Forest Service - U.S. Department of Agriculture

Soil Wettability and Wetting Agents...

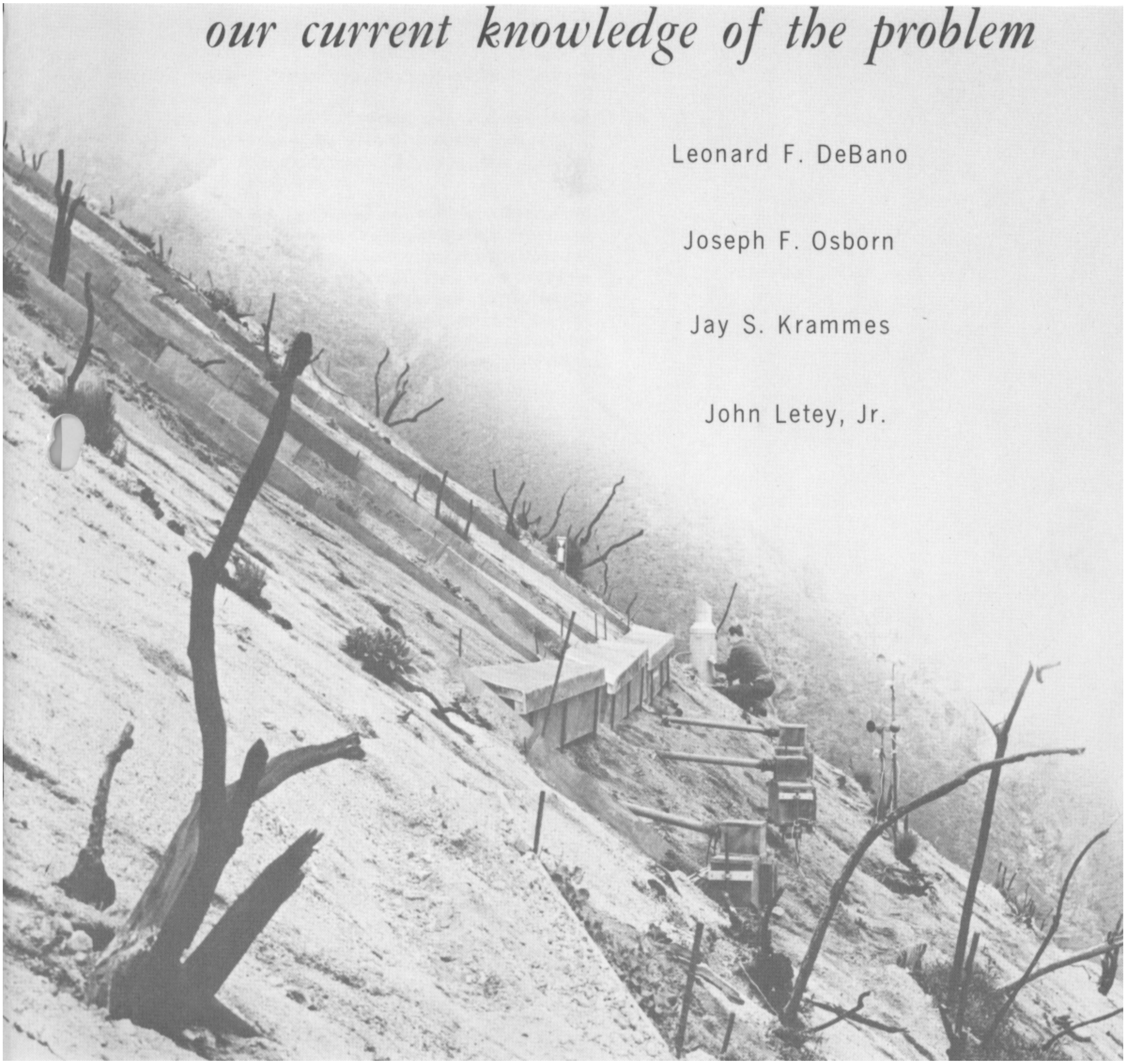
our current knowledge of the problem

Leonard F. DeBano

Joseph F. Osborn

Jay S. Krammes

John Letey, Jr.



U.S. FOREST SERVICE RESEARCH PAPER PSW-43 1967

Pacific Southwest Forest and Range Experiment Station

P 0 Box 245, Berkeley, California 94701

DeBano, Leonard F., Osborn, Joseph F., Krammes, Jay S., and Letey, John, Jr.

1967. **Soil wettability and wetting agents . . . our current knowledge of the problem.** Berkeley, Calif., Pacific SW. Forest & Range Exp. Sta. 13 pp., illus. (U.S. Forest Serv. Res. Paper PSW-43)

Soils that resist wetting are a widespread phenomenon on chaparral areas of southern California watersheds. On burned watersheds, non-wettable soils markedly reduce moisture movement during both evaporation and infiltration. The reduced infiltration rate probably contributes significantly to the high debris production from the watersheds. Factors involved in the formation of non-wettable soils include vegetation and soil temperatures during fire. Wetting agents applied to burned areas apparently help retard debris movement and enhance vegetation establishment.

Oxford: 114.123 :116.25 :116.6

Retrieval Terms: soil formation; fire effects; soil erosion control; soil wettability; wetting agents; saturation resistance; infiltration rate; hydrophobic soil. Line Project: 1605.

DeBano, Leonard F., Osborn, Joseph F., Krammes, Jay S., and Letey, John, Jr.

1967. **Soil wettability and wetting agents . . . our current knowledge of the problem.** Berkeley, Calif., Pacific SW. Forest & Range Exp. Sta. 13 pp., illus. (U.S. Forest Serv. Res. Paper PSW-43)

Soils that resist wetting are a widespread phenomenon on chaparral areas of southern California watersheds. On burned watersheds, non-wettable soils markedly reduce moisture movement during both evaporation and infiltration. The reduced infiltration rate probably contributes significantly to the high debris production from the watersheds. Factors involved in the formation of non-wettable soils include vegetation and soil temperatures during fire. Wetting agents applied to burned areas apparently help retard debris movement and enhance vegetation establishment.

Oxford: 114.12 3 :116.2 5 :116.6

Retrieval Terms: soil formation; fire effects; soil erosion control; soil wettability; wetting agents; saturation resistance; infiltration rate; hydrophobic soil. Line Project: 1605.

Contents

The Authors

LEONARD F. DEBANO heads the Station's research on improving water yield in brushlands, with headquarters at Glendora, Calif. He holds the following degrees: B.S., in range management and forestry (Colorado State University, 1955); M.S., in range management (Utah State University, 1957); and Ph.D., in soil science (University of California, 1966) . He joined the Forest Service in 1962.

JOSEPH F. OSBORN joined the staff of the University of California in 1955 as a laboratory technician, serving first on the Los Angeles campus and now on the Riverside campus. He received a B.S. degree in soil science (1955) from California State Polytechnic College.

JAY S. KRAMMES is studying hydrologic processes and ways of reducing floods, erosion, and sediment. He earned a bachelor's degree (1958) in forestry and a master's degree (1963) in watershed management from Montana State University. Since 1958 he has been on the research staff of the Pacific Southwest Station's San Dimas Experimental Forest, near Glendora, Calif.

JOHN LETEY, Jr., has been on the University of California faculty since 1959, first as an assistant professor of soil physics on the Los Angeles campus and (since 1961) as an associate professor of soil physics on the Riverside campus. A 1955 agronomy graduate of Colorado State University, he also holds a doctorate in agronomy (1959) from the University of Illinois.

Since the early 1960's, researchers have been studying a novel soil property — one considered important in the hydrology of watersheds in southern California brushlands. These watersheds have some soils that are hydrophobic, water-resistant, or—as we call it in this paper—non-wettable.

Until now, studies of soil non-wettability have been concerned with (a) factors responsible for its formation, (b) methods for quantitatively characterizing it in soils and plant materials, (c) its effect on moisture movement during infiltration and evaporation, (d) remedial treatments for reducing it, and (e) its effects and that of wetting agents on vegetation establishment. This paper summarizes some of the most significant findings to date on the problem of soil non-wettability.

Problem of Soil Non-Wettability

In the past, researchers at the San Dimas Experimental Forest, near Glendora, Calif., were puzzled by their "dusty tracks in the mud" as they trudged across freshly burned watersheds after fall and winter rains. They attached little significance to their observations for a number of years until researchers at the University of California, Los Angeles, became concerned with the problem of water-resistant soils. The research staff consisted of Arthur Pillsbury, John Letey, Jr., Joseph Osborn, and Robert Pelishek. This group was first concerned with developing a method of measuring the non-wettable property of various "problem soils." These scientists demonstrated that a large variety of soils can become resistant to wetting.

The recognition of soil non-wettability leads to a plausible explanation for the earlier observations made at the Experimental Forest. A closer examination of the soil profile on burned watersheds after rainstorms revealed that the soil wetted unevenly. The soil at or near the surface could be saturated, but present a few inches downward was an air-dry layer. Below the air-dry layer was another damp or moist layer. In some places, this layered arrangement was continuous over extended areas, while in others it occurred in patchy irregular patterns. When water droplets were placed on soil material taken from the air-dry layer, the droplets did not penetrate, but instead "balled-up" *(fig. 1)*. These observations provided an explanation of the "dusty tracks in the mud." Researchers reasoned that the mud collecting on their boots came from the wet upper soil layers, while the dusty footprints represented the exposed portions of a non-wettable soil layer.

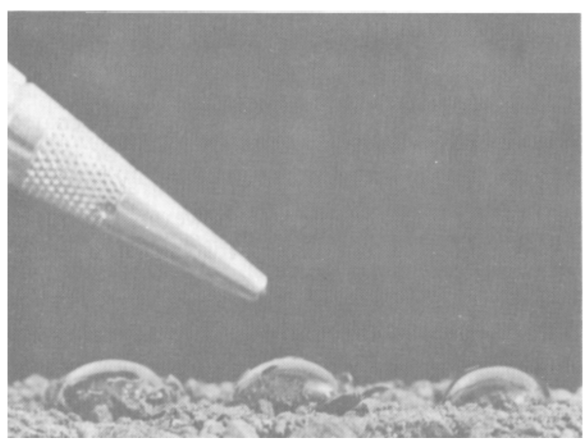


Figure 1.—*Water droplets on a non-wettable soil showing their "balled-up" appearance.*

Soil non-wettability appears to be widespread throughout wildland areas in the Western United States. It has been detected in California, Utah, Arizona, and Colorado. Its areal distribution outside of southern California has not as yet been fully determined. Non-wettable soils have also been reported in Florida (Jamison 1946), New Zealand (Van't Woudt 1959), and Australia (Bond 1964; Bond and Harris 1964). The problem seems particularly acute in chaparral brushlands of southern California. For example, a survey of the brushland areas on the San Dimas Experimental Forest and nearby areas suggested that 60 percent of the areas sampled had non-wettable soils (Krammes and DeBano 1965).

Resistance to wetting can be found on both burned and unburned watershed areas, although it is more pronounced on burned areas. Since 1963, several freshly burned brushland areas in southern California extending from Santa Barbara to San Diego have been studied for non-wettable soils. Non-wettability of various degrees were found in soils in each of these areas. In some areas, non-wettability occurred in rather irregular patterns which corresponded to a former sparse vegetation canopy and was most readily detectable near the charred remnants of brush stems. In other areas, a more uniform layer of non-wettable soil could be detected.

The widespread occurrence of soil non-wettability in chaparral brushlands represents a problem affecting thousands of acres in southern California. Wieslander and Gleason (1954) estimated that southern California has about 3.8 million acres of chaparral brushland areas. If between 1/60 and 1/30 of this acreage burns each year, then potentially 38,000 to 76,000 acres of non-wettable soils could be produced annually. This estimate assumes that 60 percent of the burned chaparral watersheds are characterized by non-wettable soils. The degree of non-wettability in these brushlands probably varies according to vegetation species, fire history, physical and chemical properties of the soil, and numerous interrelated environmental factors.

Effect of Hydrophobic Substances

The presence of water repellency in soils affects the wetting properties of the soil. The impedance to wetting has important effects on moisture movement and the subsequent hydrology of watersheds. The most apparent hydrologic effects involve (a) the reduction of infiltration which induces erosion by overland flow, and (b) modified evaporation of water from the soil profile.

Wetting Phenomena in Soils

Soil scientists generally agree that porous materials, such as soils, have a high absorptive capacity for water. Usually, when water is applied to coarse textured soils either as natural rainfall or irrigation, it will readily penetrate and infiltrate into the soil. In the non-wettable soil, however, this rapid penetration does not occur. Instead, if a water droplet is placed on the surface of these non-wettable soils, it will not be absorbed but will "ball-up" and remain on the soil surface *(fig. 1).* How long the water droplet remains on the soil surface before being absorbed depends upon the degree of soil non-wettability. In a slightly non-wettable soil, the water droplet is impeded only for a short time before being absorbed by the soil. If non-wettability is extreme, however, then the water droplet may never penetrate the soil surface but instead may evaporate.

The affinity or repellency of a surface for water originates from the attractive forces between water and solid surfaces. If the attraction between water and a solid surface, such as that of a soil particle, is greater than the attraction between individual water molecules, then water will spread out and be adsorbed on the solid surface. In a wettable soil, a strong affinity exists between soil particles and water. When the soil particles repel water, however, the attraction between water molecules are greater than that between the water and the solid surface. And the water will "ball-up" rather than penetrate the soil. The latter effect is apparent in the non-wettable soils described in this paper.

The angle between a water droplet and a solid surface has been used to characterize soil non-wettability. This characteristic is commonly referred to as the wetting angle. When a water droplet is placed on a hydrophobic surface the wetting angle is larger than the angle made on a hydrophilic surface *(fig. 2)*. In soils literature, the angle is also called the liquid-solid contact angle. In porous media, the wetting angle is calculated from

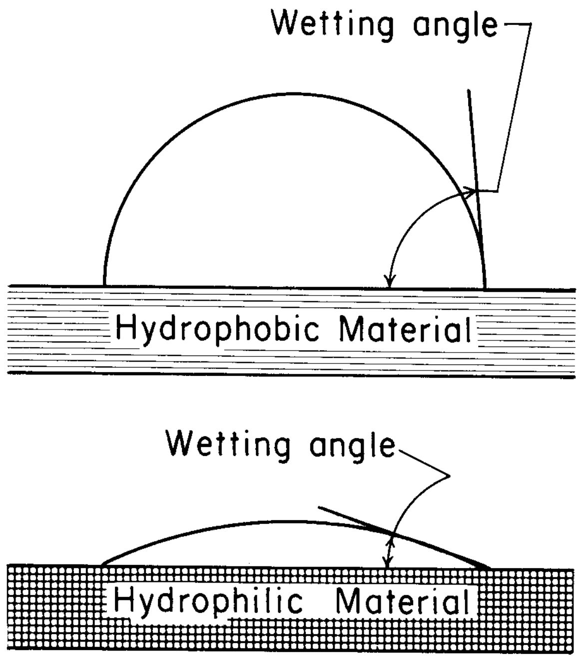


Figure *2.—The wetting angle, or angle between a water droplet and a solid surface, is much greater on hydrophobic surfaces than on hydrophilic surfaces.*

a capillary tube model and refers to the apparent angle the water meniscus makes with the pore wall. The literature on soil-water systems usually assumes that the liquid-solid contact angle is zero. But work by Letey *et al.* (1962a, 1962b) indicates that even in a wettable soil, the angle can be much larger than zero. For non-wettable soils, larger angles up to and exceeding 90 degrees have been measured.

Moisture Movement

The movement of water through soil generally occurs by two processes: saturated and unsaturated flow. Saturated flow occurs when the entire soil pore space is filled with water. Water flows through a soil in response to differences in water potentials. The nature of the solid surface affects saturated flow primarily by frictional resistance developed between the moving water and the particle surface. Saturated flow is regulated chiefly by the geometry of the saturated pores and by the liquid properties of the solution passing through the soil.

In unsaturated soils, water flows in response to the attraction forces between the soil particles and the water molecules. This attractive force is sometimes cast in terms of free energies. Thermodynamically, soil moisture moves from regions of high free-energy to those of low free energy. The attraction forces between the water and the soil can be represented by the apparent wetting angle. Therefore, because the attractive forces between the hydrophobic particle surfaces and the water molecules are less, flow rate is consequently reduced.

Evaporation

Hydrophobic substances tend to reduce evaporation from soils and sands. For example, a wettable sand made non-wettable by ammonium hydroxide extracts of chaparral litter lost 45 percent of its water after 400 hours of evaporation. In contrast, an untreated wettable sand lost 60 percent of its water during the same period (Letey, *et al.* 1962a). Both the wettable and the non-wettable sands were saturated before evaporation was started. A dry mulch layer forming at the surface was believed responsible for the lower evaporation.

Recent studies of a sandy loam on the San Dimas Experimental Forest have substantiated that non-wettable substances reduce the rate of evaporation. We obtained a non-wettable soil by using the less-than-2 mm. fraction of a naturally occurring non-wettable soil collected from a burned area of the San Gabriel Mountains. A similar textured wettable soil was prepared by heating the water-resistant soil in a muffle furnace to destroy the substances producing non-wettability. Evaporation was allowed to occur in the laboratory from soil columns packed with either wettable or non-wettable soil.

Cumulative evaporation was less from columns packed with non-wettable soil than from those filled with wettable soil *(fig. 3).* Water loss was less from non-wettable soil at the start, and the difference in evaporation became greater with time. Soil moisture distribution after the 109 days of evaporation *(fig.* 4) could explain the differences in evaporation rates. in the columns containing only wettable soil, moisture was withdrawn from all depths. In contrast, in those with non-wettable soil, the moisture was depleted primarily from the upper part of the soil column. These moisture profiles indicate that moisture moves slowly in the non-wettable soil, and water cannot be readily transmitted to the surface where it is evaporated.

Infiltration

Infiltration is also reduced by the presence of hydrophobic substances. The reduction is particularly pronounced in soils containing a non-wettable

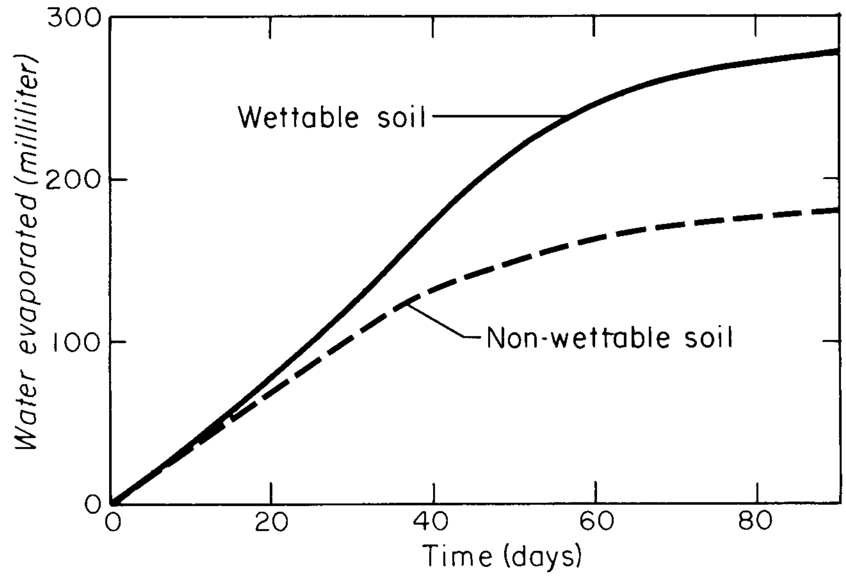


Figure 3. — *Cumulative evaporation over time from soil columns containing only wettable or non-wettable soil.*

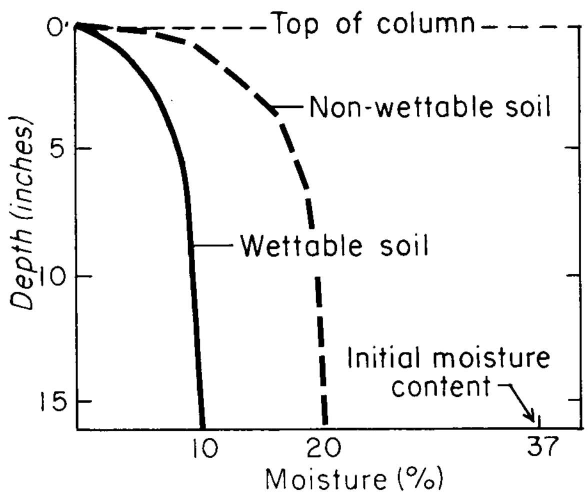


Figure 4.—*Soil moisture distribution in soil columns containing only wettable or non-wettable soil after evaporating for 109 days.*

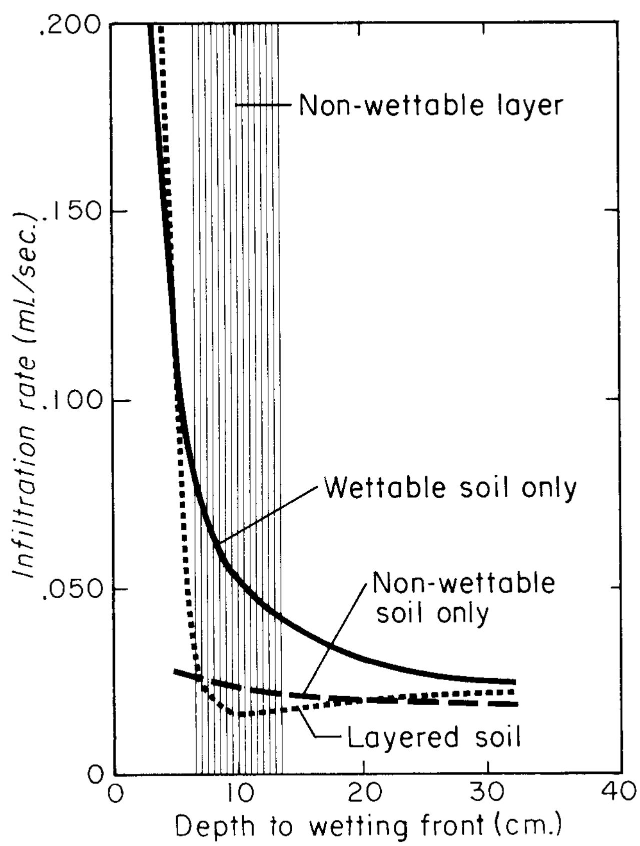


Figure 5.—*Infiltration rate when the wetting front approached different depths in soil columns packed with only wettable soil, non-wettable soil, or layered soils.*

layer below the soil surface. The effect of a non-wettable layer on infiltration can be illustrated by the results obtained from one of our laboratory infiltration experiments *(fig. 5).* One set of plastic columns was packed with only wettable soil. A second set was packed with only non-wettable soil. The third set was packed with wettable soil but had a 6 cm. layer of non-wettable soil at 7 to 13 cm. below the top of the column. The data show that the infiltration rates in the layered columns and in those containing wettable soil only were similar until the wetting front approached a depth

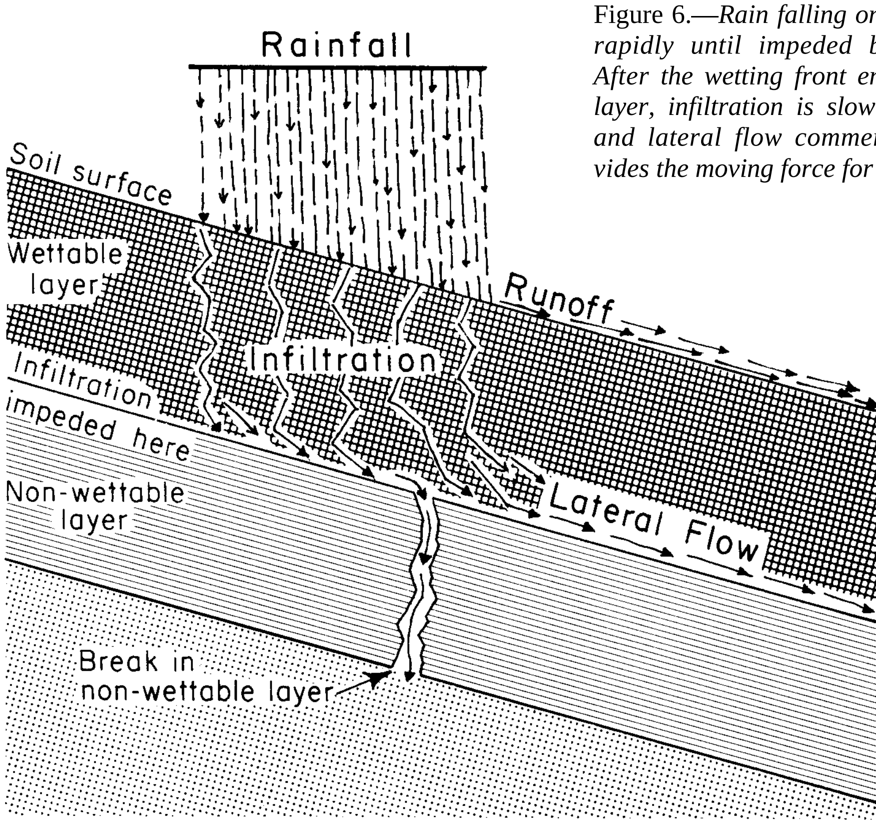


Figure 6.—*Rain falling on the soil surface infiltrates rapidly until impeded by a non-wettable layer. After the wetting front encounters the non-wettable layer, infiltration is slowed up, and surface runoff and lateral flow commences. Surface runoff provides the moving force for soil erosion.*

of 6 cm. When the wetting front approached the non-wettable layer in the layered columns (at about 6 cm.), the infiltration rates dropped below the infiltration rates in the columns packed only with non-wettable soil. When the wetting front had passed below the non-wettable layer, infiltration rates increased slightly and maintained a rate similar to that in the non-wettable soil, although the wetting front was again in wettable soil. These results suggest that the non-wettable layer decreased infiltration after the wetting front has passed through the non-wettable layer and was moving through the underlying wettable soil.

The results of the laboratory experiment probably represent the relationship which could be expected in field soils having a non-wettable soil layer. The degree of impedance of the non-wettable layer probably depends upon both the degree of non-wettability and the thickness of the non-wettable layer. In case of extreme non-wettability, it is possible that infiltration could stop completely when the wetting front encountered the non-wettable layer.

Brushland Hydrology and Erosion

Runoff and Debris Movement

The presence of a non-wettable soil layer could be partly responsible for the high surface runoff and erosion which occur during fall rains on freshly burned areas in southern California. The soils may be of particular importance where high surface runoff and debris movement occur after relatively small amounts of rainfall. High debris movement on freshly burned areas resulting from small rainstorms is a common phenomenon in southern California. Associated with the large debris movement are many rills on the eroded surface.

We can offer a plausible hypothesis on the effect of soil non-wettability on runoff *(fig. 6).* Incoming rainfall infiltrates only a very short distance before the wetting front reaches the non-wettable layer. For example, if the upper part of the non-wettable layer is 2 inches below the soil surface and the overlying wettable layer holds a maximum of 30 percent of moisture before becoming saturated, then less than 1 inch of precipitation is needed before runoff would occur if the wetting front was impeded by a non-wettable layer. After downward infiltration has stopped or been impeded, both lateral flow as well as surface runoff occurs. The runoff and lateral movement from this upper layer along with portions of non-wettable material removed by runoff could be an important source of debris production from freshly burned areas.

Recent research indicates that the debris production can be reduced by remedial treatments with wetting agents. The studies showed debris movement was reduced after storms as large as 6.16 inches with intensities up to 1.35 inches per 20 minutes.

Dry-Creep Erosion

The material accumulating in debris cones is usually non-wettable. Fairly coarse textured and sandy, it moves primarily under the influence of gravity during the summer months and extended dry periods between winter storms.

This dry-creep phenomenon may be related to a less dense packing density of the non-wettable soil. Our laboratory studies show that materials treated with hydrophobic materials to make them non-wettable do not pack as dense as before treatment. In general, the greater the degree of non-wettability produced, the less dense the air-dry material will pack under similar packing procedures, with a mechanical packing machine.

Further, densities recorded in the field have shown that non-wettable soils are less dense than comparable wettable soils from the same area. The difference in bulk densities between wettable and non-wettable soils on the sloping hillsides may be important in dry-creep erosion. A reduction in surface density would imply less individual particle contact at the surface and therefore less resistance to surface movement. On slopes approaching the angle of repose, a lower resistance to surface movement in a non-wettable soil may lower the angle at which dry creep occurs. This reduction in the angle of repose may be small, but on the steep mountainous topography of southern California the acreage and amount of debris involved could be quite large.

Some investigators have noted that non-wettable soils appear to "fluff up" after rainfall. These non-wettable soil particles do not draw together upon evaporation as do the wettable particles. As the moisture evaporates, the cohesive and adhesive forces of the water and a wettable surface tend to draw one to the other. But such is not the case between water and non-wettable surfaces because adhesive forces between the water and non-wettable surface are low. Therefore, rainfall or misting may in fact increase dry creep patterns where non-wettable soil particles are present and reduce dry creep on wettable surfaces.

Moisture Disposition

Our laboratory studies have indicated soil non-wettability may affect the disposition of moisture in the soil. These studies were concerned with the effects of non-wettability on infiltration into layered soils and evaporation from columns filled with only wettable or non-wettable soil. In the columns packed with only wettable or non-wettable soil, evaporation was less in the non-wettable soils. Likewise infiltration was impeded by the presence of a non-wettable layer located below a layer of wettable soil.

In nature, soil non-wettability is found in a layered arrangement. It is possible that this layered condition could either increase or decrease evaporation under field conditions. There is probably a decrease when moisture movement is impeded by the non-wettable layer.

In contrast, a non-wettable layer could increase evaporation under certain climatic conditions. For example, consider the case in which precipitation occurs in increments of 2 inches or less, and the rains are interspersed by periods of warm weather conducive to evaporation. This is a common sequence in southern California during winter when Santa Ana wind conditions follow rainstorms. In a soil having a non-wettable layer within a few inches of the soil surface, the water may be held near the soil surface rather than percolate downward in the soil profile. This situation produces a nearly saturated soil layer at the surface. And when the layer is exposed to highly evaporative conditions, it is conducive to large soil moisture losses. Therefore, larger evaporation losses would be expected than if this layer were not present so that the water could move downward and distribute itself deeper in the soil profile. In the latter situation the surface soil would contain less water and should therefore lose less by surface evaporation.

The application of wetting agents as remedial treatments complicates the possible evaporation relationships we have suggested. Wetting agents should increase capillarity in the non-wettable soils and thereby improve moisture transmission through the non-wettable layer. The end result should be an increase in evaporation. But preliminary laboratory experiments suggest that this may not be the case. In columns filled with non-wettable soil, those treated with wetting agents did not evaporate more than those left untreated. In contrast, wetting agents can reduce evaporation in wettable soils. The reduced evaporation in wettable soils is similar to that produced by such evaporation suppressants as hexadeconal. The results would indicate that from the standpoint of evaporation, the application of wetting agents may be desirable.

If an area has a high proportion of wettable soil, the benefits from evaporation may be outweighed by the reported drop in infiltration into wettable soil treated with wetting agents (Pelishek, *et al.* 1962). But the full effects of wetting-agent treatments cannot be determined accurately until more detailed research is done on the effects of such treatments on evaporation and infiltration in both wettable and non-wettable soils.

Factors Affecting Non-Wettability

Soil non-wettability is probably produced by a number of soil, climatic and vegetation factors, although not all of them have been isolated. Our research to date has been concerned with only a few factors. At present, the two factors best understood are vegetation and fire.

Vegetation

The primary source of non-wettable substances appears to be organic substances produced by brush species. These substances apparently coat soil particles and render them non-wettable. Substances responsible for producing non-wettability have been extracted from both plant litter and plant parts. For example, Letey *et al.* (1962a, 1962b) reported that extracts (both water and ammonium hydroxide) of chaparral litter can produce non-wettability in formerly wettable sands. In their studies, samples of wettable sand were treated with extracts of organic litter material. When dried, the treated sand demonstrated a marked resistance to wetting. Experiments at San Dimas have confirmed that extracts from plants as well as from non-wettable soil samples can induce non-wettability in sands. In general the extracts were obtained from soil samples which contained large amounts of organic material.

Work in Australia (Bond 1964; Bond and Harris 1964) indicated that fruiting bodies of actinomycetes contain hydrophobic substances. Microbial processes may also be involved in the decomposition of the organic plant material and the subsequent formation of non-wettable substances in our area. But the dry semi-arid conditions existing in southern California probably are not conducive to high rates of microbial activity.

In studies at San Dimas, we found that non-wettable substances originate from both fresh plant material and decomposition products of litter. We are seeking to develop a system for rating species according to their potential for producing non-wettable substances. The procedure involves extracting a given weight of plant material with 0.1N NH_4OH solution and then saturating a wettable sand with this extract. After the material has dried, data on capillary rise in the sand are used to determine wetting angle of water in the treated sand. The wetting angle is then used to rank the various plants and plant parts according to their potential for producing non-wettability.

Preliminary results indicate that chamise *(Adenostoma fasciculatum)*—specifically leaf material—contains large amounts of hydrophobic materials *(table 1).* In general, the leaves of all species tested—except sugar bush *(Rhus ovata)* plants—produced a greater degree of non-wettability than did the stems.

Fire

Soil non-wettability appears closely related to fire temperatures. DeBano and Krammes (1966) found that soil non-wettability may be intensified or destroyed by heating soil samples at different

Table 1.--*Plants ranked, in descending order, according to potential for producing non-wettability,* as *determined by wetting angle of water in treated sand*

Plant	Part	Wetting angle
		Degrees
Chamise (*Adenostoma fasciculatum*)	Leaves	82
	Stems	79
Mountain mahogany (*Cercocarpus betuloides*)	Leaves	80
	Stems	77
Scrub oak (*Quercus dumosa*)	Leaves	76
	Stems	75
Deer brush (*Ceanothus* spp.)	Leaves	72
	Stems	73
Sugar bush (*Rhus ovata*)	Leaves	60
	Stems	67

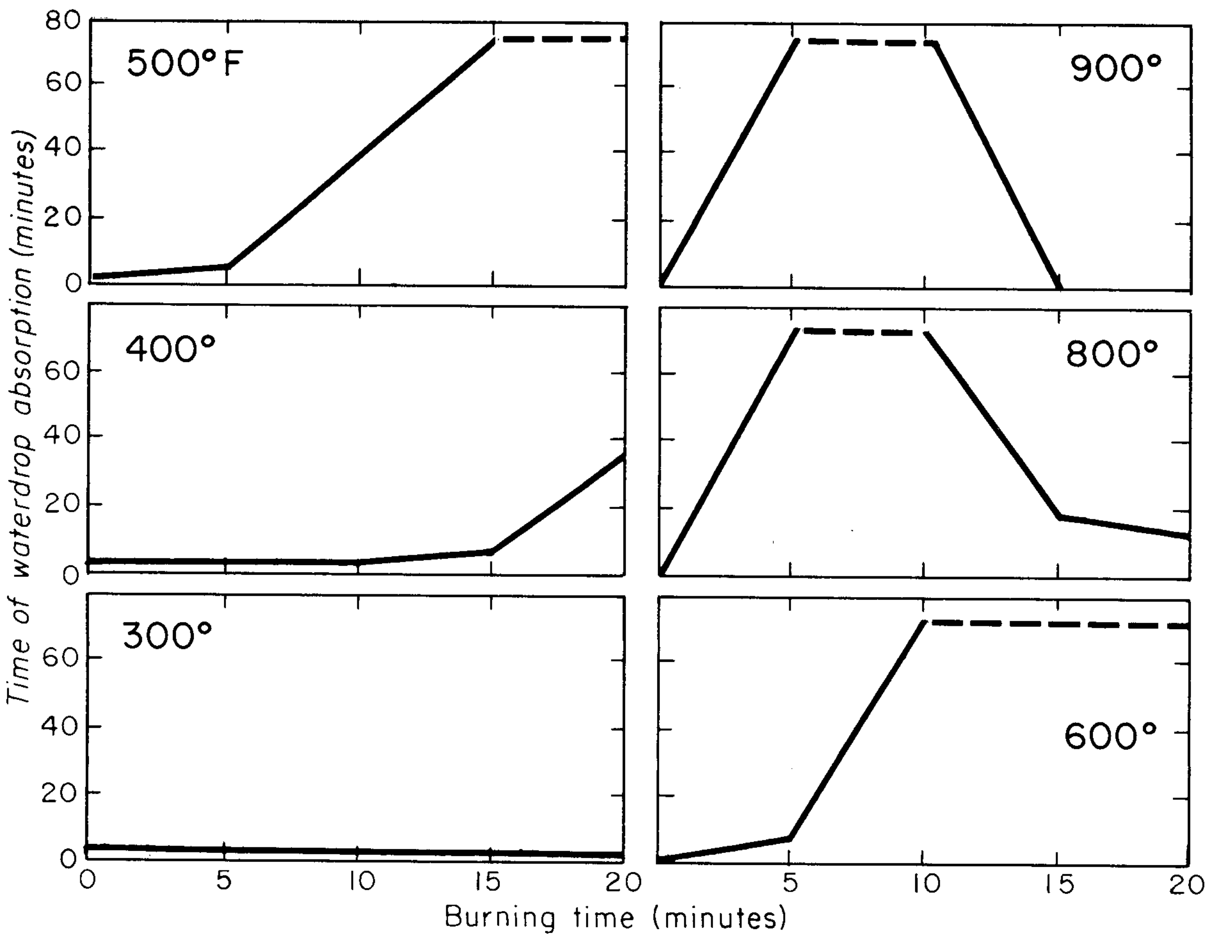


Figure 7.—*The relationship between soil non-wettability and burning time at six burning temperatures.*

temperatures for various periods of time *(fig. 7).* The soil used in their experiment was slightly non-wettable and resisted the penetration of a water droplet for about 2 minutes. The burning treatment consisted of heating a sample in a muffle furnace at different temperatures for various times.

At the lowest temperatures (300°F.), non-wettability was unaffected by burning time. When the temperature was increased to 400°F., non-wettability increased slightly at 15-minute burning times and substantially at 20 minutes. Higher temperatures at 500 and 600°F. for 10 to 15 minutes produced a soil which was completely water repellent. This water-repellent state was termed the impenetrable condition. In contrast, temperatures of 800 and 900°F. began destroying the non-wettable property after 10 minutes; in fact, the soil sample burned at 900°F. for 15 minutes was completely wettable.

The relationship between heat regime and non-wettability suggested a hypothesis that may explain the non-wettable soil layer found on burned watersheds: When fire burns an area, soil non-wettability is destroyed near the soil surface; below the wettable soil surface layer, non-wettability is not destroyed but intensified; this zone where soil non-wettability is intensified corresponds to the water-resistant layer observed in the field.

The intensification of non-wettable substance in the subsurface layer can result from two processes. First, heat *per se* may intensify incipient non-wettability in place at various depths below the soil surface, and hence non-wettability is formed *in situ.* This process precludes the movement of hydrophobic substances within the soil profile. If the process occurs, then creation of a non-wettable layer depends only on the presence of incipient non-wettability at a particular depth and the thermal regime existing during a fire. Second, the vapors and other gaseous material containing hydrophobic substances may distill from the hot soil surface and condense in the underlying cool layers.

The vaporization and condensation process has been demonstrated by other experiments (DeBano 1966). Material was burned in a 22-inch-deep asbestos container that was heated from the top by muffle furnace coils. The container was filled with a wettable sand to within 1½ to 2 inches of the top. The remaining depth of the container was filled with non-wettable soil material in one experiment and with a decomposed *Ceanothus crassifolius* litter in a second experiment. After the soil, plant, and sand material were packed into the container, a heat source preheated to 1400°F. was applied to the top of the soil container. The heat source was allowed to remain on the surface of the soil container until the upper part of the sand layer reached 250 to 300°F. (1½ to 2 inches below the top of the soil container). The heat source was then removed and the column allowed to cool.

After cooling, the burned soil and plant material as well as the underlying sand were tested for non-wettability. Non-wettability was not present in the upper ½ to 1 inch of the burned soil or plant material. The non-wettable substances in this upper layer had apparently been vaporized by the applied heat treatment. In the lower part of the burned soil and plant material, non-wettability was more intense than before burning. The upper layers of the underlying test sand also demonstrated a marked resistance to wetting. The presence of non-wettable substances in the formerly wettable soil indicated that hydrophobic substances had distilled downward and condensed on the sand particles. Therefore, it appears that vaporization and condensation may be an important process in the production of a non-wettable soil layer below the soil surface in areas where a source of hydrophobic material is present.

Summary of Vegetation and Fire Hypothesis

In southern California, a number of chaparral brush species produce organic substances that can make soil non-wettable. During the years between fires, leachate from the brush and decomposing plant parts accumulate in the upper part of the soil profile *(fig. 8a).* In the unburned condition, the maximum concentration of non-wettable substances lies in the upper part of the soil profile immediately below the litter layer. The area corresponds roughly to the transition between the A_0 and A_1 horizons. Smaller amounts may be moved below this layer by infiltrating water. In addition, some of the substances may remain in the undecomposed plant litter. The most severe soil non-wettability in this unburned situation probably results from a particle coating and intermixing of partially decomposed plant parts with the mineral soil. The accumulation of hydrophobic substances tends to build up over time, and its intensity depends upon the particular plant species occupying the area and time between fires. The average interval between fires in brush areas is about 25 years. Most likely, the multitude of interacting environmental conditions governing litter build-up, and removal plays various roles in the induced soil non-wettability.

In a fire, the native chaparral cover and underlying litter layer may be partially or wholly consumed *(fig. 8b).* Temperatures above the soil surface may soar as high as 2,000°F. (Countryman 1964). Temperatures at the soil surface are much less, and may not exceed 1,200°F. Within the soil, the temperature drops rapidly because of the low heat conductivity of soil *(fig. 8b).* At 2 inches below the soil surface maximum temperatures of 350 to 550°F. have been reported (Bentley and Fenner 1958; Sampson 1944). The temperatures existing at different depths may intensify incipient non-wettability at the various depths. More important, however, are the large temperature gradients existing in the upper few inches of the soil that cause vapor and gases containing hydrophobic substances to move downward in the soil profile where they condense on soil particles.

After the fire has swept through the area, the soil possesses a non-wettable layer *(fig. 8c).* Depth and thickness of the layer depend on the intensity of fire and the nature and amount of vegetation litter present. Under burning conditions where the surface temperatures are not high, the layer might be at or near the soil surface. Where a hot fire had burned, non-wettability could show up in deeper layers. The soil physical properties and water contact of the soil would also probably affect the movement of these hydrophobic substances.

The relationship between the temperature regime existing during a fire and the extent and degree of non-wettability in the underlying layer are

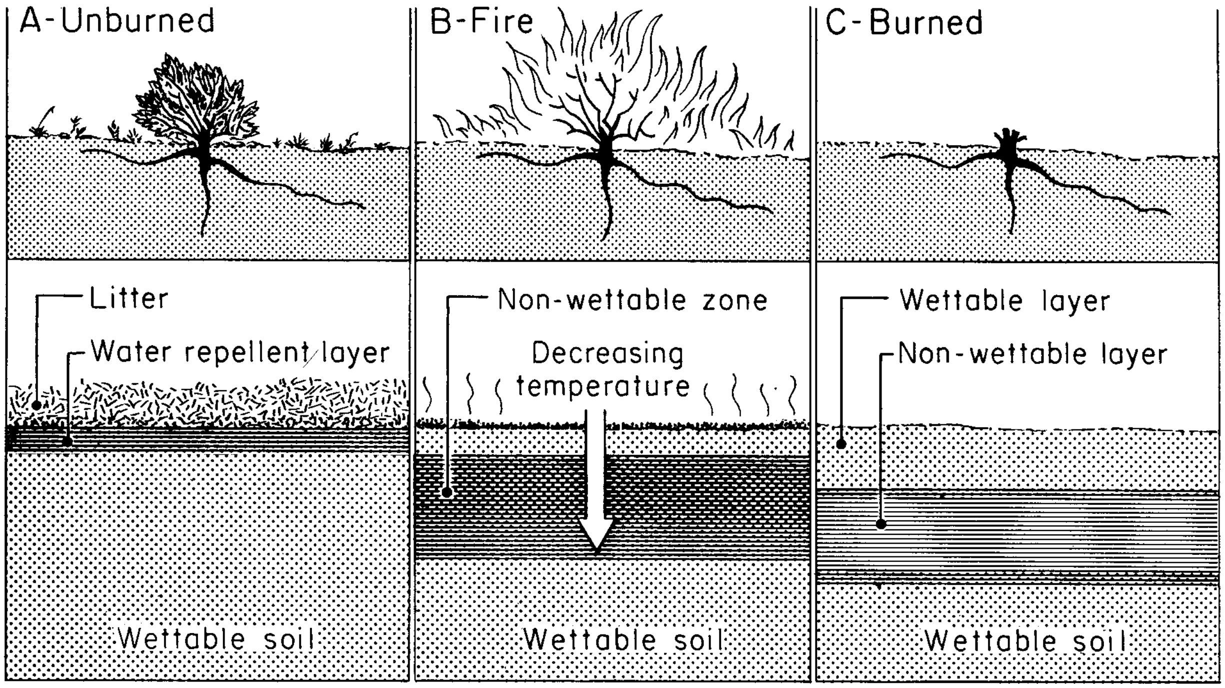


Figure 8.—*Soil non-wettability before, during, and after fire. (a) Before fire, the non-wettable substances accumulate in litter layer and mineral soil immediately beneath it; (b) fire burns vegetation and litter layer, causing non-wettable substances to move downward along temperature gradients; (c) after a fire, non-wettable substances are located below and parallel to soil surface on burned area.*

not completely understood. We need more precise measurements of temperature profiles at the soil surface and immediately below it to obtain more precise data on the amounts of hydrophobic materials that move during wildfire conditions. Furthermore, the susceptibility of different soil particles and clay minerals being rendered non-wettable under fire conditions remains obscure.

Remedial Treatments: Wetting Agents

Among the treatments being studied to overcome non-wettability in soils, the most promising to date are organic compounds known as "wetting agents." The large number of wetting agents commercially available share a common characteristic: their effect on the wetting angle of water entering water-repellent soils. Wetting agents reduce the surface tension and thereby reduce the wetting angle between the solution and the material being wetted. The reduced wetting angle allows water to enter porous media and provide a faster and more complete wetting.

Wetting agents are available in either liquid or powdered form and in either concentrated or diluted form. The common denominator is the amount of active ingredient in the product. Tests suggest that the different types of wetting agents differ only slightly when compared on a unit-active ingredient basis (Letey, *et al.* 1963).

Increasing Infiltration

Wetting agents can be used to increase infiltration of water into hydrophobic soil (Letey, *et al.* 1961). According to the general capillary laws governing wetting in soils, reducing the surface tension decreases capillarity. In contrast, decreasing the wetting angle increases capillary attraction (Pelishek, *et al.* 1962). These capillary forces are important factors in unsaturated moisture movement during infiltration. Therefore, a delicate balance exists during infiltration between the limitations of decreasing surface tension and the benefits arising from decreasing the wetting angle. If the benefits from a decrease in wetting angle exceeds the limitations of decreasing surface tension, then infiltration will be increased.

In non-wettable soils having large wetting angle, the reduction in surface tension is overcome by the decrease in wetting angle, and infiltration as a whole is increased. In contrast, in a wettable soil the wetting angle is originally low, and wetting agents do not reduce it significantly. Therefore, the reduction in capillarity brought about by a reduction in surface tension is not compensated for by a lower wetting angle, which results in a lower infiltration rate. It appears that wetting agents can either increase or decrease infiltration depending upon the initial water repellency of the soil. In non-wettable soils, the wetting angle is usually large, and in most cases application of a wetting agent increases infiltration.

Controlling Soil Erosion

The premise that wetting agents increase infiltration in non-wettable soil led to field testing of wetting agents as a treatment to control soil erosion on burned watersheds (Osborn, *et al.* 1964). The tests were carried out on small plots next to the San Dimas Experimental Forest that had been burned by a wildfire. Six plots, 10 feet wide and 40 feet long, extending down slope were established; three were treated with a liquid wetting agent and the remainder were left untreated. Surface runoff and debris were measured. Through the first rainy season after the fire the treated plots yielded 0.47 cu. ft. of debris as compared to 6.52 cu. ft. from the untreated plots. The reduction in debris was attributed to the wetting agent application. In addition, the treated plots produced four times more grass than the untreated plots.

Applying Wetting Agents

The method of applying wetting agents becomes critical if broadscale applications prove desirable as a post-fire remedial treatment. In southern California, large scale watershed treatments are usually confined to aerial application. Most brushland watersheds occupy topography too steep and rugged to permit application by land-borne machinery or implements.

The aerial application of concentrated liquid solutions is probably prohibitive both logistically and economically. A satisfactory distribution of small amounts of wetting agents by aerial means requires that the concentrated liquid form be diluted manyfold with water. The cost of transporting large quantities of water to obtain this dilution makes this treatment economically unfeasible.

Attempts have been made to absorb liquid wetting agent on dry carrier substances (Pelishek, *et al.* 1964). The concentration of the wetting agent in this powder can be varied by using different dilutions of wetting agent when saturating the carrier. The use of carriers would have the advantage of diluting the wetting agent and allowing easier aerial distribution of various concentrations of wetting agent. Because the powder material used as a carrier would be light, there is no need to transport heavy dilution material.

A study made in winter of 1964—65 on an area burned by the Coyote Fire, near Santa Barbara, California, pointed to a difficulty when using powdered wetting agents. One treatment in the study was a powdered form of wetting agent. The study did not yield any additional information on the effectiveness of wetting agents as an erosion measure, but it did point out that severe winds can blow the powdered wetting agent off the study plots. Therefore, powdered wetting agents may have to be modified to solve the problem of wind dispersion before their use can be recommended.

The residual properties of wetting agents are important when the effectiveness of remedial treatments are judged. On burned watersheds in southern California, the greatest benefits from wetting agents would come during the first rainy season after a fire, when rain falls on relatively bare soil exposed by the fire. This period probably corresponds to the most impermeable condition of a non-wettable soil layer. Later, when vegetation becomes established, some roots undoubtedly penetrate the non-wettable layer. Root penetrations provide passageways through the layer, allowing water to infiltrate. Therefore, a prime prerequisite is that the wetting agent should be effective for at least 1 year through this critical recovery period.

Present indications are that wetting agents last for at least 1 year. An earlier study had indicated that wetting agents were effective through at least two irrigations (Letey, *et al.* 1961). A more recent leaching study[1] showed that the residual effects of a wetting agent were still detectable after 8 inches

[1] Krammes, J. S., and DeBano, L. F. *Longevity of a wetting agent treatment for water resistant soils.* 1967. (Ms. submitted to Soil Sci. Soc. Amer.)

of water passed through the samples. Under rainfall conditions in southern California, this condition would represent the leaching potential of 16 to 32 inches of rainfall.

Establishing Grass

Results from a plot study (Osborn, *et al.* 1964) suggest that wetting agents may stimulate grass establishment on non-wettable soil.

A subsequent laboratory study using wettable and non-wettable soil showed that non-wettability can have a significant effect on both germination and establishment (Osborn, *et al.* 1967). Soil containers were either maintained at a level position or inclined at 30-degree slope. Half of them were treated with wetting agents; the remainder, untreated. No germination occurred on the inclined containers with the untreated non-wettable soil. Good germination occurred on the same containers treated by a wetting agent. In contrast, in the level position small differences in germination occurred between the treated and untreated containers. Germination in the inclined position was poor, probably because water ran off the containers and was not available for seed germination. Subsequent seed establishment showed the same trends in the sloping containers as in the germination trials; that is, establishment was good on non-wettable soils treated with wetting agents, but failed on the sloping non-wettable soils. On the level plots, however, establishment was low on untreated non-wettable soils. During establishment on the untreated plots, many plants died. Apparently enough moisture was available for germination but not for subsequent survival and establishment.

Summary and Prospects

Since the early 1960's a substantial amount of information has been collected on the problem of non-wettable soils. An important relationship which has been partially solved is the effect of fire temperatures on the degree of non-wettability. Test results strongly suggest that a non-wettable layer below the soil surface forms when hydrophobic substances volatize and then condense. This formation seems to be related to the large temperature gradients near the soil surface produced by extremely high temperatures at the soil surface, such as during wildfires. The extent and amounts of hydrophobic substances distilling downward under different temperature gradients have not been fully defined. And future research should be directed toward expanding knowledge of the transfer of hydrophobic substances during fire. When these relationships are better defined, it will be necessary to correlate them with temperature profiles developing in the upper few inches of the soil during wildland fires.

Preliminary findings strongly suggest that plant species vary in their potential for inducing non-wettability in soils. The relative amounts of hydrophobic substances in the plant material, underlying litter layer, and associated soil profile have not been established. The few samples of plant material analyzed to date indicate chamise has more hydrophobic materials than other chaparral brush species. The rate that these substances accumulate in the soil over time between fires is still an unknown. Field samplings suggest that between fires they accumulate in the litter layer and mineral soil immediately beneath it. These accumulated materials are moved downward by temperature gradients existing during a fire. Additional studies of the relative hydrophobicity of different plant and litter components should increase our understanding of the distribution of hydrophobic substances in the plant-soil system.

The problem of grass establishment on non-wettable soils should be carefully considered when burned watersheds are to be reseeded. Our early experiments suggest that wetting agent treatments applied to non-wettable soils may improve moisture relationship during germination and establishment. Therefore, this remedial treatment may determine whether reseedings succeed or fail on areas having non-wettable soils.

The nature of moisture movement—particularly unsaturated flow—remains an important problem. The large difference in unsaturated flow between wettable and non-wettable systems points to a possible difference in the type of moisture flow involved. For example, the extremely slow movement of water in the non-wettable system suggests the principal mechanism involved may be vapor diffusion phenomena. In contrast, more rapid movement by viscous flow may be important in a wettable soil. Before the effects of wetting agents on flow can be determined, we need better quantitative data on the mechanisms involved.

Another perplexing problem concerns the possible relationship between the textural and mineralogical nature of soils with non-wettability. For example, we have consistently observed the difficulty of inducing non-wettability in fine-textured soils with a high clay content. This resistance may be related to their specific surface. This relationship suggests that because clay soils have a greater specific area than sandy textured soil, a given quantity of hydrophobic substances may coat a smaller proportion of the available particle surface in the clay soil. The proportion of the total surface area of soil particles coated with hydrophobic materials could be an important factor in determining the degree of water repellency acquired by soils. The mineralogical make-up of the colloidal soil fraction probably also enters into this relationship.

And finally, a more practical question has to do with amount and method of treatment for remedying non-wettable soils. To date, not enough basic information is available to recommend specific techniques of treating entire watersheds with wetting agents. Fundamental research in the laboratory followed by field plot studies could fill this gap in our knowledge of soil non-wettability.

Literature Cited

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

Bond, R. D.
1964. **The influence of the microflora on the physical properties of soil. II. Field studies on water repellant sands.** Aust. J. Soil Res. 2:123-131.

Bond, R. D., and Harris, J. R.
1964. **The influence of the microflora on physical properties of soils. I. Effects associated with filamentous algae and fungi.** Aust. J. Soil Res. 2:111-122.

Countryman, C. M.
1964. **Mass fires and fire behavior.** U.S. Forest Serv. Res. Paper PSW-19. Pacific SW. Forest and Range Exp. Sta., Berkeley, Calif. 53 pp., illus.

DeBano, L. F.
1966. **Formation of non-wettable soils ... involves heat transfer mechanism.** U.S. Forest Serv. Res. Note PSW-132. Pacific SW. Forest and Range Exp. Sta., Berkeley, Calif. 8 pp., illus.

DeBano, L. F., and Krammes, J. S.
1966. **Water repellent soils and their relation to wildfire temperatures.** Int. Ass. Sci. Hydrol. 11:14-19.

Jamison, V. C.
1946. **Resistance to wetting in the surface of sandy soils under citrus trees in central Florida and its effect upon penetration and the efficiency of irrigation.** Soil Sci. Soc. Amer. Proc. 11: 103-109.

Krammes, J. S., and DeBano, L. F.
1965. **Soil wettability: A neglected factor in watershed management.** Water Resources Res. 1: 283-286.

Letey, J.; Osborn, J.; and Pelishek, R. E.
1962a. **The influence of the water-solid contact angle on water movement in soil.** Int. Ass. Sci. Hydrol. 7(3):75-81.

Letey, J.; Osborn, J.; and Pelishek, R. E.
1962b. **Measurement of liquid-solid contact angles in soil and sand.** Soil Sci. 93:149-153.

Letey, J.; Osborn, J.; and Pelishek, R. E.
1963. **Guides to value of nonionic wetting agents.** Calif. Agr. 17:11.

Letey, J.; Pelishek, R. E.; and Osborn, J.
1961. **Wetting agents.** Calif. Agr. 15:8-9.

Osborn, J. F.; Pelishek, R. E.; Krammes, J. S.; and Letey, J.
1964. **Soil wettability as a factor in erodibility.** Soil Sci. Soc. Amer. Proc. 28:294-295.

Osborn, J.; Letey, J.; DeBano, L. F.; and Terry, Earl.
1967. **Seed germination and establishment as affected by non-wettable soils and wetting agents.** Ecology 48:494-497.

Pelishek, R. E.; Osborn, J.; and Letey, J.
1962. **The effect of wetting agent on infiltration.** Soil Sci. Soc. Amer. Proc. 26:595-598.

Pelishek, R. E.; Osborn, J. F.; and Letey, J.
1964. **Carriers for air application of granulated wetting agents.** Calif. Agr. 18(4):11.

Sampson, Arthur W.
1944. **Plant succession on burned chaparral lands in northern California.** Univ. Calif. Agr. Exp. Sta. Bull. 685, 114 pp.

Van't Woudt, B.
1959. **Particle coatings affecting the wettability of soils.** J. Geophys. Res. 64:263-267.

Wieslander, A. E., and Gleason, Clark H.
1954. **Major brushland areas of the coast ranges and Sierra-Cascade foothills in California.** U.S. Forest Serv. Calif. Forest & Range Exp. Sta. Misc. Paper 15, 9 pp., illus.

GPO 975-045