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Water Repellent Soils: a state-of-the-art

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CHAPARRAL

In 1977, the Forest Service, U.S. Department of Agriculture, established a research and development program at this Station titled "Vegetation Management Alternatives for Chaparral and Related Ecosystems." This 5-year program, with headquarters at Riverside, California, is an intensive effort to develop, test, and demonstrate a wide range of operations for maintaining or increasing the productivity of chaparral and related ecosystems in southern California.

Cover: A simple field test with a water dropper shows a water repellent soil. Water repellent soils contribute to erosion after wildfires. During an intense wildfire, the temperature of the litter surface is extremely hot—as illustrated by the deformed glass bottle.

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Water repellency in soils was first described by Schreiner and Shorey (1910), who found that some soils in California could not be wetted and thereby were not suitable for agriculture. Waxy organic substances were responsible for the water repellency. Other studies in the early 1900's on the fairy ring phenomenon suggested that water repellency could be caused by fungi. These fairy rings created unsightly, circular shaped areas in otherwise healthy turf and lawn. Bayliss (1911) reported on such water repellency and referred to earlier work in 1875 by Gilbert and Laws at Rothamsted which described the same phenomenon. Later, Shantz and Piemeisel (1917) confirmed that soil dryness was associated with fairy rings on grasslands in eastern Colorado.

About 30 years passed before water repellency was reported again. Jamison (1942, 1946, 1947) found that "hard to wet" soil was responsible for citrus decline disease in Florida. Shortly thereafter, Van't Woudt (1954, 1955, 1959) reported the effects of water repellent substances on water movement in volcanic derived soils of New Zealand. Also, about that time both Robinson and Page (1950) and Hedrick and Mowry (1952) discovered that soil aggregates, which had been stabilized by adding organics to the clay fraction, became slightly water repellent.

Beginning in 1960, interest in soil-water repellency increased rapidly, and since then over 100 papers have been published. An early review by DeBano and others (1967) summarized the state-of-the-art. This review was followed by a more comprehensive review of soil-water repellency which was the product of an international symposium at Riverside, California, in May 1968 (DeBano and Letey 1969). The research on wetting agents and water repellency, conducted by other scientists, has also been summarized (Letey and others 1975).

Although many have contributed to our knowledge of water repellency, several groups in particular should be acknowledged. Research scientists at the Department of Soils and Environmental Sciences at the University of California, Riverside, are recognized worldwide for their contribution to the understanding of the physics of water movement, the formation of water repellent soils, and the chemistry and application of surfactants to related soil-water problems. Several important contributions on water movement have been made by scientists at the University of Florida, Gainesville. Likewise, research on the use of water repellent substances for water harvesting has been conducted by Agricultural Research, Science and Education Administration, U.S. Department of Agriculture, at Phoenix, Arizona, which has increased our understanding of water movement in soil and the chemistry of artificial hydrophobic substances (such as silicones and plastics). Substantial insight into the chemistry of naturally occurring water repellent substances and their relationship to microorganisms resulted from research at Northern Arizona University, Flagstaff. International recognition also must be given to Dr. Roy Bond for his pioneering research on water movement, formation, and management of water repellent soils in Australia.

Forest Service scientists have also contributed importantly to water repellency research and scholarship. The most vocal was the group working under direction of the author at the San Dimas Experimental Forest in southern California. Noteworthy contributions have also been made by Dr. Richard Meeuwig, Reno, Nevada; Dr. David Scholl, Albuquerque, New Mexico; and Dr. Norbert DeByle, Logan, Utah.

The abundant documentation generated by this worldwide interest in soil-water repellency is scattered throughout the literature. Therefore, a state-of-the-art publication which summarized this information was considered germane. This report, however, should not be considered definitive; several areas in water repellency are unsolved and require major research efforts.

This report focuses on the nature and formation of water repellent soils, kinds of water repellent substances, effects of soil-water repellency on water movement, fire-induced soil-water repellency, management problems and implications of water repellency, and future research needs.

NATURE AND FORMATION OF WATER REPELLENT SOILS

Normally, dry soils readily imbibe water. A strong attraction exists between mineral soil particles and water; however, not all soils display these wettable characteristics, but repel water. For example, when water droplets are placed on the surface of an air-dry soil that is water repellent, the droplets bead up; water will not penetrate (*fig. 1*) because the mineral soil particles are coated with substances that repel water, that is, they are hydrophobic. In chemistry, hydrophobic substances have no polarity and therefore do not attract water.

This difference in wetting behavior is reflected in the comparative infiltration curves of wettable versus water repellent soils (*fig. 2*). In a wettable soil, the initial rate of water uptake is rapid because of the strong attraction between water and dry soil particles; however, as these soils wet up, the hydraulic gradient decreases and infiltration rates decrease. Conversely, a dry water repellent soil strongly resists water penetration. The initial infiltration rates are extremely slow, even nonexistent. Though generally, infiltration slowly increases if water remains in contact with the repellent soil, probably because water vapor advances into the soil, coalesces on isolated wettable organic and inorganic sites, and preconditions the soil. Finally, the repellent soil, once saturated, conducts water almost as rapidly as wettable soil, although some entrapped air in the water repellent soil may slightly lower hydraulic conductivity.

Water repellency, produced by soil heating, is common on burned watersheds in southern California. Researchers typically notice that they leave dusty tracks in the mud as they trudge across freshly burned watersheds after fall and winter rains. Closer examination reveals the soil to be unevenly wet. At or near the surface, a darkly colored soil layer can be saturated, but a few inches downward is an air-dry layer of varying thickness. Another damp or moist soil layer is present below the air-dry layer. This layered arrangement may be continuous over large areas or patchy and irregular. The dusty tracks in the mud occur because the wet upper soil layers collect on the researcher's boots exposing the underlying water repellent soil which is dry. This layered arrangement was labeled the tin-roof effect by early watershed researchers.

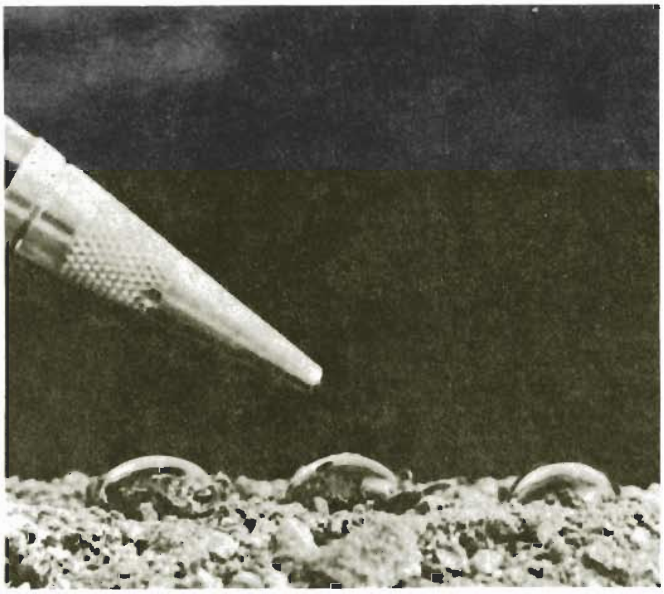

Figure 1—Droplet of water placed on the surface of a naturally occurring hydrophobic soil (DeBano and Rice 1973).

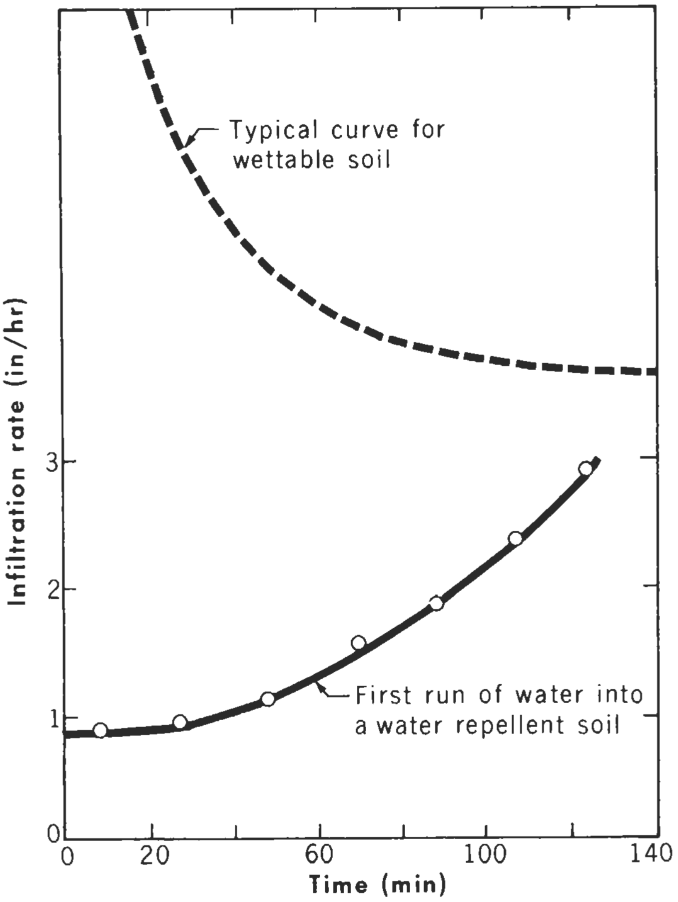

Figure 2—Infiltration rates in a water repellent soil compared to a typical infiltration curve for a wettable soil (Letey and others 1962b).

Distribution of Water Repellent Soils

Water repellent soils are not isolated curiosities. They are found throughout the world on both wildlands and on intensively cultivated lands. In the United States, water repellent soils have been reported in forests,[1] brushfields,[2] grasslands,[3] agricultural lands,[4] and on golf greens.[5]

Outside the United States, water repellent soils have been reported in Australia,[6] Canada,[7] Egypt,[8] Holland,[9] India,[10] Japan,[11] Russia,[12] and New Zealand.[13]

The intensity and persistence of water repellency seems to vary widely, although fire-induced water repellency generally is more severe. For example, many of the burned soils examined in southern California were so completely waterproofed that water drops, when placed on the surface, would evaporate before being absorbed by the soil (DeBano and Krammes 1966). Water repellency in burned soils can persist yearlong if the soils remain dry, although more transient seasonal water repellency has been reported in some southern California chaparral areas where the soils were wettable when desiccated in the summer, but extremely water repellent following autumn rains (Holzhey 1969a,b). A moss-like plant became active and created water repellency after rains. The persistence of heat-induced water repellency depends partly on the intensity of the fire.

Water repellency persisted for thousands of years in Palesols, in Alberta (Dormaar and Lutwick 1975). Many of these soils contain charcoal and burned plant parts. Research postulated, therefore, that the associated brown to reddish-brown horizons in these soils resulted from heat produced by burning vegetation. The extent of soil heating in the different horizons could be estimated by testing for water repellency. Those horizons containing charcoal and partly burned peat were highest in organic matter and water repellency and therefore had been subjected to temperatures ≤400° C. The brown and reddish-brown horizons were lowest in water repellency and probably had been subjected to temperatures ranging from 480 to 600° C.

Factors Affecting Water Repellency

The severity of water repellency in soils is dependent on several factors. Organic matter and soil texture are the most important factors, although fire intensity and soil water are also important parameters affecting fire-induced water repellency.

Organic Matter

Organic matter induces water repellency in soils by several means. First, irreversible drying of organic matter can induce water repellency (Hooghoudt 1950), mainly in the surface layers of peat soils which are difficult to rewet after drying (Van't Woudt 1969). Second, organic substances leached from plant litter can induce water repellency in sand and in coarse grained soils (Letey and others 1962b, Roberts and Carbon 1971, Van't Woudt 1959). Third, hydrophobic microbial by-products coating a mineral soil particle may induce a wetting resistance (Bond 1965, 1969; Bond and Harris 1964; Fehl and Lange 1965; Mathur 1970; Savage and others 1969b). Fourth, mineral particles need not be individually coated with hydrophobic materials; merely intermixing mineral soil particles with organic matter may induce severe water repellency (DeBano 1969, Meeuwig 1969). Finally, heating the coated particles or the intermixed soil can markedly increase water repellency (Cory and Morris 1969, DeBano and Krammes 1966). Heating distills hydrophobic organic substances which then condense at cooler sites (DeBano 1966, Savage 1974). If the soil is a mixture of organic matter and mineral soil, heating causes the organic matter to coat the adjacent mineral soil particles (DeBano and Krammes 1966).

The intensity and distribution of water repellency in soils seems partly related to plant species and cover density. After infiltration trials in Australia, the soil between plants remained dry, whereas the soil beneath the grass roots was wet (Bond 1964). Moreover, different types of plant covers produced different degrees of water repellency; the order of decreasing water repellency was phalaris, mallee, heath, and pine.

In contrast, other studies showed that water repellency was confined to the soil immediately beneath a plant canopy (Adams and others 1969, 1970; Gilmour 1968; Jamison 1942, 1946, 1947; Scholl 1971). In Florida, water repellency was found to extend from the trunk outward to the margin of the leaf drip (Jamison

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[1] Agee 1973; Bashir 1969; Campbell and others 1977; DeBano 1969a, 1979; DeBano and Rice 1971, 1973; DeByle 1973; Dyrness 1976; Meeuwig 1969, 1971a,b; Reeder 1978; Scholl 1971; Singer and Ugolini 1976; U.S. Department of Agriculture 1971; Wells and others 1979; Zwolinski 1971.

[2] Adams and others 1969, 1970; Bashir 1969; Cleveland 1973; DeBano 1969a, 1974; DeBano and others 1977; Hays 1975; Holzhey 1969a,b; Krammes and DeBano 1965; Salih and others 1973; Teramura 1973; Vogl and Schorr 1972; Wells and others 1979.

[3] Mathur 1970, Richardson and Hole 1978, Schantz and Piemeisel 1917.

[4] DeBano 1969c; DeBano and Letey 1969; Jamison 1942, 1946, 1947; Schreiner and Storey 1910.

[5] Miller and Wilkinson 1977, Paul and Henry 1973, Waddington 1969, Wilkinson and Miller 1978.

[6] Bond 1960, 1964, 1965, 1968, 1969; Bond and Harris 1964; Gilmour 1968; King 1974a,b; Prescott and Piper 1932; Roberts and Carbon 1971, 1972.

[7] Dormaar and Lutwick 1975, Mathur 1970.

[8] Bishay and Bakhati 1976.

[9] Hooghoudt 1950.

[10] Adhikari and Chakrabarti 1976, Das and Das 1972.

[11] Nakaya and others 1977a,b.

[12] Kolyasev and Holodov 1958, Rybina 1967, Vladychenskiy and Rybina 1965, Wladitchensky 1966.

[13] Van't Woudt 1954, 1955, 1959.

1942). In the Sierra Nevada, water repellency was discovered mainly in the subsoil on bare areas where the decaying roots of nearby trees and shrubs were present (Meeuwig 1971b). In Wisconsin, water repellency was weak in Mollisols under an unburned prairie but very pronounced in the mor litter layers with observable fungal mycelia (Richardson and Hole 1978). Water repellency was observed in Spodisols under red pine, hemlock, and under a mixed hardwood-softwood stand with dense ericaceous shrub understory. The repellency of mor horizons in the Spodisols seemed related to the genesis of the Spodic horizon. In Wisconsin, Reeder (1978) found that water repellency was associated with aspen but not with other forest types.

Holzhey (1969a,b) examined water repellency in southern California, across a transect of several vegetation types. In the chaparral plant communities, water repellency was least in the coastal sage scrub where a scant litter layer was present and greatest in the woodland chaparral dominated by *Arctostaphylos* sp., *Ceanothus* sp., *Quercus dumosa*, and *Rhamnus crocea*. In pinyon-juniper woodlands, water repellency was least severe under *Artemisia tridentata* and most severe under stands of *Pseudotsuga macrocarpa*. No attempt was made to correlate plant species to type of microorganism present under each vegetation type. Teramura (1973) observed that water repellency in chaparral stands was related to stand age but not species composition.

Soil Texture

Soil texture affects the degree of water repellency when organic matter is added to, or allowed to decompose in, soils. Normally, organic matter added to soils is considered desirable; soil structure improves, which correspondingly enhances aeration and water movement. Contrarily, however, organic matter can induce water repellency in coarse textured soils, which severely restricts water movement (Meeuwig 1969, 1971a,b). In Australia, water repellency in sandy soils produces severe management problems (Bond 1965, King 1974b). Conversely, in finely textured soils, organic matter forms water-stable aggregates which improve aggregate stability and water and air movement (Hedrick and Mowry 1952).

Chemistry of Water Repellency

The characterization and identification of naturally occurring water repellent substances has been studied with varying degrees of complexity. Although the substances responsible for producing water repellency are definitely organic, the amount of organic carbon and the degree of water repellency are not directly related (DeBano and others 1976). The ease of extracting hydrophobic substances has been used to characterize water repellency. Simple water solutions containing substances extracted from chaparral plants can make sands water repellent (Letey and others 1962b). Alkali solutions such as ammonium hydroxide also remove substances from plant litter that can induce water repellency in sand or coarse-textured soil (Letey and others 1962a).

The solubility of hydrophobic coatings in various organic solvents also has been used to characterize water repellency. Wander (1949) showed that such coatings from Florida soils were soluble in methanol; he believed they were calcium and magnesium soaps. Van't Woudt (1959) found that the particle coatings causing water repellency in Taupe volcanic soils in New Zealand were so strongly adsorbed that they could not be removed with 2 hours of refluxing with ether in a Soxhlet apparatus. In another study (Montana Agric. Exp. Station 1963), substantial amounts of organic materials were removed by extraction with hot alcohol in a Soxhlet. The tenacity of adsorption was also demonstrated in Hawaiian soils where neither ethyl nor petroleum ether could extract the hydrophobic substances (Uehara 1962).

The hydrophobic organic skins on sandy soils of southwestern Australia were resistant to removal by cold water, concentrated acid, diethyl ether, ethanol, benzene, chloroform, and acetone (Roberts and Carbon 1972). Prolonged treatment with hot diethyl ether, ethanol, and benzene removed part of the coating. Treatment with dilute solutions of alkali removed the skin as suspended particles. The organic hydrophobic substances produced by fire cannot be extracted from naturally occurring soils with mixtures of either benzene-acetone (Savage and others 1972) or benzene-methanol (Savage 1974), although these substances are extractable when collected on angular quartz sand.

The chemical identification of substances responsible for water repellency is complex; a host of organic substances of unknown composition seems involved. An early study (Prescott and Piper 1932) suggested that essential oils from xerophytic vegetation produced water repellency. Work on southern California chaparral showed that both water soluble and highly volatile secondary products contribute to water repellency (Teramura 1973). Wander (1949) concluded that calcium and magnesium salts of fatty acids were responsible for water repellency. Attempts to characterize the substances as crude fat have been futile (Van't Woudt 1959, Uehara 1962).

Much has been done to chemically characterize these substances via humic acids (Roberts and Carbon 1972; Savage and others 1969a,b; Singer and Ugolini 1976; Wladitchensky 1966; Adhikari and Chakrabarti 1976); however, not all humic acids can cause water repellency. Of the several humic acids tested, only one which was recovered from a culture solution of *Stachybotrys atra* has produced water repellency in sand and soil (Savage and others 1969a). The analysis of soils collected from beneath a hemlock-fir forest in Washington showed that water repellency was highly correlated with the humic-fulvic acid ratio (Singer and Ugolini 1976). Chen and Schnitzer (1978) found that a fulvic acid deficiency in the soil solution would produce water repellency, and conversely, an ample supply of fulvic acid increased soil wettability. The organic coatings on water repellent sand grains from localized dry spots on golf greens produced an infrared spectrum similar to fulvic acid (Miller and Wilkinson 1977). A comprehensive elemental and spectroscopic analysis of the organic substances contributing to fire-induced water repellency in soils revealed that the organic substances were basically aliphatic hydrocarbons (Savage 1974).

The extractive resistance of hydrophobic soil coatings suggests that they are strongly adsorbed; however, the nature of the bonding is not fully understood. Van't Woudt (1959) concluded that the hydrophobic coatings were strongly adsorbed on the mineral surfaces by complex radicals. Cory and Morris (1969) suggested that extensive polymerization occurs, possibly by hydrogen bonding. A mineralogical study by Uehara and Huong (1963) showed that silanol groups on the clay surfaces of minerals were partly responsible for water repellency. The hydrophobic substances produced during burning exhibit high polarity which is believed to be responsible for their becoming tightly fixed in the soil (Savage 1974).

Fire-Induced Water Repellency

Water repellency caused by wildfires in southern California chaparral has received the most attention (DeBano and others 1967, DeBano 1979), although repellency has been reported after wildfires in forests (Campbell and others 1977, Dyrness 1976) and in grasslands (Richardson and Hole 1978). In southern California, organic matter accumulates in the litter layer during the intervals between fires. During these intervals, the upper soil layers become water repellent due to the intermixing of partially decomposed organic matter and mineral soil (*fig. 3A*) and due to the leachate from brush and decomposing plant parts which become deposited in the upper soil profile. Fungal growth also can produce water repellency in this part of the soil.

Heating during a fire markedly changes and intensifies water repellency. When a fire occurs, the litter and upper soil layers are exposed to very intense heating, particularly during an intense burn (*fig. 3B*). Temperatures in the plant canopy may soar to 1093° C (Countryman 1964). Temperatures at the soil surface are less but may reach 843° C (Dunn and DeBano 1977). Within the upper soil layers, the temperature drops rapidly because dry soil is a poor conductor of heat. At 5 cm below the surface, the temperature is not likely to exceed 150° C (DeBano and others 1977). Incipient water repellency at the different depths may be intensified in

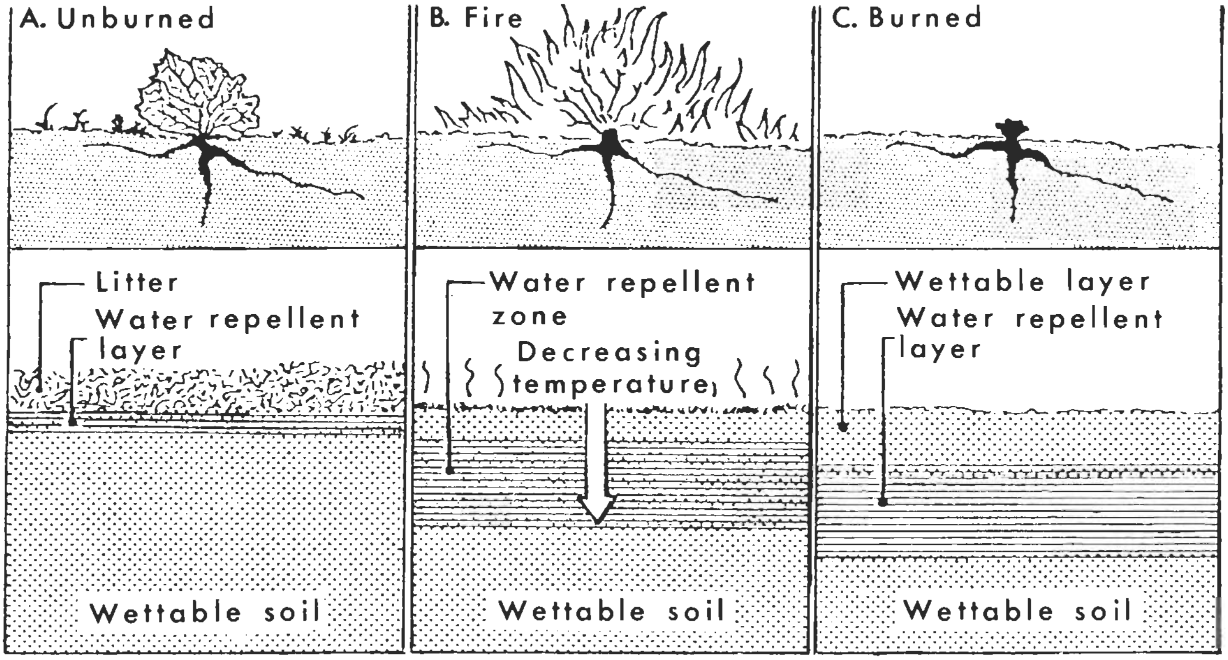

Figure 3 — Soil-water repellency as altered by fire: *(A)* before fire, hydrophobic substances accumulate in the litter layer and mineral soil immediately beneath; *(B)* fire burns the vegetation and litter layer, causing hydrophobic substances to move downward along temperature gradients; *(C)* after fire, a water repellent layer is present below and parallel to the soil surface on the burned area (DeBano 1969).

place by heating because the organic particles are heated to such an extent that they coat and are chemically bonded to the nearby mineral particles.

More important than the absolute temperature at any depth are the temperature gradients developing across the upper few centimeters of soil. Substances which are vaporized at the soil surface can be moved downward into the underlying soil by these gradients. The vaporized substances then condense on mineral soil particles and are rendered extremely water repellent (DeBano 1966). After a fire has swept through an area, a water repellent layer of varying thickness remains (*fig. 3C*). This layered arrangement allows rainfall to infiltrate only to a limited depth before the wetting front reaches the water repellent layer.

Experimental Confirmation of Theory

Letey and his co-workers (1962a) were the first investigators to show that water repellency in chaparral soils was caused by organic substances. Later, DeBano and Krammes (1966) found that water repellency could be changed radically by heating. Samples of slightly water repellent topsoil containing some organic matter were placed in a muffle furnace and heated; the water repellency was either intensified or destroyed. For example, heating for 20 minutes to 260° C produced an extremely water repellent condition. In contrast, heating to 371° C for only 20 minutes started to reduce water repellency. That substances must move along temperature gradients became apparent after field observations revealed water repellency at deeper depths where soil heating was not sufficient to intensify water repellency. The translocation of hydrophobic substances was confirmed by experiments in which heat was applied to the surface much as occurs during a natural fire (DeBano 1966, DeBano and others 1970). These experiments were designed to measure the hydrophobic substances distilled downward into formerly wettable sand, thereby demonstrating that hydrophobic substances are moved along temperature gradients.

Chemistry and Thermal Stability

Once established that organic substances moved along temperature gradients, experiments were made on the chemistry of these substances, their thermal stability, and the soil physical factors affecting them. Chemical analysis was made of the compounds causing heat-induced water repellency since chemical identification was thought necessary before remedial treatments could be intelligently prescribed. Wetting agents had been used with varying degrees of success, but their specific interaction with hydrophobic substances was obscure (Osborn and others 1964, Pelishek and others 1962). In one such experiment, substances emanating from a heated water repellent soil were captured, fractionated by adsorption chromatography, and subjected to elemental and spectroscopic analyses (Savage and others 1972). These analyses showed that the greatest amount of organic substances was released above 300° C and that the amount released increased with the rising oxygen content (up to 20 percent) of the gas passing through the combustion chamber.

Chemical analyses of these fractions showed that the substances causing water repellency were aliphatic hydrocarbons formed from partly decomposed plant materials in the soil. When these substances were placed on wettable sand, extreme water repellency was produced only after heating the treated sand. The suggestion was that additional heating after condensation was necessary to fix the hydrophobic substance and produce extreme water repellency. Savage (1974) later confirmed these results. He used sand columns under burning manzanita litter to show that the degree of water repellency was less when burning litter was immediately removed, before the heat had penetrated into the sand, than when the burning litter was left in place and allowed to heat the underlying sand. He concluded that the movement of organic substances from litter occurred mainly when the fire was actively burning. After burning, heat moving downward through the underlying sand fixed some of the more polar hydrophobic substances and revolatilized the less polar ones, thereby broadening the water repellent layer. The temperature required to fix and revolatilize the substances was greater than 250° C. DeBano and others (1976) analyzed polarity, extractability, oxygen content, and related water repellency. Their tests showed that substances with greater polarity and higher oxygen contents produced less hydrophobicity when heated to 250° C. The less polar substances moved further downward in the soil, producing a higher degree of water repellency.

These studies provide general guidelines on the thermal stability of substances responsible for water repellency. Most studies (Savage 1974, Scholl 1975, DeBano and others 1976, Dormaar and Lutwick 1975) generally agree that the substances responsible for water repellency are destroyed when heated over 288° C. Very intense water repellency is formed when soils containing hydrophobic substances are heated between 176 and 204° C. Temperatures of at least 250° C are necessary to fix the translocated substances.

Fire Intensity and Soil Water

In burned soils, the severity of water repellency not only depends on soil texture, but also appears related to both intensity of fire and soil-water content (DeBano and others 1976). Light burns in chaparral over dry soils produce the thickest and most highly water repellent condition. The least severe water repellency is produced when a light-intensity-chaparral fire burns over a wet soil. To this end, Dyrness (1976) found that the wettability of soils in stands of lodgepole pine burned lightly by a wildfire recovered more rapidly than soils in intensely burned areas. By the sixth year after the fire, the wettability of both lightly and intensely burned soils was approaching that of the unburned soil.

SOIL-WATER MOVEMENT

Water movement can be severely limited by hydrophobic organic materials which are either intermixed with the soil or coat the mineral soil particles. The infiltration curves for wettable and water repellent soils presented earlier reflect this effect (*fig. 2*). The practical implications of water relations in these hard-to-wet soils (such as the effects on plants, runoff, and erosion) has led to numerous studies on water movement.

The effect of hydrophobic substances on water movement in soils provides a basis for characterizing water repellency. Several methods of varying sophistication used to characterize water repellency include waterdrop penetration time (WDPT), equilibrium liquid-solid contact angles, solid-air surface tension indices, and the characterization of dynamic wetting angles during infiltration. The in-depth principles of soil physics used to develop some of these methods are contained in two excellent reviews describing the basic theory—Letey and others (1975) and DeBano (1975).

Classifying Water Repellency

Letey and his co-workers (1975) point out that soils are usually classified as either wettable or water repellent, implying a sharp dichotomy; however, water repellency is a relative soil property and may vary widely in intensity. Any practical method of classification must be able to quantify or, at most, index the degree of water repellency with time. Most of the methods described here are quantitative and treat water repellency as a relative soil property. The simpler techniques, such as waterdrop penetration time, are described in sufficient detail to allow the reader to use them. The more fundamental principles provide a basis for describing the effect of hydrophobic substances on water movement during infiltration and evaporation.

Waterdrop Penetration Time

One of the simplest and most common methods of classifying water repellency is to determine the time a waterdrop takes to be absorbed by the soil sample. A waterdrop is placed on the sample surface (*fig. 1*) and the length of time to be absorbed is timed. Theoretically, if the wetting angle is greater than 90 degrees, the water droplet will remain on the surface until it evaporates; if the angle is less than 90 degrees, pore capillary forces will pull the water into the soil. In fact, the distinction between a wettable (wetting angle less than 90 degrees) and a water repellent soil (wetting angle greater than 90 degrees) is not that simple because water repellency seems to be time dependent in many cases. That is, the wetting angle of the water droplet will change over time and the water droplet, although not immediately absorbed, will penetrate the sample at a later time. Some water repellent soils have wettable soil particles and organic debris that will move onto the water droplet, causing it to penetrate into the soil. Such complications arising from the time dependency have led to the establishment of arbitrary time limits when classifying soils as wettable or water repellent. Researchers found that water droplets remaining longer than 5 seconds usually resisted penetration for several minutes and thus the soil could be classified as water repellent (Krammes and DeBano 1965).

Sometimes measurement of waterdrop penetration longer than 5 seconds is desirable for obtaining information on the persistency of water repellency. Another technique was therefore developed which uses the critical surface tension of the infiltrating solution (Watson and Letey 1970, Watson and others 1971). Critical surface tension is defined as the liquid surface tension which permits just wetting of a soil (that is a 90-degree contact angle). The critical surface tension can be easily and quickly determined in the field or laboratory with a series of aqueous ethanol solutions. Pure ethanol is diluted with distilled water into separate solutions containing different percentages of ethanol on a volume basis. (The corresponding surface tension of these solutions can be obtained from a physics and chemistry handbook.) A drop of each solution is placed on the soil surface and the time of penetration determined. If the drop penetrates instantaneously (less than 5 seconds), the surface tension of that solution is considered to be at the critical surface tension. A water repellency index is then obtained by dividing the critical surface tension (dynes/cm) into the time (up to 600 seconds) required for a water droplet to be absorbed by the soil (Letey and others 1975). For practical purposes, waterdrop penetration times are not measured beyond 10 minutes. A repellency index value greater than 10 indicates an extremely water repellent soil; 1 to 10 is moderately water repellent; 0.1 to .1 is slightly water repellent; and less than 0.1 is wettable (Letey and others 1975). When this technique was compared with other, more complicated, techniques involving liquid-solid contact angles during capillary rise, the results agreed closely (Letey and others 1975).

Equilibrium Liquid-Solid Contact Angles

Porous media such as soils are often viewed as simple or multiple capillary systems. The pores are considered analogous to capillary tubes (Emerson and Bond 1963, Letey and others 1962a, Vladychenskiy and Rybina 1965, Yuan and Hammond 1968). Water movement can thus be described by capillary rise models which are based on the attraction between water molecules and the walls of the capillary tube. In soils, capillary rise occurs because of an attraction between the water molecules and soil particle surfaces.

When water moves up a capillary tube, the water meniscus forms a definite and measurable angle with the glass wall of the tube. The capillary rise equation relates the height of rise of the water and the contact angle, as follows:

$$h = \frac{2\gamma}{r\rho g}\cos\theta$$

in which

h = height of rise
γ = surface tension
r = radius of capillary
ρ = density of the liquid
g = gravitational term
θ = angle between the water meniscus and the wall (wetting angle).

If the capillary wall is made of clean glass, the wetting angle, θ, should be zero. If the angle is zero, the height of rise is directly related to the surface tension and inversely related to the tube radius (that is, the smaller the radius of the tube, the higher the capillary rise). Coating the capillary tubes with hydrophobic substances reduces the attraction between the water and the glass walls. The water therefore will not rise as high as in a clean tube.

The concept of a wetting angle provides a useful technique for quantifying soil wettability (Letey and others 1962a). Pure ethanol wets all solids (even hydrophobic ones) at a zero contact angle. Various liquids, including n-heptane (Bahrani and others 1973, Kijne 1967, Miyamoto and Letey 1971), have been used experimentally, but not as widely as ethanol. Therefore, equation (1) can describe capillary rise of water and ethanol. In both cases, two parameters (θ and r) are not known or readily measured. The surface tension and density of water and ethanol can be measured or referenced in a handbook. The known gravitational constant is the same for both liquids. The height of rise for both water and ethanol can be measured easily in the laboratory. Finally, if the wetting angle of ethanol is assumed to equal zero (thus, $\cos\theta = 1$) and the capillary radius remains constant, then equation (2) can calculate the apparent liquid-solid contact angle:

$$\cos\theta_w = 0.369\frac{hw}{he}$$

in which

θ_w = apparent liquid-solid contact angle
hw = height of rise of water (cm)
he = height of rise of ethanol (cm)

The factor of 0.369 was derived from known values of density and surface tension of water and ethanol (at 20° C).

Laboratory tests determine the apparent liquid-solid contact angle (θ_w) by packing two similar glass tubes with the test soil. Though the size can vary, glass tubes averaging about 4.8 cm in diameter by 53 cm long have been used (Letey and others 1962a). Smaller diameter tubes may complicate the results because of edge and boundary effects. The bottom of the glass tubes are covered with cheesecloth or fine mesh screen which retains the soil at the bottom of the tube but allows the water or ethanol to move up. When filling the two tubes with soil, care should be taken to pack them to identical density. Finally, the end of one column is immersed in water, the other in pure ethanol. The height of capillary rise of both solutions can be readily observed through the walls of the glass tubing. After 24 hours, the height of capillary rise of the two solutions is measured and used in equation (2) to calculate the apparent liquid-solid contact angle. The larger the angle, the greater the water repellency, with angles up to 90 degrees obtainable.

Energetics of the Soil-Water-Air Interface

The theoretical basis underlying the above methods, particularly the apparent liquid-solid contact angle, has caused reexamination of the theory of wetting in water repellent soils. Several inadequacies arise when characterizing water repellency by liquid-solid contact angles (Bahrani and others 1970). A liquid-solid contact angle (θ_w) in a porous medium with the complex pore geometry of soil is difficult to visualize. Electron microscopic examination of wetting on the surface of hydrophobic sand grains illustrates the traditional liquid-solid contact angle model based on capillary rise, but does not represent a real soil (Bond and Hammond 1970). Such examinations reveal that the effective contact angle really is the sum of a finite contact angle measured between the solid and the liquid-air interface and the angle of divergence of the soil pore. Although some media are considered completely water repellent, some attraction for the water usually exists and water enters slowly. This action is probably related to the persistency of waterdrops. Extremely water repellent materials have been shown to adsorb some water slowly by vapor diffusion (Hanks 1958, DeBano 1969b, Miyamoto and others 1972). Also, liquid-solid contact angles do not explain the physical nature of water repellency, particularly in terms of the energetics of the soil-water-air interface.

Two methods for evaluating water repellency have been developed which are not subject to the above limitations: one determines a wetting coefficient (Bahrani and others 1970), the other determines the solid-air surface tension of the medium (Miyamoto and Letey 1971). Two wetting coefficients based on Young's "Work of Adhesion" and Moillets' "Work of Droplet Adhesion" are described and discussed in detail by Bahrani and others (1970). The technique for determining solid-air surface tension of porous media has a different theoretical basis and is derived from Fowkes' dispersion theory and the capillary rise equation (Miyamoto and Letey 1971).

Characterizing Water Repellency During Infiltration

Soils with wetting angles less than 90 degrees but greater than 0 should transmit water, although infiltration is slower than if completely wettable. The intensity and persistence of water repellency determines the flow rate. Several techniques have been developed to characterize wettability during infiltration. A couple techniques employ saturated flow equations to derive liquid-solid contact angles from the measurements taken on the advancing wetting front (Letey and others 1962a, Emerson and Bond 1963). Another approach utilizes unsaturated flow rates, characterized within the framework of a diffusivity analysis, to evaluate the effect of water repellency on water movement at different soil-water contents (DeBano 1969b, 1971).

The first attempt to characterize the liquid-solid contact angle during infiltration was based on Poiseuille's equation (Letey and others 1962a). Both water and ethanol were infiltrated into the test soil. The relative rates derived from those tests served as the basis to calculate liquid-solid contact angles in much the same method as for capillary rise. The Darcy flow equation was applied in another infiltration technique to calculate the advancing contact angle for water repellent sands (Emerson and Bond 1963). Instead of using ethanol to establish a zero contact angle, part of the sand was ignited to destroy the organic matter responsible for water repellency. The ignited sand was assumed to be wet at zero contact angle by water.

Unsaturated flow measurements have also served to calculate liquid-solid contact angles at different soil-water contents in wettable and water repellent soil (DeBano 1969b). This approach employed the concept of intrinsic soil-water diffusivities (Mustafa and others 1970). The diffusivities were determined from laboratory measurements during the horizontal infiltration of water or ethanol into wettable and water repellent soils and served to calculate liquid-solid contact angles at different volumetric water contents. The results showed that as the water content of a wettable soil increased, the liquid-solid contact angle increased as well. In a water repellent soil, however, the wetting angle decreased with increasing water content because some of the hydrophobic sites wetted up after exposure to water. The results presented here agree well with our understanding of water movement in wettable and water repellent soils.

Water Repellency and Water Movement

Usually, dry soil readily absorbs water because of a strong attraction between the mineral particles and water. In terms of the liquid-solid contact angles, highly wettable soil behaves as though these angles are zero. The affinity of soils for water can be reduced by coating the particles with hydrophobic substances, thereby increasing the liquid-solid contact angle (Wladitchensky 1966, Letey and others 1962a,b, Rybina 1967). As an important water moving force, changing capillarity also affects infiltration and evaporation.

Infiltration

Wetting Patterns—The infiltration curve given for a water repellent soil in *figure 2* reflects increasing wettability over time once the soil is placed in contact with water. Infiltration increases with time because the substances responsible for water repellency are slightly water soluble and slowly dissolve, thereby increasing wettability. Also, the hydrophobic substances on the particle surface may not be continuous and water may move into the soil by vapor diffusion where it is adsorbed on wettable sites which improves wettability of the entire soil.

Under field conditions the water repellent layer is usually not continuous, so irregular wetting patterns are

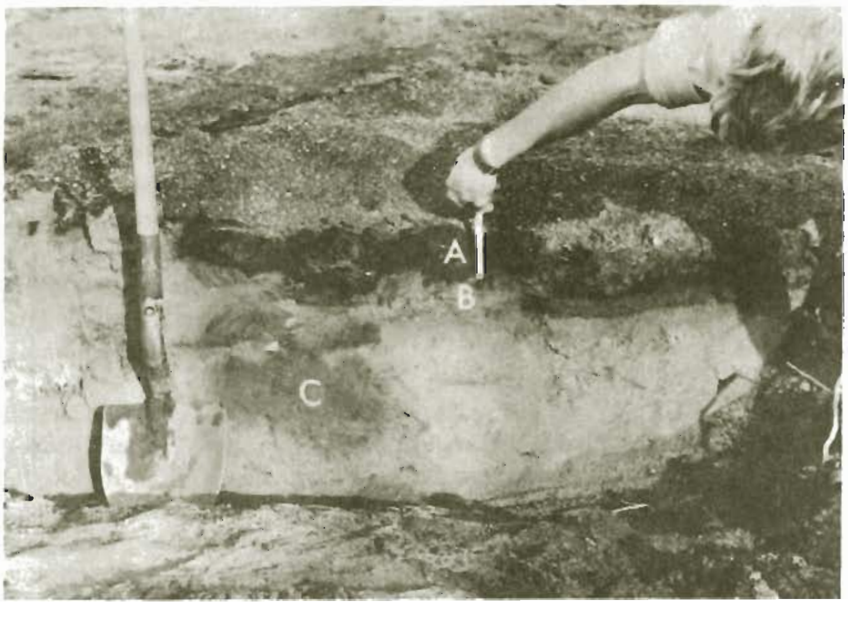

Figure 4—Exposed soil profile showing the tin roof effect. The moist surface layer *(A)* is underlaid by dry water repellent soil *(B)*, with some evidence of moisture penetration through the water repellent layer *(C)* (DeBano 1969).

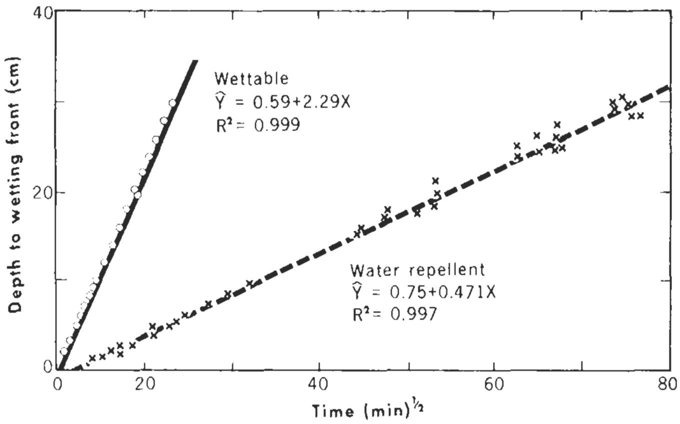

Figure 5 — Relationship between time and distance to the wetting front during a horizontal infiltration trial into wettable and water repellent soil (DeBano 1971).

common (*fig. 4*). Irregular wetting has been reported under citrus trees in Florida (Jamison 1942). In Australia, the severest water repellency has been observed in bare areas between clumps of grass; following rainstorms, wetted areas were found primarily beneath the crown of the grasses, but not in the spaces between plants (Bond 1964). Large water repellent areas in grasslands, historically described as fairy ring phenomena caused by microbe-induced water repellency, also produce irregular wetting (Shantz and Piemeisel 1917). Meeuwig (1971a) found irregular wetting patterns developing during infiltrometer trials on unburned forest and brush areas. In desert communities, soil beneath the shrub canopy was discovered to be water repellent, whereas the area outside the canopy was completely wettable (Adams and others 1969).

Laboratory Studies—Infiltration into wettable and water repellent soils has been the subject of intense laboratory testing. These studies showed that the wetting front during infiltration in wettable soils not only develops faster but has a different shape than those developing in water repellent soils (DeBano 1971). In one case, infiltration was 25 times faster in wettable soils than in water repellent soil (*fig. 5*). The linear relationship between distance to the wetting front and the square root of time commonly found in wettable soils was less well defined (although the correlation was high) in the water repellent soil because of irregular wetting. The irregular and incomplete wetting was also reflected in the soil-water distribution pattern (*fig. 6*). For example, the water content decreased as much as 20 to 25 percent between the water source and the wetting front which was very diffuse and poorly defined. By comparison, the water content of the wettable soil decreased only 10 percent over the same distance. A subsequent diffusivity analysis of the infiltration data indicated that hydrophobic substances had a greater effect on water movement in unsaturated soil when the soil was dry; the effect diminished as water content increased. The slow water uptake at the beginning of infiltration is important from the standpoint of erosion and runoff, although the effect on cumulative infiltration over longer periods of time may not be large.

Layered Soil—A water repellent layer is common in soils under field conditions. As in southern California, this layer may be formed after fire (*fig. 3C*). These water repellent layers affect infiltration in much the same manner as a coarse textured layer in the soil profile. When this water repellent layer is beneath a wettable surface layer, the wetting front moves rapidly through the wettable layer until it reaches the water repellent layer (*fig. 7*). The infiltration rate then drops immediately to that of the water repellent layer, where it remains even after the wetting front has again moved into the wettable soil beneath the water repellent layer (DeBano 1969b). The depth to the water repellent layer also affects infiltration rates. A water repellent layer near the surface will more effectively restrict infiltration than a deeper layer (Mansell 1969).

Evaporation

Hydrophobic substances reduce evaporation because the capillary forces necessary to move water to the soil surface are lessened. For example, sands made water repellent with a chaparral litter extract lost 45 percent of the water in contrast to a wettable sand which lost 60 percent of the water during the same period (Letey and others 1962b). Another laboratory experiment (DeBano 1969b) showed that the water loss from a water repellent sandy loam soil was less than from a wettable soil of similar texture. Examining the soil-water distribution patterns after evaporation revealed that water was withdrawn from all depths in the columns filled with wettable soil. In contrast, columns containing only water repellent soil lost water primarily from the upper

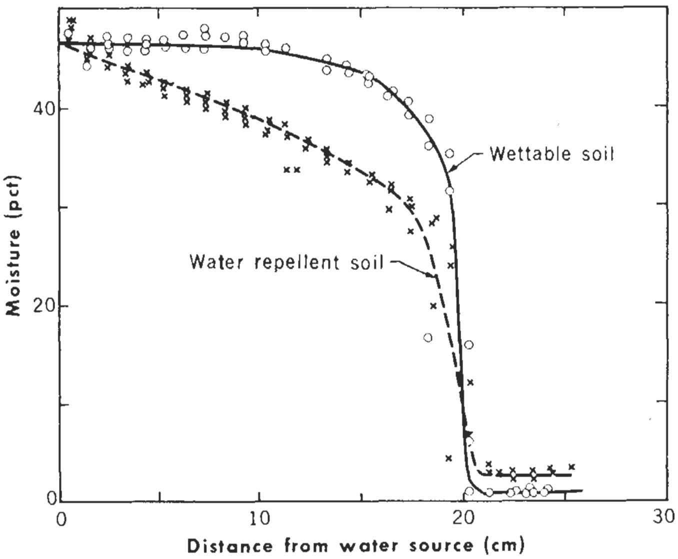

Figure 6 — Soil-water distributions developed during infiltration into columns packed with wettable and water repellent soils (DeBano 1971).

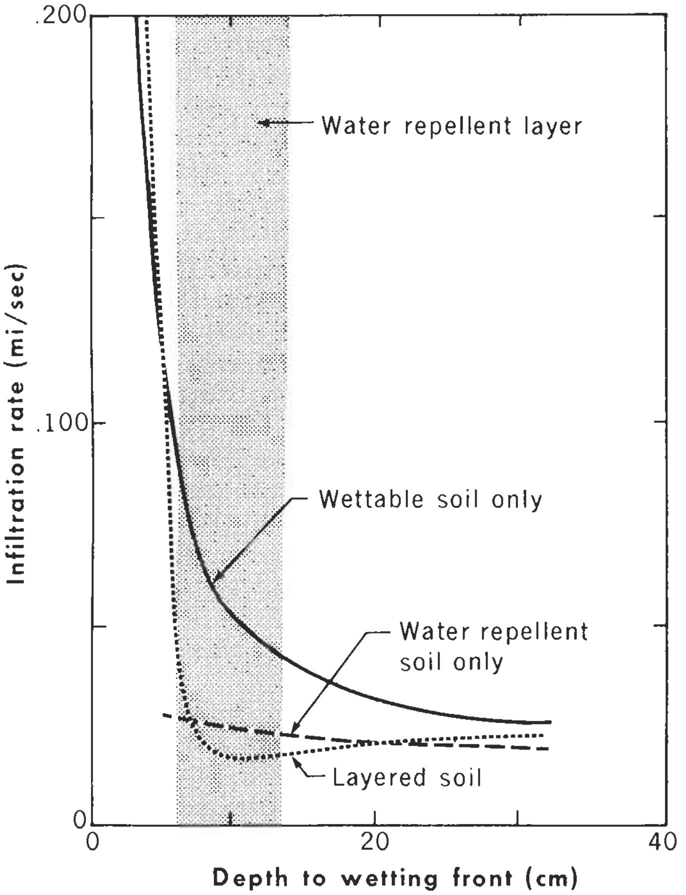

Figure 7—Infiltration rate when the wetting front approached different depths in soil columns packed with only wettable soil, water repellent soil, or layered soils (DeBano 1969c).

layers because water in the deeper layers was unable to reach the surface by capillary flow.

Other investigators (Kolyasev and Holodov 1958) reported that water repellent samples lost water faster than wettable samples; however, evaporation occurred in thin layers of hydrophobic soil, and capillarity apparently did not play a major role in moving water through the soil mass to the evaporating surface. Instead, the attraction between the particles and water directly controlled the evaporation rate. Therefore, water repellency appears to decrease evaporation where water must move to the evaporating surface by capillary flow. For this reason, many of the hydrophobic mulch materials added to the soil surface are effective in conserving soil water (Hergenhan 1972, Hillel and Berliner 1974, Lemon 1956, Kimball 1973).

Other Soil-Water Characteristics

Soil-Water Potentials—Water repellent substances affect water held at different soil-water potentials. Water repellent sands hold less water at 0 to −0.05 bar soil-water potential during sorption and desorption than similar wettable sands (Letey and others 1962b). The same is true for soils having water potentials between 0 and −1/2 bar. At soil-water potentials between −1/2 and −15 bars, however, water repellent soils hold more than wettable soils (DeBano 1975). At soil-water potentials between 0 and −1/2 bar, the weaker attraction between the soil and water (large liquid-solid contact angle) permits more water to be drawn out of the water repellent soil. In contrast, at potentials more negative than −1/2 bar, the hydrophobic substances hinder the movement of water out of water repellent soil and more water is retained in water repellent soil than in wettable soil.

Water Transfer Mechanisms—Some studies on water movement suggest that different water transfer mechanisms are operating in wettable and water repellent soils. Water moves in soil by liquid or vapor flow. In water repellent soils, liquid flow across particle surfaces coated with hydrophobic substances probably is severely hindered. Differences in capillary rise suggest weaker liquid particle attraction and less liquid flow. When liquid flow is restricted, vapor movement undoubtedly begins to play a major role in water movement because most studies suggest vapor flow is perhaps not affected by hydrophobic coatings (Brandt 1969a, Hanks 1958, Hemwall and Bozer 1964, Miyamoto and others 1972).

WATER REPELLENCY MANAGEMENT

The effects of water repellent soils may be adverse or benign, depending on the efficiency of repellency management programs. In some cases, water repellency is induced by naturally occurring organic substances or artificial materials in order to conserve water, reduce nutrient loss, or improve soil structure. But water repellency may be undesirable and require some special management action to counteract its deleterious effects. An acute management problem in southern California is the high runoff and erosion rates caused, in part, by heat-induced water repellency.

Beneficial Applications

Water Conservation

The relationship between water repellency and soil-water movement has been successfully utilized to conserve water. Water loss by evaporation from the soil surface can be reduced by several methods, thereby making it available for plant growth or other applications such as ground water recharge. Sealing the soil surface with water repellent materials also allows for water harvesting—a method of efficiently harvesting precipitation.

Evaporation Control—Water can be conserved and stored in the soil if it is not permitted to move to the soil surface where it can be lost by evaporation. The amount of water moving to the soil surface can be reduced by decreasing the surface tension of the soil water, decreasing the wettability of the pore walls, and increasing the size of the soil pores (equation [1]). The surface tension of soil water can be decreased by applying surfactants (Lemon 1956). The wettability of the soil pore walls can be decreased by coating the soil particles with hydrophobic substances (DeBano and others 1967, DeBano 1975). The effective pore size of the surface layers can be increased by mulching (Kimball 1973) or by aggregating the small particles with chemicals such as soil conditioners (Gabriels and others 1973, Hillel and Berliner 1974, Rawitz and Hazan 1978).

Water Harvesting—The technique of water harvesting has been successful in developing local water supplies in remote areas for livestock, wildlife, runoff farming, and domestic use (Frasier 1975, Myers 1964). The runoff water produced by waterproofing the soil surface can be collected and stored or used on site, depending on the local need.

Although water harvesting can be accomplished in several ways, one effective method treats the soil surface with materials which prevent water from soaking into the soil (Cooley and others 1975). Several types of materials to waterproof the soil surface are asphalts (Frasier and Myers 1972), waxes (Fink 1977, Fink and others 1973, Hillel 1967), silicones (Myers and Frasier 1969), plastics (Myers 1964), and oils (Fink and Mitchell 1975, Hillel 1967). Both laboratory (Fink 1974, 1976) and field (Fink and Frasier 1977) evaluations have been made of most currently available materials. These tests show that silicone and wax-treated water repellent catchments weather quite differently (Fink and Frasier 1977). The silicone treatment showed a uniform deterioration throughout the treated zone, whereas the wax treatment showed a progressive deterioration beginning at the top of the treated profile. A laboratory test (Fink 1976) showed that when two repellents (petroleum resin and paraffin wax) were combined, the soil was rendered generally more resistant to total weathering effects than either repellent alone.

Nutrient Leaching

The leaching of soluble fertilizers out of the root zone of vegetable beds is an important management problem in parts of Florida (Snyder and Ozaki 1971). The leaching losses are greatest in coarse textured soils which have a low exchange capacity because clay and organic matter are lacking. This problem was successfully solved by applying water repellent mulches to reduce leaching and fertilizer loss (Snyder and Ozaki 1971, Snyder and others 1974). Nitrogen and potassium leaching from a fertilizer band in sandy soil (on the flat surface of raised vegetable beds) was reduced by a 1 percent siliconate spray in quantities sufficient to penetrate a 20-cm wide area to a depth of about 3 cm.

Soil Improvement

Both naturally occurring and artificial water repellent substances have been utilized to improve the physical, chemical, and electrical properties of soils. The properties are improved because these substances improve either aggregation (soil structure) or waterproofing, thereby preventing water from entering the soil and changing its physical properties.

Aggregation—Soil aggregation, which is important for soil structure, is highly dependent on soil wettability. Aggregation occurs when individual soil particles are bound together by naturally occurring or artificial organic compounds (Harris and others 1966). Not only do these organic compounds hold the soil particles together, but the more effective materials stabilize the aggregates by making them water repellent (Hartmann and others 1976, Gabriels and others 1973). Water repellency affects flow in saturated soils by increasing the stability of aggregates, thereby maintaining soil structure (Brandt 1969a). Treating these stable aggregates with a wetting agent causes them to wet up and become less stable (Mustafa and Letey 1969). The stability of aggregates to slaking in water (Yoder 1936) has been recognized as a desirable soil property when evaluating erodibility of different soils (Anderson 1951).

Naturally occurring organic matter increases aggregation and soil stability by reducing swelling and the destructive forces of entrapped air, decreasing wettability, and strengthening the aggregates (Robinson and Page 1950). The mechanism responsible for aggregation in a Krasnozem soil were found to vary among different particle size classes (Coughlan and others 1973). Basic soil properties were important for aggregating the<0.5-mm particles, whereas the hydrophobic properties of organic matter had the greatest effect on aggregate stability in the 0.5- to 5.0-mm size class of aggregates. Above 5.0 mm, binding by plant roots was the most important aggregate mechanism. Organic matter, when modified by microbial growth, can also increase the water stability of soil aggregates (Fehl and Lange 1965).

Organic matter in soils has been customarily considered beneficial to soil structure and related soil properties that affect water movement; however, this concept must be modified in view of our present understanding of water repellency. Previously, organic matter in any amount was assumed to be beneficial to any soil, since organic matter aggregated soil particles and produced a more porous soil structure that allowed water to infiltrate and move more readily through the soil. The current view is that organic matter is beneficial to fine-textured soils because individual mineral particles are aggregated, producing large pores which permit water to move more readily; when not aggregated, the fine soil particles provide small pores which restrict water movement. In a coarse-textured soil, larger particles become packed as single grains so that large pores are produced. These pores are sufficiently large to permit rapid water movement. But when organic hydrophobic substances are added, they increase aggregation only slightly; moreover, these substances coat individual soil particles and restrict, or in some cases completely impede, water movement (Meeuwig 1969). The impermeability of coarse textured soils has been reported as a severe management problem in sandy Australian soils (Bond 1968). Apparently, therefore, undesirable features of water repellency in coarse-textured soils must be balanced against the advantages of water-stable aggregates produced by organic matter in fine-textured soils.

The desirable features of aggregation have led to extensive research of synthetic organic materials as soil aggregating agents. The organic materials most widely applied in aggregation are usually large molecular organic compounds whose structure ranges from well-defined synthetic polymers to complex mixtures of poorly defined and understood products, which are frequently waste products (Schamp and others 1975). These substances are generally referred to as soil conditioners. The wide variety of soil conditioners, their adsorption and adhesion properties, and their effect on water movement are discussed in a comprehensive review by Stewart and others (1975). The usefulness and desirability of these soil conditioners depend, however, on their ability to produce water-stable aggregates.

Waterproofing and Structural Stability—Some engineering applications require that a soil be made essentially waterproof. Although the treatments per se may not improve the physical properties—such as soil strength—they do allow the dry strength of the treated soils to be retained when exposed to water (Brandt 1969b, Hemwall 1963, Hemwall and Bozer 1964, Hemwall and others 1962, Kolyasev and Holodov 1958). Waterproofing has been successful in maintaining the stability of highways exposed to freezing and thawing. If water is permitted to penetrate under the pavement during freezing, a saturated nonfrozen layer is produced over a frozen layer during thaw. When traffic loads are applied to this system, the release of hydrostatic pressure tends to be upward, resulting in pavement blowouts. Waterproofing the layer immediately below the pavement prevents moisture accumulation and subsequent problems. Waterproofing chemicals for this purpose include substituted phenols, long-chain amines, chlorosilanes, and benoxazines (Bozer and others 1969).

Management Problems

Fire-Induced Water Repellency

Any mineral soil containing more than a couple percent of organic matter is likely to become water repellent to some degree when heated. The severity and distribution of water repellency produced by a fire will determine the subsequent management problems on the site.

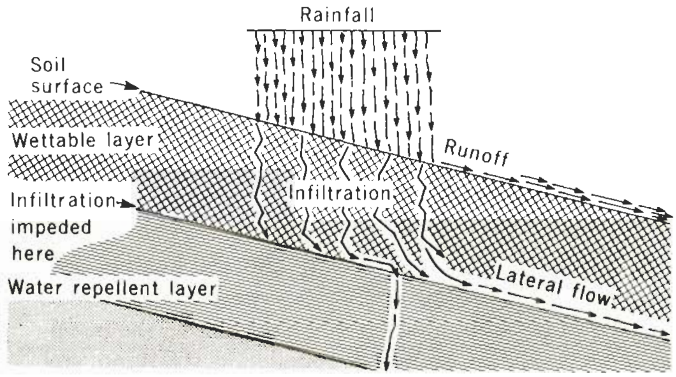

Figure 8—Water repellent layer impedes infiltration and causes surface runoff (DeBano 1969d).

Wildfires burning over coarse textured soil in both forests (DeByle 1973, DeBano 1969, Bashir 1969, Dyrness 1976) and brush areas (DeBano 1969a, 1979; Krammes and DeBano 1965; Reeder 1978; Vogl and Schorr 1972; Salih and others 1973; Wells and others 1979) can produce extreme water repellency. The water repellent soils formed during wildfires in chaparral areas in southern California (DeBano 1969c, 1974; DeBano and Rice 1971, 1973; Cleveland 1973; Foggin and DeBano 1971; Hays 1975; U.S. Department of Agriculture 1971) are considered partly responsible for the high rates of runoff and erosion from burned chaparral areas. On these burned areas, the soil at or near the surface may be wettable beneath which lies a layer of water repellent soil. This layered arrangement allows rainfall to infiltrate only a short distance before the wetting front encounters a water repellent layer (*fig. 8*). If the infiltrating water is impeded, or temporarily slowed down, then the thin mantle of wettable soil becomes saturated. Water then flows laterally and runs off, taking with it the soil from this upper layer along with some of the water repellent layer below. The amount of runoff and debris depends on the continuity and nature of the water repellent layer, steepness of slope, and intensity and amount of rainfall.

Solutions to Fire-Induced Water Repellency—Two methods are applied to manage water repellency caused by soil heating—improved infiltration and prescribed fire. Once water repellency is produced, such as during a wildfire, the management options available for improving infiltration are limited. The most common treatment has been with chemical wetting agents, although on small level areas the water repellent layer could perhaps be broken up by disking (DeBano and Rice 1973).

Prescribed fire, however, affords a more practical method of modifying water repellency by controlling the occurrence and behavior of fire, as opposed to permitting fuels to accumulate and burn by wildfire. Burning conditions could be prescribed in order to minimize water repellency. At present, sufficient knowledge is available about water repellency to develop general guidelines minimizing its impact. Given the less intense the fire, the finer the texture, the wetter the soil, and the smaller the quantities of organic matter on the soil surface, it follows that the less severe is the water repellency produced. These relationships allow prediction of how different soils, fire, and vegetation conditions may affect the production of water repellency.

The differences in fire intensity and soil heating during prescribed burning in forests, compared to brush areas, must be accounted for when predicting the possible impacts of fire on water repellency (DeBano and others 1979). Soil heating during brush fires is usually more severe than prescribed burns in forests, for several reasons (DeBano 1979). Both prescribed fires and wildfires are carried by the canopy and standing dead stems which leads to rapid and intense combustion, even during cooler prescribed fires in brush. In contrast, prescribed fires in forests are designed to minimize damage to standing trees (Biswell 1975) and are applied during moister conditions which restrict the fire to dead fuels. Chaparral fires usually burn only under drier conditions, when the live fuel moisture is low, so consequently both dead and live fuels are consumed during burning. Usually, the litter layer present in chaparral is thin, providing less efficient insulation against heat radiated downward during a fire. The forest floor duff and litter layer is normally thick, enhancing insulation against heat from fire. Consequently, chaparral fires create temperatures at and beneath the soil surface which generally are higher than corresponding temperatures caused by prescribed fires in forests (DeBano and Rice 1971).

Changes in chemical, physical, and biological properties of soils are minimized when less soil heating occurs. Water repellency problems are therefore less likely to develop after prescribed fires in forests; conversely, a higher incidence of water repellency is more likely to occur in chaparral areas. Several studies of prescribed burning in forests support this relationship. The broadcast burning of slash over a wet medium or fine textured soil did not produce enough water repellency to present a problem (DeByle 1973); however, in some ponderosa pine areas, even light prescribed burning can reduce significantly the initial infiltration rates (Zwolinski 1971). In some cases, light intensity fires may only concentrate water repellency in litter, thereby producing a negligible effect on the soil (Agee 1973). In chaparral areas, fire intensity may be decreased by burning during cooler times of the year when humidities are higher. Burning when the soils are moist would also minimize water repellency problems (DeBano and others 1976).

Treating the water repellent layer to make it wettable, such as with a wetting agent, reduces both runoff and erosion. Experiments on burned areas in southern California showed that runoff from untreated plots ranged from 4 to 10 cm during seasons when rainfall varied from 18 to 97 cm (Krammes and Osborn 1969). By comparison, plots treated with wetting agents yielded only 2- to 7-cm runoff under the same rainfall. Erosion was also reduced by about 40 percent with the wetting agent treatment. Although wetting agents were effective on small plots, they were extremely expensive and difficult to apply successfully on large areas (Rice and Osborn 1970). At present, the best solution seems to be prescribed fire—by burning with a light intensity fire or when the soil is moist—so that formation of water repellent soil is minimized.

Vegetation Management and Plant Establishment

Turf, Pasture, and Crop Management—The effect of water repellency on vegetation management was first described as the fairy ring phenomenon (Bayliss 1911, Shantz and Piemeisel 1917). This condition produces unsightly circular-shaped bare areas in otherwise healthy turf and lawns (Wilkinson and Miller 1978). Early folklore attributed these bare areas to the paths of dancing fairies, places where the devil churned his butter, the habitat of enormous toads with bulging eyes, and places where treasures were buried. Notwithstanding mythology, bare spots are actually places in the soil where dense fungal mycelia proliferated. The mycelia stimulate growth of grass for a short time which quickly exhausts the soil moisture. Once the soil is dry, the fungal growth prevents rewetting, that is, the soil becomes water repellent. An intense drought then kills the grass, leaving the area bare and subject to an invasion of weeds.

These fairy rings pose special and serious problems to the turf grass industry because a uniform, velvety green grass is esthetically desirable (Waddington 1969). Various preventive and corrective measures have been used to treat these localized dry spots. These practices are usually limited to cutting the grass short on putting greens, although aerating tools also have been used to break through the thatch and soil surface to improve uniformity of wetting. Topdressing with a good soil mixture, applied alone or in combination with mechanical aeration, has also been shown to decrease the incidence of these dry spots. Another approach improves the uniformity of wetting by applying wetting agents.

In Victoria, South Australia, and western Australia, water repellent soils present a problem in coarse-textured soils covering thousands of hectares (Bond 1960, 1964, 1965, 1968; Bond and Harris 1964). The soils in these Australian states support a grass cover on an annual rainfall of 64 cm or less. The pastures look patchy where well-grassed areas alternate with bare areas over small distances. Closer examination reveals that moisture penetrates only the grassed areas; the intervening bare patches are dry. These areas remain dry, even after rainstorms because the soil is extremely water repellent. The organic substances responsible for this water repellency are produced by microorganisms, particularly the basidiomycetes group of fungi (Bond and Harris 1964). Irregular wetting causes uneven germination and a patchy, less productive pasture. Various tillage techniques are currently in use to reduce the effects of the repellency on crops and pastures (King 1974b). Cultivation during the rainy season sufficiently increases water entry to allow germination and growth. Another successful ameliorative measure involves sowing cereals and pastures in furrows where rainwater can concentrate (Bond 1972).

Plant Diseases—Water repellency is indirectly responsible for a disease called citrus decline. During droughts in Florida (Jamison 1942, 1946, 1947) and Egypt (Bishay and Bakhati 1976), older trees in citrus groves sometimes drop their fruit, even after irrigating. The irrigation water wets only a small part of the soil in the root zone beneath the branches. Organic material in the surface horizon was found to resist wetting. The surface layer under the tree crown therefore acts like a roof, shedding water to the wettable soil beyond the leaf drop areas where it is less available to the tree roots. Treating the soil with polyacrylamide, a soil conditioner, increased soil-water relations and improved the condition (Bishay and Bakhati 1976).

Seed Germination and Plant Establishment—Water repellent soils can affect plant establishment on an area by reducing the amount of water available for germination and growth or inducing overland flow and erosion which carries the seeds off the site before they can germinate and become established. Laboratory experiments using ryegrass have verified that germination and establishment can be severely restricted by water repellent soils and sands (Osborn and others 1967, Osborn 1969). The reduction in plant establishment was most severe when the test containers were placed on a 30-percent slope, at which angle the runoff was more abundant than in a level position, thereby reducing the amount of water available for germination. Treating the sloping soils and sands with wetting agents increased germination of the ryegrass and decreased runoff. Although wetting agents favor ryegrass establishment, it may be at the expense of other plant species. For example, a study by DeBano and Conrad (1974) showed that when a wetting agent was applied to a burned chaparral watershed, germination and growth of ryegrass was favored, but it had a deleterious effect on mustards.

The resistance of forest litter to wetting may be responsible for poor germination of important tree species. Tests using *Sequoiadendron giganteum* seeds showed that when the litter surface resists wetting and dries quickly, a poor seedbed is produced (Stark 1968). The best condition for germination was found to be disturbed mineral soil in the shade.

Other Problems

Water repellent soils are created by the heat from campfires (Fenn and others 1976). This condition appeared only in sandy soils which were initially moist and whose temperature remained below 350° C during the campfire burn. If campfires were located randomly throughout the campsite, the harmful effect could be spread over a large part of the campground. Therefore, the harmful effect could be minimized if, as recommended, the campfires were restricted to the same area, even when permanent concrete fireplaces could not be installed; stone fire rings in a chosen location can accomplish the same objective.

RESEARCH NEEDS

Formation and Occurrence of Water Repellent Soils

Research of southern California chaparral has contributed substantially toward an understanding of water repellency and the relationships which exist between soil heating and organic matter, soil texture, and soil-water content. Future research should continue verifying and refining these relationships in other vegetation types. Moreover, water repellency measurements should be considered an integral part of fire-related studies. To this end, water repellency should be viewed in relation to other pertinent plant, fire, and soils data collected during fires.

A large gap exists in our understanding of microbially produced water repellency in chaparral, although the subject has been studied in other vegetation types. Microbially produced water repellency undoubtedly is present in chaparral and may function as part of the long-term ecological and successional aspects of this ecosystem, although little is known about this role. Future research in chaparral ecosystems perhaps will uncover some of the functional relationships governing the role of water repellency in mature chaparral stands.

Only a limited amount of information is available on the distribution of water repellent soils on wildland areas in the western United States (DeBano 1969a). A detailed survey of water repellent soils in California is however currently in preparation and will provide detailed information on the distribution of water repellency in California as related to the soil classification system used in the United States.

Chemistry of Hydrophobic Substances

Several research studies have examined the chemistry of both naturally occurring or fire-related hydrophobic substances, but this research has not revealed the detailed chemical make-up of the substances responsible for water repellency in unburned soils. The chemistry of hydrophobic substances produced by the heating of organic matter becomes more complex because an infinite number of organic compounds can be acted upon by fire to produce long chain, aliphatic hydrocarbons responsible for fire-induced water repellency. The difficulty in determining the complex chemical identity of the hydrophobic substances responsible for fire-induced water repellency probably restricts future studies in this area.

Soil-Water Movement

The theoretical principles underlying water movement in soils containing hydrophobic substances are adequately established. Currently, the largest gap in our knowledge is the application of these basic theories to a large-scale field situation where they can serve to describe the hydrology of entire watersheds or other management units. Logically, the first step in applying these basic principles to a watershed involves characterizing water repellency as a three-dimensional flow process, affected by three major features of the water repellent soil—intensity, thickness, and continuity of the water repellent layer. Any sampling procedure which is devised to quantify these features must necessarily be simple and not require excessive field sampling. In the simplest sampling scheme, the soil profile is merely exposed after a rainstorm, or an infiltrometer trial is made, and the horizontal and vertical distribution of the water repellent layer is mapped. Alternatively, a rapid sampling procedure could be developed by utilizing a few known relationships. For example, water repellency is restricted to areas where the surface of the soil is covered with heavy litter or where the subsoil layers contain decomposing roots. Knowledge of these relationships allows the thickness and intensity of the water repellent layer to be characterized easily and quickly at several locations by the waterdrop penetration time or critical surface tension. The thickness and intensity, once obtained, can be combined with plant cover data to develop a water repellency index for the site. Finally, the site index and pertinent hydrologic variables affecting runoff, such as slope, cover, drainage, and size, could be related to runoff on small plots or watersheds.

Vegetation Establishment and Growth

The germination and establishment of seedlings are affected by water repellent soils. Differences in competition between native and introduced species in water repellent soils particularly needs further study. The seeds of introduced species, mainly grasses, are easily moved downslope and tend to accumulate in small sheltered areas throughout the reseeded area. Native annuals, although sometimes irregularly distributed, apparently are not translocated as easily and are better able to seek out the discontinuities in the water repellent layer and become established, perhaps because they are covered more deeply by duff or soil. The resprouting perennial species probably are not affected directly by water repellency immediately after a fire. Although not yet studied, water repellency conceivably may affect the long-term ecology and water relations of chaparral ecosystems.

Runoff and Erosion

The relationship between erosion and water repellency is understood to some measure. When water repellent soils are treated with a wetting agent, runoff and erosion are usually reduced significantly because infiltration is more rapid; however, only a few cursory examinations of the wetting patterns of plots treated with wetting agents have been made. If wetting agent treatments are considered usable, the water transmitting ability of the soil profile in response to treatment must be better characterized; but, wetting agents currently are too expensive and logistically unsuited for wide scale application.

Runoff and erosion produced by water repellent soils probably contain large quantities of important plant nutrients. After a fire, the ashy soil surface contains a high concentration of highly soluble nutrients (DeBano and Conrad 1978). Surface runoff or downslope movement of debris undoubtedly carry nutrients, but only a few measurements of nutrient loss have been made during past studies (DeBano and Conrad 1976). Neither short- nor long-term nutrient losses have been related to the role of water repellency in the ecology of chaparral stands.

Research Needs in Southern California

Several water repellency problems remain unsolved; however, not all of these problems are of equal importance in terms of current management objectives for chaparral areas in southern California. A chief concern of current research in southern California is fuel modification and fire as a management tool. Because the regular use of fire is planned, special attention must be given to fire-related processes, for example, water repellency, nutrient loss, plant succession, runoff, and erosion. The priority issue confronting research is to characterize water repellency on a large-scale watershed basis in relation to runoff and erosion. A series of studies which would shift in scope from small plots to larger areas, and finally to watersheds would provide data relevant to developing and verifying a method for assessing water repellency on large areas. Such research, moreover, could be easily achieved within the context of concurrent studies on erosion and nutrient loss.

The prescribed burning studies would also provide excellent field testing of the interrelationships between water repellency, soil texture, soil water, and fire intensity. With minimal effort, evaluations could be made of changes in water repellency during fire. These changes could then be related to variables measured as part of an already instrumented prescribed fire.

Research Needs in Australia

The future research activities by Australian researchers have been reviewed by King (1974b). Research aimed at wetting the water repellent sand near seed and improving the wettability of turf on bowling greens and golf courses is planned. An intensive mapping of problem areas is also under consideration. Evaluations are being made of surfactants, soil aggregating compounds, and different plant species as possible means of improving soil wettability. Finally, improving the productivity of these lands can be expected only by imposing a regime dedicated to reversing the deleterious effects of nutrient deficiencies, plant pathogens, water imbalances, erosion, and other yield-limiting factors.

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