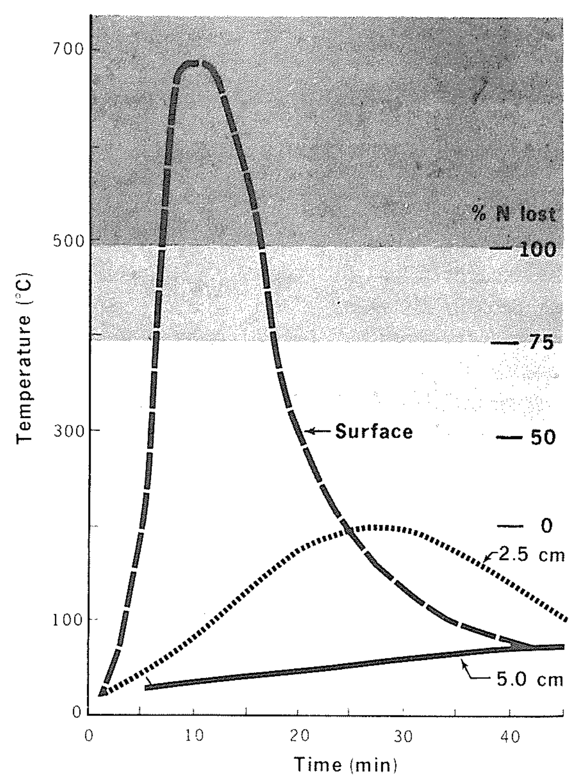

Figure 8—Nitrogen losses during an intense chaparral fire.

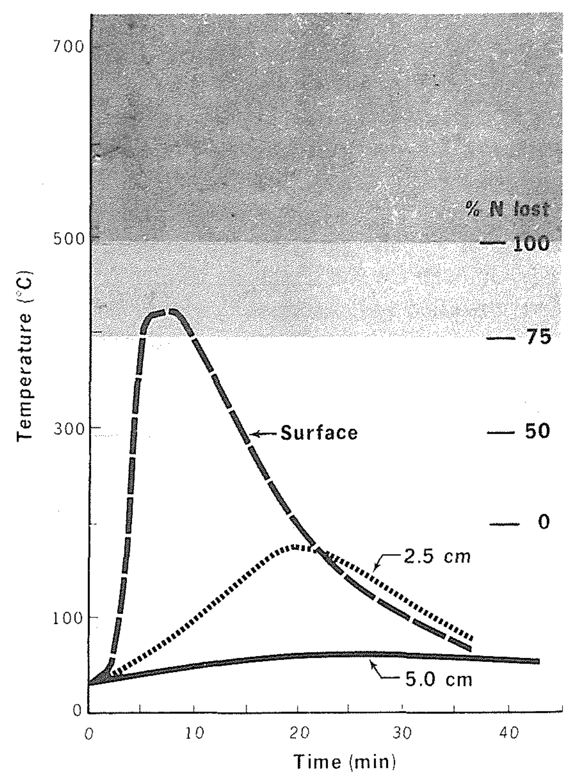

Figure 9—Nitrogen losses during a chaparral fire of moderate intensity.

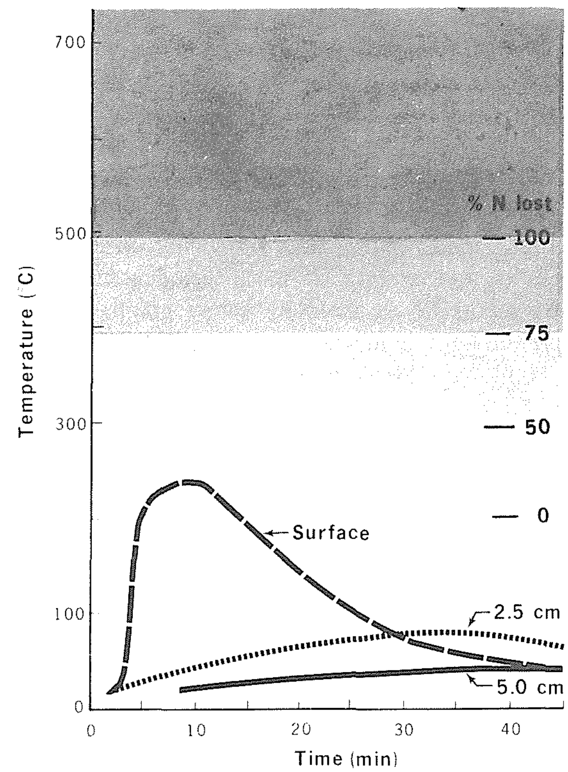

Figure 10—Nitrogen losses during a chaparral fire of low intensity.

Although total nitrogen is lost during a wildfire or prescribed burn, higher concentrations of nitrogen and other plant nutrients have been reported on burned areas than on unburned sites. This contradiction occurs partly because nitrogen is expressed in concentrations rather than in amount per unit area, before and after fire. Knight (1966) illustrated this point well by showing percent nitrogen, in the same experiment, can increase or decrease by merely changing the reference base. If nitrogen is based on ash material remaining after fire, then the concentration will increase; but, if this same amount of nitrogen is based on initial weight of the unburned material, then the percent nitrogen is usually decreased by fire. Another reason nitrogen appears more abundant after fire is because nitrogen availability increases and plant growth is more rapid. Total nitrogen on the site, however, may well have decreased. A way to avoid the pitfall just described, although more time consuming, is to express nutrients in terms of weight per unit area or volume. Recent studies on nutrient cycling have done this.

Soil Micro-organisms

Soil heating directly affects micro-organisms either by killing them or altering their reproductive capability. Indirectly, soil heating alters organic matter, which increases nutrient availability (particularly nitrogen), and stimulates microbial growth rates.

Information is becoming available on the effects of soil heating on micro-organisms in chaparral. One study, which isolated 27 different species of fungi from the soils, concluded that no differences existed between fungal populations on burned and unburned sites (Cooke 1970). Another study (Christensen and Muller 1975) showed substantial differences in fungal and bacterial numbers in wet and dry soil from burned and unburned chaparral areas. Under wet conditions, numbers of bacteria and fungi were higher in the burned chaparral soil than in the unburned. Higher microbial numbers in the burned soil were attributed to an optimum pH and more readily decomposable organic matter.

Results of recent studies in our laboratory show that complex interrelationships exist between soil heating and microbial populations in chaparral soils (Dunn and DeBano 1977). Duration of heating and maximum temperature along with soil water content appear to be the most important factors affecting microbial responses to soil heating. Generally, bacteria are more resistant to heating in both wet and dry soil than are fungi. The lethal temperature for bacteria was found to be 210°C in dry and 110°C in wet soil. Similar lethal temperatures have been reported in forest soils (Ahlgren and Ahlgren 1965) where bacterial numbers were reduced significantly by heating to 200°C for 25 minutes. Fungi in chaparral soils have been found to tolerate temperatures of only 155°C in dry soil and 100°C in wet soil (Dunn and DeBano 1977). In addition to being sensitive to heating, a shift in the species of fungi present occurs as temperature of heating increases. In temperatures up to 120°C in dry and 60°C in wet soil, regular saprophytic fungi prevail; above these temperatures, "heat shock" fungi appear. These "heat shock" fungi persist until they are finally killed at 155°C in dry and 100°C in wet soil.

Nitrifying bacteria appear to be particularly sensitive to soil heating. Experiments in our laboratory have shown *Nitrosomonas* bacteria can be killed in dry soil at temperatures of 140°C and in wet soil at 75°C (Dunn and DeBano 1977). *Nitrobacter* are even more sensitive and are killed at 100°C in dry and 50°C in wet soil. The sensitivity of these nitrifying bacteria to heating has important implications concerning nutrient availability and the nutrition of chaparral plants because nitrogen is frequently a limiting nutrient in chaparral soils (Hellmers and others 1955a). In unburned stands, high levels of the total nitrogen are present as organic nitrogen, and relatively low levels of inorganic mineral nitrogen are present (ammonia and nitrate nitrogen). Christensen (1973) hypothesized that this occurred in unburned stands (a) because heterotrophic micro-organisms responsible for mineralization were inhibited by alleleopathic substances present in chaparral soils, or (b) because the high lignin content of chaparral plant leaves resisted decomposition and subsequent mineralization of nitrogen. After a fire, however, higher concentrations of ammonia and nitrate nitrogen are generally present than are present before burning (Christensen and Muller 1975, Sampson 1944). Recent detailed studies of these inorganic nitrogen compounds before and after burning reveal that ammonia and nitrate nitrogen are formed by different processes in response to a fire. Apparently, large amounts of ammonia nitrogen are produced chemically by soil heating during a fire, and also microbially shortly after burning. Nitrates are not produced directly by heating during a fire, but are formed during subsequent mineralization and nitrification. Postfire nitrification does not appear to be carried out by the classical nitrifying bacteria (*Nitrosomonas* and *Nitrobacter*). These bacteria are extremely sensitive to heating and are absent or at extremely low levels for several months following burning. Results from this study also suggest that nitrification in burned chaparral soils is carried out by fungi.

Any management plan involving winter and summer burning must balance the tradeoffs between soil micro-organisms and nitrogen (Dunn and DeBano 1977). Prescribed burns during the winter over moist soil will be cool and volatilize the least amount of nitrogen from a site. However, micro-organisms are more sensitive to heating in a wet soil than in a dry soil. Results of experiments thus far show that winter burns are cooler and the effect on microbes is about equal to that of most hot, dry summer burns (Dunn and DeBano 1977). It is possible, however, 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 micro-organisms and nitrogen must be considered also in terms of both short- and long-term effects on chaparral succession and site productivity.

Plant Nutrients

Nutrient Availability

Both burning and natural biological decomposition release mineral elements from organic matter. Biological decomposition releases most nutrients slowly over time and the nutrients probably are used by plants before they are lost from the site by erosion or seepage. In unburned chaparral, litter decomposition by micro-organisms is slow because it may be inhibited by phytotoxins or a high lignin content (Christensen 1973) and unfavorable decomposition conditions (Olson 1963). Fires burning chaparral brush quickly release nutrients which are highly soluble (Christensen and Muller 1975, Sampson 1944). Although some nitrogen may be volatilized and lost during a fire, the remaining ammonia and nitrate nitrogen are highly available (Christensen 1973, Christensen and Muller 1975, Sampson 1944). The quantity of nutrients available after fire depends on how much organic matter burned. When litter is only partly burned, as during a light intensity burn, most of the unburned plant residue has to undergo further microbial decomposition and mineralization before the nutrients become available for plant growth.

Nutrients are more available after fire, and fertilizing with nitrogen, phosphorus, and sulfur does not produce responses on burned chaparral soils (DeBano and Conrad 1974, Vlamis and Gowans 1961).

Nutrient Loss

Plant nutrients are lost from burned watersheds in runoff water and eroded debris. Unfortunately, most past studies have not measured these amounts.

Some information has been collected recently on nutrient loss after prescribed burning on an area east of Santa Maria in the Los Padres National Forest (DeBano and Conrad 1978). A 42-ha chaparral watershed in this area was burned in August 1973. The soils in the study area were a loamy texture although they contained more clay and silt than soils found further south in the San Gabriel Mountains near Los Angeles. Erosion plots established in the area showed steep-burned plots (50 percent slope) lost larger amounts of plant nutrients during the first rainy season than did plots on gentle slopes (20 percent slope). Most nutrients were lost in the debris with smaller amounts in the runoff water *(table 3)*. The nutrients lost with the debris were probably contained in the organic matter. Organic matter made up 5.6 percent of the debris leaving the steep slopes, and 10.9 percent of the debris leaving the gentle slopes *(table 3)*. There was more organic matter in the debris from the gentle slopes because the runoff water had less transporting ability and carried higher proportions of the less dense organic matter. The erosive power of runoff water from the steep slopes was greater, however, and the debris contained a higher proportion of dense mineral soil. In spite of the difference in organic matter content of the debris, the steep slopes lost about 99 kg per ha more organic matter than did the gentle slopes.

Unusually high amounts of calcium were yielded by the plots probably because the soil and parent rock in the area was calcareous (Bergwall 1973). Analysis of plants, litter, and soil showed high quantities of calcium. Only small quantities of nutrients were lost from the unburned control sites *(table 3)*. No erosion occurred on the unburned plots having gentle slopes, so the only nutrients lost were contained in the runoff water.

Nutrient losses reported for the Santa Maria study may not be useful for predicting losses further south in the San Gabriel Mountains because of different parent material, soils, and climate. The rock material in the Santa Maria area was calcareous sandstones and conglomerates (Bergwall 1973). The San Gabriel Mountains are made up primarily of crystalline metamorphic and granitic rocks (Storey 1948). These geologic differences are reflected in the highly calcareous soils at Santa Maria. The 38.1 cm of annual rainfall at the Santa Maria site were also less than normally occur in chaparral areas of the San Gabriel Mountains. The long term average at the headquarters of the San Dimas Experimental Forest near Los Angeles, California, is about 69 cm annually. Nitrogen, phosphorus, potassium, and sodium losses were probably less at Santa Maria because total erosion is less than would be expected in the San Gabriel Mountains. The amounts of calcium and, perhaps, magnesium lost were probably higher at Santa Maria because the soils are calcareous.

Table 3—*Loss of nutrients by erosion from burned and unburned areas on steep and gentle slopes during the first year after a prescribed burn, southern California, 1973*

Slopes	Total debris	Nutrients in debris						Organic Matter		Total Runoff	Nutrients in runoff water			
		N	P	K	Mg	Ca	Na				K	Mg	Ca	Na
	Kg/ha								*Pct.*	*L/ha x 10⁴*	*Kg/ha*			
							Burned							
Steep	7340	15.08	3.37	19.34	28.02	47.39	2.57	410.4	5.6	78.59	7.67	3.63	20.04	2.00
Gentle	2848	7.50	1.00	7.64	6.15	18.47	0.84	311.5	10.9	58.36	3.26	1.91	9.14	1.29
							Unburned							
Steep	211	0.29	0.08	0.50	0.47	0.52	0.07	7.1	3.4	2.40	0.09	0.07	0.41	0.10
Gentle	0	0	0	0	0	0	0	0	0	0.45	.01	.00	.04	.01

The amounts of plant nutrients lost by erosion depend on several conditions (e.g., total amount of plant nutrients, site, intensity of burn, soil properties . . .). Assuming all other variables equal, however, fire intensity probably affects the amount of plant nutrients lost from a site. Intense fires would be expected to release larger quantities of plant nutrients from the litter and plants than those of low intensity. Loss of organic matter under different fire intensities described earlier may be useful for predicting the amounts of highly soluble nutrients available for erosion after fire.

Soil Wettability

Brush fires can decrease infiltration by producing a water repellent layer. On burned areas, a water repellent layer is frequently found below and parallel to the soil surface (DeBano and others 1967). The soil at or near the surface may be wettable, but a layer of varying thickness below it repels water. The nature of this water repellency can be described by comparing it to the way in which water enters a dry soil. If a water droplet is placed on the surface of wettable soil, it quickly penetrates the dry, wettable soil because there is a strong attraction between the water films and the soil particles. But if a water droplet is placed on the surface of a water repellent soil, it will "ball-up" and remain on the soil surface for some time before being absorbed. Although in some cases water repellency is severe enough to completely prohibit water absorption, it usually only impedes absorption for a short time. Severe water repellency in a soil is caused when soil particles are more completely coated with hydrophobic organic substances.

From laboratory and field observations, we have developed a theory of how fire intensifies water repellency *(fig. 11)*. During years between fires, decomposing plant parts containing hydrophobic substances accumulate in the upper part of the soil profile *(fig. 11A)*. This layer corresponds roughly to the A_0 and A_1 soil horizons. The more severe water repellency in this unburned soil probably results when the soil particles are coated with partially decomposed plant parts that are intermixed with mineral soil. Micro-organisms, particularly fungi, also release decomposition products which can induce water repellency in the unburned condition (Bond 1960).

When fire occurs, it consumes the chaparral cover and the underlying litter layer *(fig. 11B)*. An increase in the soil temperature below the soil surface may intensify water repellency in place by coating the soil particles with hydrophobic materials and fixing them in place (Savage 1974). Several investigators have studied the temperatures necessary to intensify or destroy water repellency (Cory and Morris 1969, DeBano and Krammes 1966, Savage 1974, Scholl 1975). These studies indicate both temperature and duration of heating affect the degree of water repellency (that is, intensify or destroy it). When soil containing organic matter is heated for 15 minutes at 204°C to 260°C, water repellency is intensified so water will not penetrate the soil (DeBano and Krammes 1966). If the same soil is heated instead for 15 minutes at 371°C or more, however, the water repellency will be destroyed and the soil will become highly wettable. As the duration of heating is increased, the temperature required to intensify or destroy water repellency is reduced accordingly. Most studies agree that the substances responsible for water repellency are destroyed when heated to over 288°C for short periods. Between 177°C and 204°C, however, water repellency is intensified and can become very severe. During intense burns, therefore, severe water repellency could be produced within 2.5 cm of the soil surface *(fig. 5)*, although the hydrophobic substances would be destroyed at the soil surface. During a moderately intense burn, water repellency would be located closer to the soil surface than for the intense burn, but still could have a thin layer of wettable soil at the surface. During a light intensity burn, it is likely that any water repellency would be found at the soil surface. If the burn is very light, water repellency may be confined to the litter and would not coat the soil particles.

Although the temperature at any particular soil depth during a fire is important for intensifying water repellency in place, vaporization and condensation of organic materials move downward in the soil where they are fixed more tightly by subsequent heating (DeBano 1966, Savage 1974). Large temperature gradients are present during most fires. For example, the temperature dropped 167°C per cm in the upper 2.5-cm layer of soil during an intense burn *(table 2)*. During a moderate burn, the temperature gradient amounts to only 98°C per cm, and during a light burn 49°C per cm. The different temperature gradients would move varying amounts of hydrophobic substances downward during different intensities of burning.

After the fire has swept through an area, the soil has an altered water repellent layer *(fig. 11C)*. As discussed earlier, the thickness and depth of the layer depend on the intensity of the fire and the nature and amount of litter present. If the surface temperatures are not hot during a fire, water repellency might be at or near the soil surface. If the soil were heated to higher temperatures, water repellency could show up in deeper layers, and the surface be wettable.

Soil physical properties and water content also affect the downward movement of hydrophobic substances. Sand and sandy loam soils tend to become more severely water repellent than do finer-textured clay soils (DeBano and others 1970). In coarse-textured soils, organic matter coats the soil particles more completely than it does in finer-textured soils that have a larger amount of particle surface area. In wet soil, hydrophobic substances tend to concentrate in a thin layer near the soil surface; in a dry soil, hydrophobic substances move farther downward in the soil, if temperature gradients allow, causing a thicker water repellent layer (DeBano and others 1976).

Infiltration

The affinity of soils for water can be reduced by coating soil particles with hydrophobic substances (DeBano 1971, 1975). These hydrophobic substances change the apparent liquid-solid contact angle which in turn affects water movement during both evaporation and infiltration (DeBano and others 1967, Letey and others 1962). The resistance to wetting produces anomalies during infiltration. One such anomaly is that water uptake is slower at the beginning of infiltration than after water has been entering the soil for some time (Letey and others 1962). In a normal dry soil that is wettable, the initial infiltration rate is high and decreases exponentially over time until it eventually assumes a constant rate equivalent to the hydraulic conductivity of the soil.

Laboratory studies have shown infiltration rates can be 25 times slower in the water repellent soil than in a similar wettable soil (DeBano 1971). The effect of water repellent soil on infiltration decreases as the soil wets up and, once the water repellent soil has wet up, it transmits water as rapidly as a normal wettable soil—sometimes even faster.

A second peculiarity is that infiltration rates are more rapid in moist soils than in similar air-dry soils (Gilmour 1968). These anomalies probably occur be-

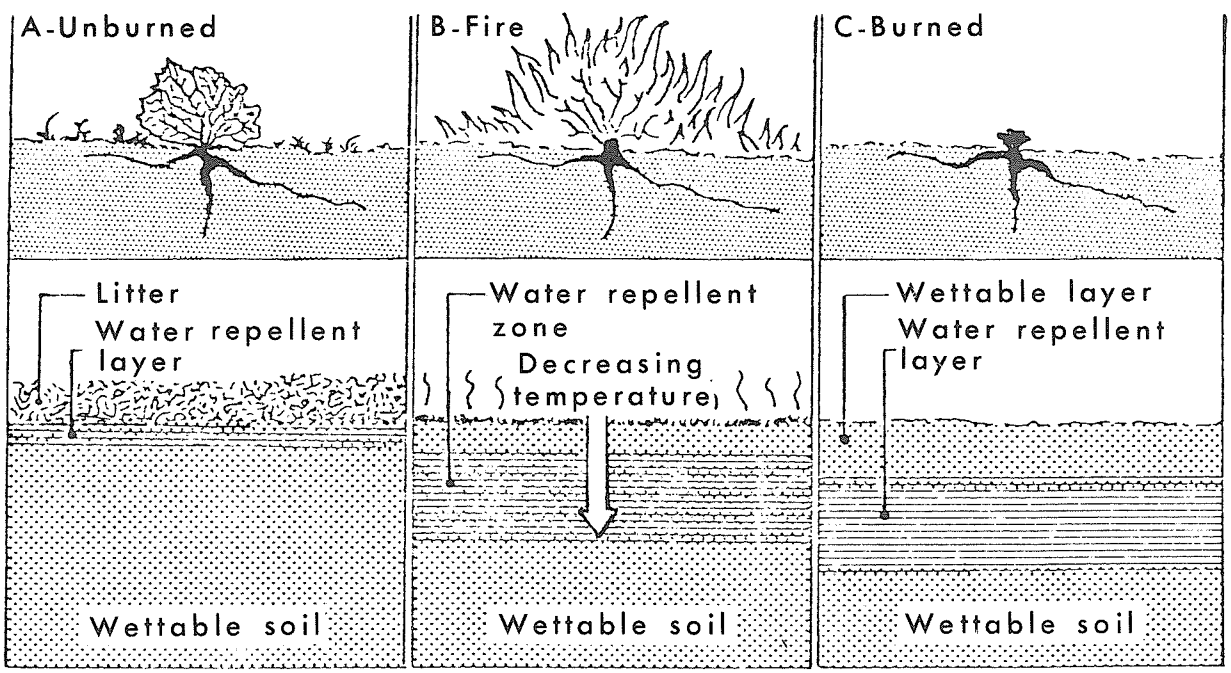

Figure 11—Soil water repellency is altered by fire. *(A)* Before fire, hydrophobic substances accumulate in litter layer and mineral soil immediately beneath it. *(B)* Fire burns vegetation and litter layer, causing hydrophobic substances to move downward along temperature gradients. *(C)* After fire, water repellent layer is present below and parallel to soil surface on burned area.

cause the wettability of the particle surface increases over time when a water repellent soil is placed in contact with water (DeBano 1975).

The high runoff and erosion rates following wildfires in chaparral areas of southern California are thought to be the result of the combined effect of a water repellent soil layer and raindrop splash. On these burned areas, the soil at or near the surface may be wettable, but a layer beneath it repels water. This layered arrangement allows incoming rainfall to infiltrate only a limited depth before the wetting front reaches the water repellent layer *(fig. 12)*. When the thin mantle above the water repellent layer becomes saturated, water flows laterally and runs off. The surface layer is also constantly being churned by incoming raindrops and saturated soil from this upper layer, along with some of the water repellent layer, is easily carried away by surface runoff. Wetting agents used to correct this hard-to-wet condition have reduced runoff 40 percent (Krammes and Osborn 1969). In these studies, runoff from untreated plots ranged from 4.0 to 10.5 cm when the seasonal amounts varied from 20.3 to 94.0 cm.

Runoff and Erosion

Fully vegetated, unburned chaparral watersheds, in common with other forested watersheds, seldom show overland flow. Surface litter promotes infiltration by reducing a raindrop impact and impeding overland flow, thereby providing temporary storage for short periods of high-intensity rainfall. High infiltration rates and the storage capacity of chaparral soil leave little water available for overland flow on the surface. Further, chaparral soils and geologic parent materials are characteristically permeable compared to prevailing rainfall intensities (Krammes 1969). When surface erosion occurs, it is generally restricted to established rills and gullies. As an example of the effect of these characteristics of chaparral watersheds, consider the behavior of research areas on the San Dimas Experimental Forest during a large storm in March 1938. Less than 1 percent of the precipitation was measured as surface runoff on research plots, even though streamflow from various experimental watersheds ranged from 16 to 38 percent of the storm precipitation (Coleman 1953).

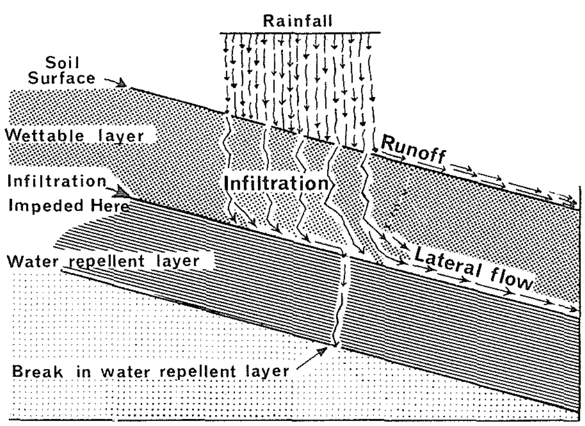

Figure 12—A water repellent layer impedes infiltration and causes surface runoff.

The relative stability of the chaparral watersheds is changed by wildfires and investigators find that high rates of runoff and debris usually follow burning (Krammes 1965, Krammes and Osborn 1969, Rowe 1941, Sinclair 1954). These high runoff rates result partly from a marked intensification of a water repellent layer. This layer greatly decreases infiltration rates and reduces the hydrologically active portion of the watershed surface from a meter or more in thickness to only a few centimeters. This means that relatively small storms and low rainfall intensities can produce substantial amounts of overland flow and result in substantial sheet and rill erosion. DeBano and Conrad (1976) found 34 times more soil and debris moved on a 50 percent slope following a moderately intense prescribed burn than on a similar unburned area. The erosion rate for burned plots was 7340 kg per ha and for unburned plots was 211 kg per ha. It seems reasonable to assume that an increase in overland flow also increases gully erosion. The significance of an increase in overland flow is not that it directly increases erosion; rather, the increased flow provides a transporting mechanism for landslide and dry ravel deposits which have accumulated near the stream channel. On an average, nearly 70 percent of the long term sedimentation movement on chaparral watersheds occurs during the first year after fire (Rice 1974). Most of the increase in sediment does not result from erosion occurring at that time, but results from remobilization of existing deposits.

Debris production from chaparral watersheds seems to be a two-phase process. Although erosion on side slopes is primarily by gravity-activated landslides and dry ravel, some debris is delivered to the channel by overland flow after fires. These processes deliver sediment to gentler slopes (often adjacent to stream channels) where they can no longer operate. From here, flowing water acts as a mechanism for sediment transport. About 25 percent of the chaparral areas are steep enough for gravity-related erosional processes to operate. If erosion were directly related to steepness of slope, this 25 percent of the chaparral would produce about half of the area's sedimentation. Recent data suggest that the proportion of sediment coming from these steep slopes may be much higher. DeBano and Conrad (1976) found that following a prescribed burn, plots on 50 percent slopes yielded about 250 percent more surface erosion than did plots on a 20 percent slope.

Landslides may account for about half the erosion on steep chaparral slopes (Rice 1974). Landslides are relatively infrequent and are dependent upon storms of such a size that they occur only once every 8 years, or less frequently. Consequently, the importance of landslide erosion has been underestimated in the past and few studies have been concerned with measuring it (Rice and Foggin 1971, Rice and others 1969). Data from these studies and the observations of other investigators (Campbell 1975, Scott and Williams 1974), however, tend to support the importance of landslides. Immediately after fire, surface erosion and movement of existing sediment stored in channels dominates the erosion process. Reduced infiltration rates make landslides less likely. Later, landslide erosion on recently burned areas increases because roots of fire-killed vegetation decay. Rice (1974) reported that the volume of landslide erosion on an area which had burned 9 years previously was over 18 times greater than on a chaparral-covered area which had not burned for 50 years. While landslides usually occur during large storms, they often produce debris in excess of the stream's ability to transport it out of the watershed. Such deposits accumulate in a pseudostable condition near stream channels.

Dry ravel produces about one-third of the erosion from steep unburned chaparral watersheds (Rice 1974). Annual rates of dry ravel ranging from 224 to 4300 kg per ha have been measured by Anderson and others (1959). Later, Krammes (1965) found about 45 percent of the surface erosion occurring during the dry season and 55 percent during the wet season. During the wet season, sheet and rill erosion occurred and, in the dry season, dry ravel occurred. A later study (Krammes and Osborn 1969) found that at least one-third, and perhaps as much as three-quarters of the wet season erosion was actually occurring as dry ravel between rainstorms. Taking this into account, we find that from 63 to 86 percent of the surface erosion is dry ravel. Rates of dry ravel erosion are also affected by fire. On an unburned watershed much potentially unstable soil is perched behind stems and litter and prevented from moving downhill by gravity. When the fire destroys these barriers, dry ravel immediately begins. Krammes (1960) measured a nine-fold increase in dry ravel erosion during the first year following fire. In the first 88 days after the fire, 89 percent of this erosion occurred. Since dry ravel occurs when there is little or no streamflow, debris routinely accumulates in deposits at the base of steep slopes. These deposits, together with untransported remnants of landslide debris, act as magazines supplying readily transportable sediments to high stream discharges whenever they occur.

CONCLUSIONS

Soil heating and fire temperatures vary widely between fires and within any particular fire because of differences in fuel loading, weather conditions, and soil water content. Despite these variations, it is possible to use soil temperature data to develop soil heating curves for light, moderate, and intense chaparral fires. The maximum temperatures for these soil heating curves, although stylized, agree well with maximum temperatures reported by other investigators.

The effect of soil heating by these three intensities on many soil physical, chemical, and biological properties is related to the amount of organic matter destroyed. Soil nutrients are either lost by volatilization, or are transformed into highly available ions by burning. Nitrogen, for example, is easily volatilized and lost during burning. The nutrients not volatilized—calcium, magnesium, potassium, sodium, and phosphorus—are released as highly mobile ions which can be metabolized rapidly either by plants or micro-organisms on the sites, or can be lost by erosion and runoff.

Soil heating data during light, moderate, and intense fires can be used to estimate the amounts of nitrogen that can be expected. Up to 100 percent of the nitrogen could be lost from the surface litter layer during an intense chaparral fire.

The effect of soil heating on micro-organisms is less well understood but, undoubtedly, micro-organisms are affected lethally at much lower temperatures than those necessary to change nonliving organic matter.

Erosion rates are high after a fire because "buffering" action of vegetation and litter is eliminated, dry ravel and landslides are increased, infiltration is reduced, and peak runoff rates are greatly increased. Peak runoffs carry away substantial amounts of plant nutrients. Light intensity prescribed burns on chaparral areas would be expected to release smaller amounts of plant nutrients and smaller erosional losses of these nutrients would occur.

Differences in erosional rates can result from site differences as well as from variations in soil heating between wildfires and prescribed burns. Steep slopes encourage dry ravel and landslides. Differences in soil and rainfall also affect erosional rates. Despite large site differences, a greater degree of soil heating during a wildfire would be expected to do more damage to the site than would a cooler, prescribed burn.

LITERATURE CITED

Ahlgren, Isabel F., and Clifford E. Ahlgren.
1965. **Effects of prescribed burning on soil microorganisms in a Minnesota jack pine forest.** Ecology 46(3):304-310.

Anderson, H.W., G.B. Coleman, and P.J. Zinke.
1959. **Summer slides and winter scour . . . dry-wet erosion in southern California mountains.** USDA Forest Serv. Tech. Paper 36, 12 p., illus. Pacific Southwest Forest and Range Exp. Stn., Berkeley, Calif.

Aston, A.R., and A.M. Gill.
1976. **Coupled soil moisture, heat and water vapour transfers under simulated fire conditions.** Aust. J. Soil Res. 14:55-66.

Bentley, J.R., and R.L. Fenner.
1958. **Soil temperatures during burning related to postfire seedbeds on woodland range.** J. For. 56:737-740.

Bergwall, Frank.
1973. **Geology and soils report. Paradise burn, Stanley-Logan-Wilcox fuelbreak, Santa Lucia Ranger District, Santa Maria, Calif.** 26 p.

Biswell, Harold H.
1975. **Effects of fire on chaparral.** *In* Fire and ecosystems. T.T. Kozlowski and C.E. Ahlgren, eds. p. 321-364. Academic Press, New York.

Bond, R.D.
1960. **The occurrence of microbial filaments in soils and their effect on some soil properties.** C.S.I.R.O., Div. of Soils, Div. Rep. 10/60, 9 p.

Burgy, R.H., and V.H. Scott.
1953. **Discussion of "some effects of fire and ash on the infiltration capacity of soils."** Trans. Amer. Geophys. Union 34(2):293-295.

Campbell, Russell H.
1975. **Soil slips, debris flows, and rainstorms in the Santa Monica Mountains and vicinity, southern California.** U.S. Geol. Surv. Prof. Paper 851, 51 p.

Christensen, Norman L.
1973. **Fire and the nitrogen cycle in California chaparral.** Science 181(4094):66-68.

Christensen, Norman L., and Cornelius H. Muller.
1975. **Effects of fire on factors controlling plant growth in *Adenostoma* chaparral.** Ecol. Monogr. 45(1):29-55.

Colman, E.A.
1953. **Fire and water in southern California's mountains.** Calif. Forest and Range Exp. Stn., Misc. Paper 3, USDA Forest Serv., Berkeley, Calif. 8 p.

Cooke, Wm. Bridge.
1970. **Fungi in burned and unburned chaparral soils.** Sydowia, Ann. Mycol., Ser. 2, 24:164-168.

Cory, John T., and Robert J. Morris.
1969. **Factors restricting infiltration rates on decomposed granitic soils.** *In* Symposium Water Repellent Soils Proceedings [Riverside, Calif., May 6-10, 1968], L.F. DeBano and J. Letey (eds.). p. 149-161. Univ. Calif., Riverside.

Countryman, Clive M.
1964. **Mass fires and fire behavior.** USDA Forest Serv. Res. Paper PSW-19, 53 p., illus. Pacific Southwest Forest and Range Exp. Stn., Berkeley, Calif.

DeBano, Leonard F.
1966. **Formation of non-wettable soils . . . involves heat transfer mechanism.** USDA Forest Serv. Res. Note PSW-132, 8 p., illus. Pacific Southwest Forest and Range Exp. Stn., Berkeley, Calif.

DeBano, Leonard F.
1971. **The effect of hydrophobic substances on water movement during infiltration.** Soil Sci. Soc. Amer. Proc. 35:340-343.

DeBano, L.F.
1974. **Chaparral soils.** *In* Symposium on Living with the Chaparral Proceedings [Riverside, Calif., March 30-31, 1973], p. 19-26, Sierra Club.

DeBano, L.F.
1975. **Infiltration, evaporation, and water movement as related to water repellency.** *In* "Soil Conditioners," Soil Sci. Soc. Amer. Proceedings Spec. Publ. 7:155-163.

DeBano, Leonard F., and C. Eugene Conrad.
1974. **Effect of a wetting agent and nitrogen fertilizer on establishment of ryegrass and mustard on a burned watershed.** J. Range Manage. 27(1):57-60.

DeBano, L.F., and C.E. Conrad.
1976. **Nutrients lost in debris and runoff water from a burned chaparral watershed.** Third Inter-Agency Sedimentation Conference [Denver, Colo., March 1976] Proceedings, p. 3-13 to 3-27.

DeBano, L.F., and C.E. Conrad.
1978. **The effect of fire on nutrients in a chaparral ecosystem.** Ecology 59(3):489-497.

DeBano, L.F., and J.S. Krammes.
1966. **Water repellent soils and their relation to wildfire temperatures.** Bull. I.A.S.H., XI Année No. 2, p. 14-19, illus.

DeBano, L.F., and Raymond M. Rice.
1971. **Fire in vegetation management: its effects on soil. Symposium on Interdisciplinary Aspects of Watershed Management Proceedings** [Bozeman, Mont., August 1970], illus., p. 327-346.

DeBano, L.F., P.H. Dunn, and C.E. Conrad.
1977. **Fire's effect on physical and chemical properties of chaparral soils.** *In* International Symposium on the Environmental Consequences of Fire and Fuel Management in Mediterranean Climate Ecosystems [Palo Alto, Calif., August

1-5, 1977], p. 65-74. USDA Forest Serv. Gen. Tech. Rep. WO-3, 498 p.

DeBano, L.F., L.D. Mann, and D.A. Hamilton.
1970. **Translocation of hydrophobic substances into soil by burning organic litter.** Soil Sci. Soc. Amer. Proceedings 34(1):130-133.

DeBano, L.F., S.M. Savage, and D.A. Hamilton.
1976. **The transfer of heat and hydrophobic substances during burning.** Soil Sci. Soc. Amer. Proceedings 40:779-782.

DeBano, Leonard F., Joseph F. Osborn, Jay S. Krammes, and John Letey, Jr.
1967. **Soil wettability and wetting agents... our current knowledge of the problem.** USDA Forest Serv. Res. Paper PSW-43, 13 p., illus. Pacific Southwest Forest and Range Exp. Stn., Berkeley, Calif.

Dunn, P.H., L.F. DeBano, and G.E. Eberlein.
1979. **Effects of burning on chaparral soils. II. Soil microbes and nitrogen mineralization.** Soil Sci. Soc. Amer. J. 43:509-514.

Dunn, Paul H., and Leonard F. DeBano.
1977. **Fire's effect on the biological and chemical properties of chaparral soils.** *In* International Symposium on the Environmental Consequences of Fire and Fuel Management in Mediterranean Climate Ecosystems [Palo Alto, Calif., August 1-5, 1977], p. 75-84. USDA Forest Serv. Gen. Tech Rep. WO-3, 498 p.

Gaylor, Harry P.
1974. **Wildfires—prevention and control.** 319 p. Prentice-Hall Co., Bowie, Maryland.

Gilmour, D.A.
1968. **Water repellence of soils related to surface dryness.** Aust. For. 32:143-148.

Green, Lisle R.
1970. **An experimental prescribed burn to reduce fuel hazard in chaparral.** USDA Forest Serv. Res. Note PSW-216, 6 p. Pacific Southwest Forest and Range Exp. Stn., Berkeley, Calif.

Hellmers, Henry, James F. Bonner, and John M. Kelleher.
1955a. **Soil fertility: a watershed management problem in the San Gabriel Mountains of southern California.** Soil Sci. 80(3):189-197.

Hellmers, H., J.S. Horton, G. Juhren, and J. O'Keefe.
1955b. **Root systems of some chaparral plants in southern California.** Ecology 36(4):667-678.

Hosking, J.S.
1938. **The ignition at low temperatures of the organic matter in soils.** J. Agric. Sci. 38(3):393-400.

Kittredge, Joseph.
1955. **Litter and forest floor of the chaparral in parts of the San Dimas Experimental Forest, California.** Hilgardia 23(13):563-596.

Knight, H.
1966. **Loss of nitrogen from the forest floor by burning.** For. Chron. 42(2):149-152.

Krammes, Jay S.
1960. **Erosion from mountain side slopes following fire in southern California.** USDA Forest Serv. Res. Note PSW-171, 8 p. Pacific Southwest Forest and Range Exp. Stn., Berkeley, Calif.

Krammes, Jay S.
1965. **Seasonal debris movement from steep mountainside slopes in southern California.** Federal Interagency Sedimentation Conference [Oxford, Miss., January 28-February 1, 1963]. Proceedings, U.S. Dep. Agric. Misc. Publ. 970, p. 85-88.

Krammes, J.S., and J. Osborn.
1969. **Water-repellent soils and wetting agents as factors influencing erosion.** *In* Symposium Water Repellent Soils Proceedings [Riverside, Calif., May 6-10, 1968], L.F. DeBano and J. Letey (eds.). p. 177-187. Univ. Calif., Riverside.

Krammes, Jay Samuel.
1969. **Hydrologic significance of the granitic parent material of the San Gabriel Mountains, California.** Ph.D. dissertation, Oregon State Univ., Corvallis, June 1969.

Lawrence, George E.
1966. **Ecology of vertebrate animals in relation to chaparral fire in the Sierra Nevada foothills.** Ecology 47(2):278-291.

Letey, J., J. Osborn, and R.E. Pelishek.
1962. **The influence of the water-solid contact angle on water movement in soil.** Bull. Int. Assoc. Sci. Hydrol. 3:75-81, illus.

Muller, Cornelius H., Ronald B. Hanawalt, and James K. McPherson.
1968. **Allelopathic control of herb growth in the fire cycle of California chaparral.** Bull. Torrey Bot. Club 95(3):225-231.

Olson, Jerry S.
1963. **Energy storage and the balance of producers and decomposers in ecological systems.** Ecology 44(2):322-331.

Rice, Raymond M.
1974. **The hydrology of chaparral soils.** *In* Symposium On Living with the Chaparral Proceedings [Riverside, Calif., March 30-31, 1973], p. 27-34. Sierra Club.

Rice, R.M., and G.T. Foggin III.
1971. **Effect of high intensity storms on soil slippage on mountainous watersheds in southern California.** Water Resour. Res. 7(6):1485-1496.

Rice, R.M., E.S. Corbett, and R.G. Bailey.
1969. **Soil slips related to vegetation, topography, and soil in southern California.** Water Resour. Res. 5(3):647-659.

Rowe, P.B.
1941. **Some factors of the hydrology of the Sierra Nevada foothills.** Natl. Res. Counc., Amer. Geophys. Union Trans. 1941. p. 90-101.

Sampson, Arthur W.
1944. **Plant succession on burned chaparral lands in northern California.** Univ. Calif., Coll. Agric., Agric. Exp. Stn. Bull. 685. 144 p.

Savage, S.M.
1974. **Mechanism of fire-induced water repellency in soil.** Soil Sci. Soc. Amer. Proc. 38(4):652-657.

Scholl, David G.
1975. **Soil wettability and fire in Arizona chaparral.** Soil Sci. Soc. Amer. Proc. 39:356-361.

Scott, Keven M., and Rhea P. Williams.
1974. **Erosion and sediment yields in mountain watersheds of the Transverse Ranges, Ventura and Los Angeles Counties, California—analysis of rates and processes.** U.S. Geol. Surv., Water Resour. Investigation 47-73, 66 p.

Scott, V.H., and R.H. Burgy.
1956. **Effects of heat and brush burning on the physical properties of certain upland soils that influence infiltration.** Soil Sci. 82: 63-70.

Scotter, D.R.
1970. **Soil temperatures under grass fires.** Aust. J. Soil Res. 8:273-279.

Sinclair, J.D.
1954. **Erosion in the San Gabriel Mountains of California.** Trans. Amer. Geophys. Union 35(2):264-268.

Specht, R.L.
1969. **A comparison of the sclerophyllous vegetation charac-**

teristic of Mediterranean type climates in France, California, and Southern Australia: II. Dry matter, energy, and nutrient accumulation. Aust. J. Bot. 17:293-308.

Storey, H.C.
1948. **Geology of the San Gabriel Mountains, California, and its relation to water distribution.** Calif. Nat. Resour., Div. For. p. 1-19.

U.S. Department of Agriculture, Forest Service.
1977. **Evaluation of fire management activities on the National Forests.** Policy Anal. Staff Rep., Forest Serv., U.S. Dep. Agric., November 1977.

Vlamis, J., and K.D. Gowans.
1961. **Availability of nitrogen, phosphorus, and sulfur after brush burning.** J. Range Manage. 14(1):38-40.

Vogl, Richard J., and Paul K. Schorr.
1972. **Fire and manzanita chaparral in the San Jacinto Mountains, California.** Ecology 53(6):1179-1188.

White, E.M., W.W. Thompson, and F.R. Gartner.
1973. **Heat effects on nutrient release from soils under ponderosa pine.** J. Range Manage. 26(1):22-24.

APPENDIX

Table 1—*Maximum surface and soil temperatures measured at different burn sites (1968-75)*

Burn	Type of burn	Vegetation	Soil moisture	Date and time	Site	Location of measurement	Maximum temperature (°C)[1]
Mission Viejo	Prescribed burn for range improvement	Dense chamise and *Salvia*	Dry	9/4/68 1230	1	Surface 2.5 cm 5.0 cm	382 66 49
		Dense scrub oak	Dry	9/4/68 1600	2	Surface 2.5 cm 5.0 cm	282 66 49
		Grassy canyon bottom dense tree canopy	Dry	9/4/68 1500	3	Surface 2.5 cm 5.0 cm 10.0 cm	516 57 57 38
		Dense oak with grass understory	Dry	9/5/68 1130	6	Surface 2.5 cm 5.0 cm	432 166 29
		Scrub oak	Dry	9/5/68 1400	7	Surface 2.5 cm 5.0 cm	216 74 54
		Scrub oak	Dry	9/5/68 1415	8	Surface 2.5 cm 5.0 cm	116 57 35
Lone Pine Canyon	Wildfire	Chamise	Dry	9/8/68 1630	1	Surface 2.5 cm 5.0 cm 10.0 cm	641 82 43 27
		Chamise	Dry	9/8/68 1910	2	Surface 2.5 cm 5.0 cm	299 91 43
		Chamise	Dry	9/8/68 1905	3	Surface 2.5 cm 5.0 cm	166 49 32
Lone Pine Canyon	Wildfire	Mixed chaparral *Ceanothus*, chamise (light to moderate density)	Dry	9/9/68 1330	4	Surface 2.5 cm 5.0 cm	716 91 43
		Mixed chaparral *Ceanothus*, chamise	Dry	9/9/68 1330	5	Surface 2.5 cm 5.0 cm	616 174 66
		Dense stand mixed chaparral	Dry	9/9/68 1730	6	Surface 2.5 cm 5.0 cm	716 124 54
North Mountain	Experimental burn (Green 1970)	Mixed chaparral	Dry	6/26/69 1430	1	Surface Surface 1 cm 2 cm 3 cm	569 607 222 219 167

Table 1—*Maximum surface and soil temperatures measured at different burn sites (1968-75)* (continued)

Burn	Type of burn	Vegetation	Soil moisture	Date and time	Site	Location of measurement	Maximum temperature (°C)[1]
		Mixed chaparral	Dry	6/26/69	4	Surface	382
				1430		2.5 cm	132
						5.0 cm	49
						10.0 cm	24
North	Experimental	Mixed chaparral	8 pct.	4/24/70	1	Surface	516
Mountain	burn	chamise, manzanita	10 pct.	1330		1 cm	516
			15 pct.			2 cm	277
			15 pct.			4 cm	82
		Mixed chaparral			2	Surface	843
		chamise, manzanita	(same as			1 cm	499
		heavy concentration	site 1)			2 cm	410
		of fuel				4 cm	204
Cameron	Prescribed	Scrub oak		6/28/72	1	Surface	[2]427
(San Diego	burn, fuel			1030		1 cm	177
County)	modification		5 pct.			2 cm	66
						4 cm	46
Cameron	Prescribed	Scrub oak	5 pct.	6/28/72	2	Surface	649
(San Diego	burn, fuel					Surface	716
County)	modification					Surface	632
						Surface	749
Palomar	Prescribed	Scrub oak,	[3]16 pct.	5/8/73	1	Surface	538
(San Diego	burn, fuel	manzanita		1300		1 cm	82
County)	modification					3 cm	43
					2	Surface	732
						Surface	599
						Surface	416
						Surface	549
Paradise	Test plots	*Ceanothus,*		9/7/73	1	Surface	649
Valley	burned before	crushed chamise	Dry	1130		Surface	516
(east of	prescribed					Surface	549
Santa Maria)	fire					Surface	599
			Dry	9/7/73	3	Surface	782
				1130		Surface	649
						Surface	716
						Surface	616
Pine	Prescribed	Chamise with	10 pct.	2/28/73	1	Surface	600
Canyon	burn for	small amounts	9 pct.			1 cm	250
	experimental	of *Salvia*	9 pct.			3 cm	60
	study	and manzanita					
			11 pct.		2	Surface	650
			12 pct.			1 cm	370
			11 pct.			3 cm	85
			7 pct.		3	Surface	320
			8 pct.			1 cm	160
			12 pct.			3 cm	60

[1] Taken from continuous temperature measurements. Does not include data obtained from tempils.
[2] Exceeded limits of recorder chart (5 minutes >427°C).
[3] Soil water contents before burning. See *table 3* for change in water content during fire.

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This state-of-the-art report summarizes what is known about the effects of heat on soil during chaparral fires. It reviews the literature on the effects of such fires on soil properties, availability and loss of plant nutrients, soil wettability, erosion, and surface runoff. And it reports new data collected during recent prescribed burns and a wildfire in southern California. From the data, stylized curves that characterize soil heating during light, moderate, and intense chaparral fires were developed. The information is useful in estimating the effects of fire on soils in chaparral ecosystems.

Retrieval Terms: chaparral; brush fires; soil heating; heat effects.

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