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ABSTRACT: After a wildfire, some brushland soils in southern California have been found to include a non-wettable layer. This formation may be the result of hydrophobic material volatilizing and later condensing. In burning experiments, hydrophobic substances from ceanothus litter and non-wettable soil were moved downward into an underlying wettable sand by temperature gradients. The wettable sand acquired a marked resistance to wetting after the burning treatment.

Formation of Non-Wettable Soils . . .

involves heat transfer mechanism

LEONARD F. DEBANO

When winter rains fall on freshly burned watersheds in southern California, they may not penetrate the soil immediately. Instead, the water droplets may "ball-up " (fig. 1). This characteristic of some soils to resist water penetration and infiltration has important hydrologic meaning. How fire can induce water repellency in soils is now being studied at the San Dimas Experimental Forest, near Glendora, Calif.

As part of this work, we conducted laboratory experiments to test this hypothesis: hydrophobic substances vaporized at a hot surface will move downward and condense in the cooler underlying wettable material. The results supported the hypothesis. We also found that hydrophobic substances could be detected in the sand layer under the burned ceanothus litter used in the trials.

EARLIER WORK

In the last few years, research on the problem of water-resistant soils has uncovered previously unknown relationships between water repellency in soils, fire temperature, and plant species (DeBano and Krammes 1966). Of particular interest has been the relationship between heat treatment and water repellency.

The water repellency in watershed soils appears to be produced by organic substances in chaparral brush plants. For example, Letey, *et al.* (1962b) have demonstrated that ammonium hydroxide extracts of chaparral brush and litter material can induce water repellency in wettable sands. These same hydrophobic substances were also soluble in water but to a lesser extent.

On unburned watersheds, hydrophobic substances are commonly detectable in the litter layer and the soil immediately beneath it. This region includes the O_{oo} and the transition between the O_o and A_1 soil horizons. In some unburned areas, slight indications of water repellency can be detected further downward in the soil profile.

In contrast, on burned watersheds non-wettability is present in a well defined layer located below and parallel to the soil surface (fig. 2). The ash-dust surface and mineral soil immediately beneath it are wettable. The

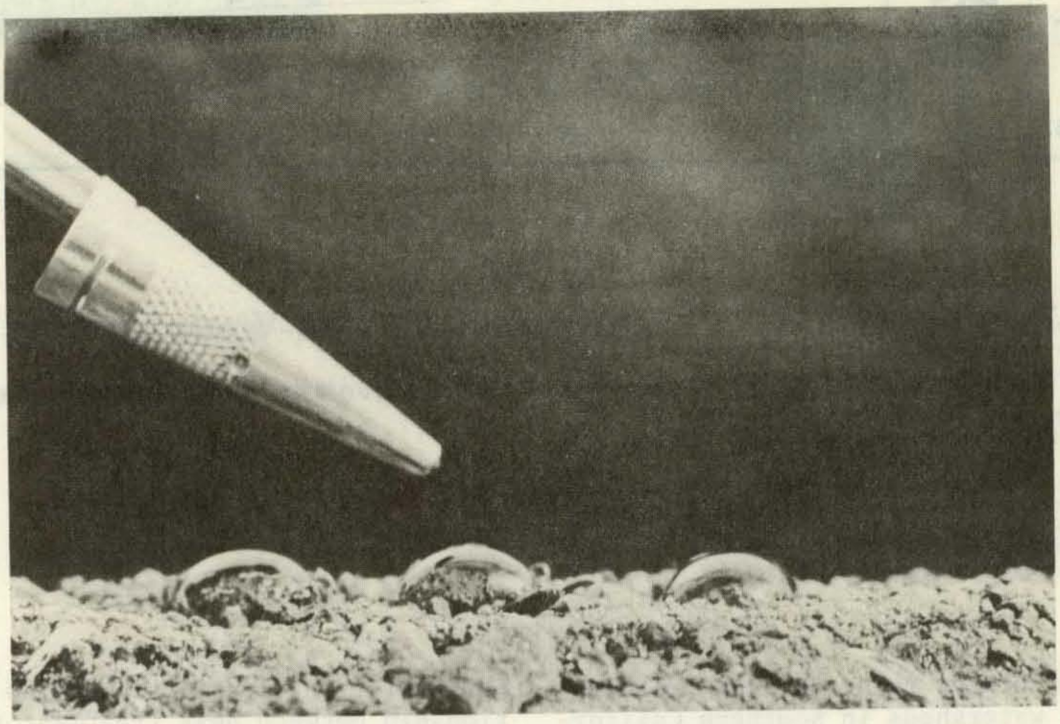

Figure 1.--*A water droplet 'balls-up' upon contacting a non-wettable soil.*

wettable surface layer may vary in thickness from a thin ash-dust covering to about 2 inches. Below it is a non-wettable layer that varies in thickness from 2 to 4 inches. Non-wettability is more intense in this layer of soil than in soil material from an equivalent depth on unburned watersheds. The soil material below the non-wettable layer is again wettable.

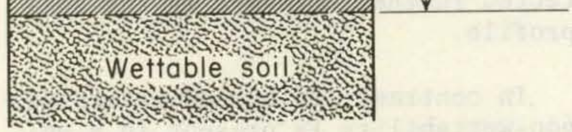

Figure 2.--*A non-wettable soil layer on burned brushland watersheds lies about 2 inches below the wettable soil surface.*

The location of the water repellent layer on burned watersheds appears related to soil temperature regimes that exist during wildfires (DeBano and Krammes 1966; Krammes and DeBano 1965). A laboratory burning experiment has shown that soil non-wettability can be intensified or destroyed, depending upon temperature and time of heating, by heating a slightly non-wettable soil in a muffle furnace (DeBano and Krammes 1966). If a slightly non-wettable soil is heated to more than 400°F. in a muffle furnace for 5 to 10 minutes, then water repellency is intensified. When soil samples are burned for 15 to 20 minutes, soil non-wettability increases at lower temperatures (300-700°F.) but is destroyed at the higher temperatures (800 and 900°F.).

The close relationship between heat treatment and soil non-wettability helps to explain the presence of a commonly observed non-wettable layer on freshly burned watersheds in southern California. According to our present hypothesis, soil non-wettability is destroyed in the upper part of the soil by extremely high surface temperatures during a fire. Downward in the soil, temperatures are cooler. And soil non-wettability is not destroyed but instead is intensified. The zone of intensification corresponds to the water resistant layer commonly observed on freshly burned watersheds (fig. 2).

We had postulated that non-wettability in the subsurface layer could be intensified by two processes (DeBano and Krammes 1966). First, heat *per se* alters incipient non-wettability present in a subsurface layer, and non-wettability is intensified *in situ*. This hypothesis precluded any movement of hydrophobic substances as a result of burning. If this process occurred, then the formation of a non-wettable layer depended only on the presence of a non-wettable substance in the soil at a particular depth and a temperature regime during a fire capable of intensifying this incipient soil non-wettability.

Calculations by the diffusion equation describing heat flow in soils did not support the intensification of soil non-wettability in place (DeBano and Krammes 1966). Instead, calculations indicated that 2 inches below the soil surface the temperatures during a fire were not high enough to intensify existing non-wettability.

Because of these inconsistencies we postulated a second hypothesis: during fire, hydrophobic materials are vaporized and then condensed. According to this hypothesis, the large temperature gradients existing within a few inches of the soil surface are responsible for moving hydrophobic substances downward in the soil profile. The high temperatures at the soil surface vaporize organic materials which distill downward in the soil where they condense in the cooler underlying layers. The region where condensation occurs corresponds to the non-wettable layer (fig. 2). To test this hypothesis, two burning experiments were done.

EXPERIMENTAL WORK

APPARATUS

An apparatus was constructed to heat soil and plant material at different temperatures in the laboratory. It was designed to produce high temperatures at the soil surface, thus inducing large temperature gradients within a few inches of the soil surface. The test apparatus consisted of: (a) a heat source and (b) a soil container (fig. 3). The heating device was constructed from muffle furnace heating coils embedded in an asbestos box, which had a 9- by 9-inch opening in the bottom. Heat loss upward was reduced by 4 inches of asbestos insulation on the top of the heating coils. The soil container constructed of 1/4-inch asbestos sheets was 9 inches square and 22 inches deep.

Before each test, the heat source was placed on an asbestos pad and allowed to preheat for about 2 hours to reach a prescribed temperature of 1,400°F. At the start of the burning experiment, the preheated source was quickly moved from the asbestos pad and set on the soil container. Temperature dropped 200-300°F. during this transfer, but returned to 1,400° F. within about 5 minutes. Surface temperature was measured by a chromel-alumel thermocouple attached to a temperature controller that regulated the electrical power input to the heating coils.

BURNING EXPERIMENTS

In the first experiment, the soil container was filled with 50-mesh wettable beach sand to within 1-1/2 inches of the top of the soil container.

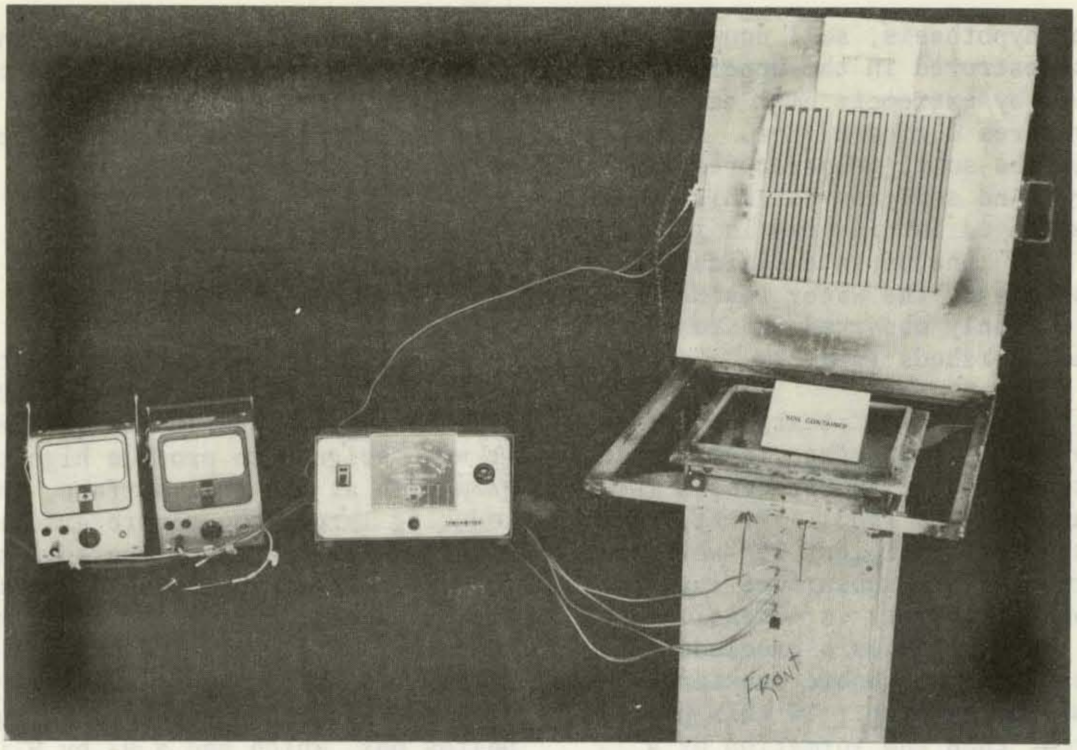

Figure 3.--*Apparatus used for burning experiments included a heat source, top right, and below it, a soil container.*

The upper 1-1/2 inches was filled with a naturally occurring non-wettable soil which had been sieved through a 2-mm. sieve. The soil had a sandy loam texture and included large amounts of undecomposed plant material.

In the second experiment, the container was filled with sand to within 2 inches of the top of the container. The upper 2 inches of the soil container were filled with undecomposed litter collected under a mature stand of ceanothus (*Ceanothus crassifolius*).

During the tests, temperatures were recorded at the surface and at 1-inch intervals below the top of the container. Previous trial runs indicated that when these temperatures were reached, large temperature gradients existed in the upper few inches of the soil column. Therefore, heat was applied to the surface until the temperature at the 3-inch depth reached about 200°F. In the container of ceanothus litter, about 40 minutes of heating were required for the 3-inch layer to reach this temperature. About 100 minutes of heating were necessary before the non-wettable soil layer reached this temperature because of slow heat conduction in the soil material. The tests were completed when the heat source was removed. After cooling, the soil or plant material residues and underlying sand were removed and tested for non-wettability.

Two techniques were used to gauge non-wettability in the litter, soil, and underlying sand material before and after burning. One method consisted of soaking filter paper with ammonium hydroxide extract of the plant material, placing water droplets on the dried paper, and then recording the penetration time. This method was used to index non-wettability in the plant litter material before and after burning because it is impossible to determine non-wettability directly on intact plant material. The other method used to determine non-wettability in the soil and sand material before and after burning involved timing water-droplet penetration directly into the test material. The latter technique has been used in other experiments to test for soil non-wettability (Bond and Harris 1964; Krammes and DeBano 1965).

A third technique for determining non-wettability in the underlying sand material was used. Liquid-solid contact angles were calculated from data on experiments measuring the capillary rise of water and pure ethanol (Letey, *et al.* 1962a).

RESULTS

The burning experiments showed that materials vaporized at or near the surface, distilled downward, and condensed in the cooler underlying layers (fig. 4). The materials distilling downward during both heating trials induced non-wettability in a wettable sand. When a 1-1/2-inch layer of non-wettable soil was heated, substances with hydrophobic properties were detected 3 inches below the top of the column. Non-wettability was most intense immediately below the soil-sand interface and decreased as depth of sand layer increased. In the upper sand layer, a water drop did not penetrate for 64 minutes. The heat treatment destroyed non-wettability in the upper inch of the soil material, but intensified it in the lower 1/2 inch of soil layer. The intensification of non-wettability in the lower part of the soil layer probably resulted from condensation of hydrophobic material transported from the upper inch of soil.

Hydrophobic substances were also detectable in the sand layer under the burned ceanothus litter (fig. 4). In this test, however, non-wettability was not as pronounced in the sand layer as under the burned soil layer. Non-wettability in the ceanothus experiment could be detected only in the upper inch of underlying sand. A water droplet placed on sand extracted from beneath the ceanothus litter penetrated in 1/4 minute, but took almost 64 minutes to penetrate sand from under the burned non-wettable soil. The amount of hydrophobic substances distilling from the burned layer probably depended on both the burning time and the initial amounts of hydrophobic substances in the soil and plant material.

Soil scientists generally agree that as wetting angles increase non-wettability also increases. At wetting angles of 90 degrees or greater, water is no longer adsorbed because the attraction between water molecules is greater than that between the water and soil. In this study, the wetting angle measurements in the sand followed the same trend as the water drop penetration data. The wetting angle of the sand before burning was 68 degrees. The wetting angles of the sand immediately beneath the ceanothus litter and non-wettable soil layer were 79 and 85 degrees, respectively.

The temperature data from the two burning experiments showed that large temperature gradients existed in the upper few inches of the soil container (fig. 5). In both experiments the surface remained at a temperature of about 1,400°F. That temperature decreased to 1,100-1,200°F. in the first inch of the litter or soil material by the end of the burning experiment. Temperatures of at least 500°F. were recorded during the tests at the interface between the material being burned and the underlying sand. Therefore, the gradients existing at the soil or litter and sand interface were more than 600°F./in. The temperatures never exceeded 200°F. at depths of 4 inches below the top of the container.

DISCUSSION

According to the vaporization and condensation hypothesis of this study, hydrophobic substances are vaporized

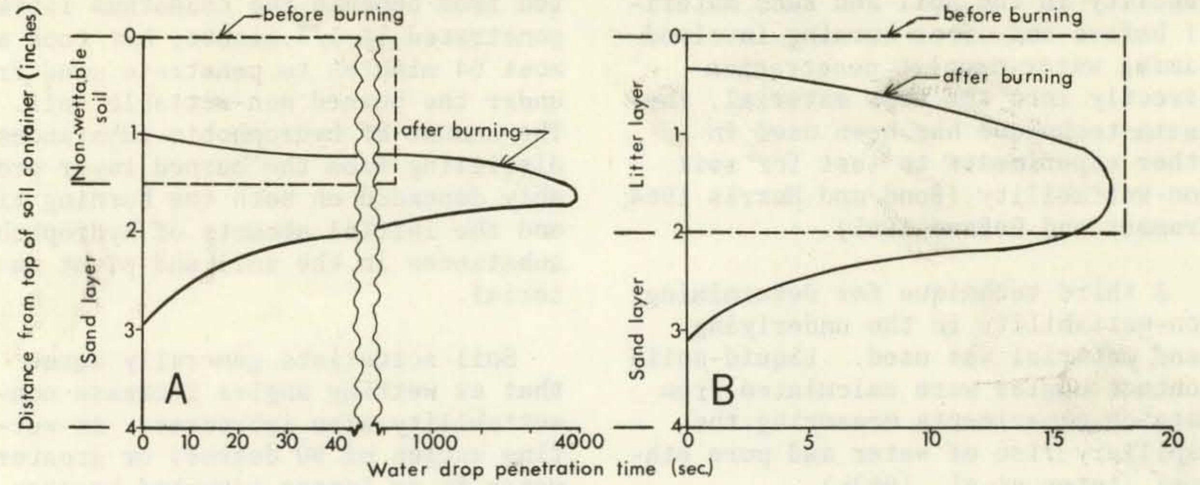

Figure 4.--*Non-wettability at different depths before and after burning in soil containers containing wettable sand covered by (a) 1-1/2 inches of non-wettable soil, and (b) a 2-inch layer of ceanothus litter.*

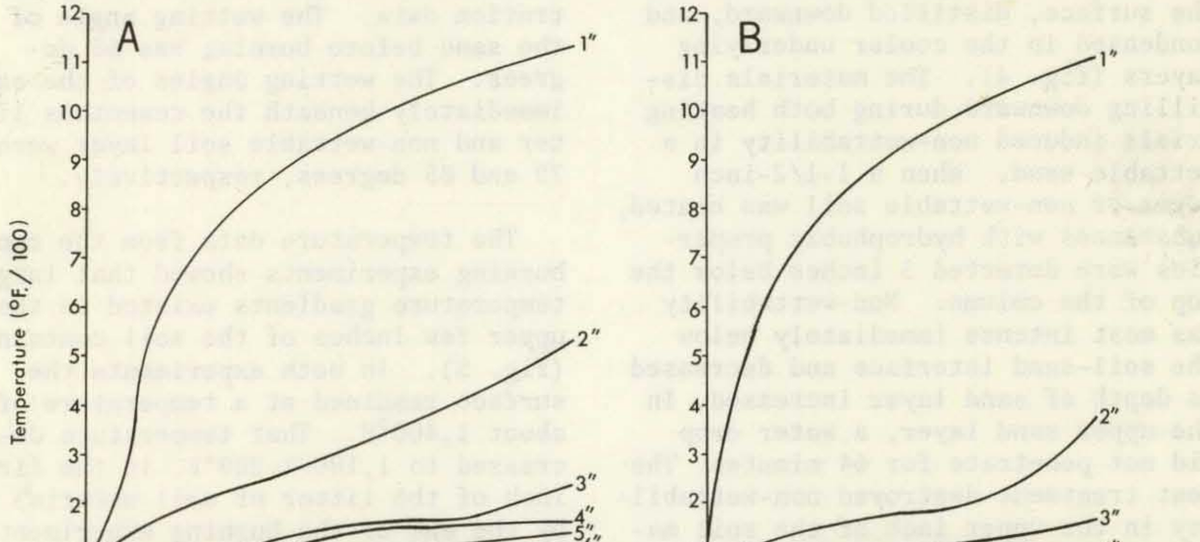

Figure 5.--*Temperatures at different depths below top of soil container during burning experiments (top of container was maintained at 1,400°F.); (a) 1-1/2-inch layer of non-wettable soil over sand; (b) 2-inch layer of ceanothus litter over sand.*

by the high surface temperature (1,400°F. in these experiments). Undoubtedly some of the vaporized materials move upward and are lost. But some of these vaporized substances probably distill downward into the underlying layers in response to large temperature gradients existing near the soil surface. The materials distilling downward condense at some point in the underlying layers and produce a water repellent condition.

The formation of a non-wettable layer during wildfires probably involves the distillation of hydrophobic substances in response to temperature gradients. Heat alone cannot intensify non-wettability deeper than 2 to 3 inches below the soil surface--even though an incipient condition may be present. There must be movement of material into the sub-surface layer from somewhere else to obtain the high degree of non-wettability that has been found at depths of 3 inches or more. According to our present understanding, a non-wettable condition at this level requires higher temperatures than have been reported for wildfires. Previous burning experiments showed that temperatures of 400°F. or higher would be necessary to intensify any existing non-wettability (DeBano and Krammes 1966). Yet published reports of soil temperatures during wildfires show that temperatures at 2 inches rarely exceed 400°F. (Bentley and Fenner 1958; Sampson 1944). These reports do not include data on temperatures 2 inches below the soil surface, but the poor heat conduction in soil makes it unlikely that temperatures above 200°F. would exist below 3 inches. In this study, the temperature at 3 inches never exceeded about 200°F.

If the concept of vapor distillation is introduced into the theory of how non-wettable soils are formed, then the requirement for high temperature becomes less important. This difference was illustrated by the presence of non-wettability at depths where the temperatures were less than 300°F. The results suggest that temperature gradients existing in the upper few inches of the soil surface may be more important for inducing non-wettability than the temperature in any particular layer below the surface.

The surface temperatures of 1,400° F. used in this study probably represent the upper temperature range which could be expected during wildfires. Little data are available on surface temperature of wildfires and how long a given temperature is maintained. The limited data available indicate that a maximum of 1,150°F. can be reached during a brush fire producing a "white-ash" condition (Bentley and Fenner 1958). Sampson (1944) reported temperatures of 1,200°F. in the 1/2-inch litter layer under a burning chamise cover. Lower surface temperatures would undoubtedly decrease the depth hydrophobic substances distill downward in the soil profile.

The variation in the depth of the non-wettable layer in burned watersheds probably reflects the various surface temperatures which exist during a fire. Under light burning conditions, the non-wettable soil layer may be present near the soil surface immediately beneath a wettable ash dust layer. At the other extreme, heavy stem material would probably smolder for longer periods and maintain higher temperatures which may cause hydrophobic substances to distill downward to the deeper soil layers.

Experiments are now being planned to evaluate the effect of different surface temperatures and of times of burning on the downward movement of hydrophobic substances. Such trials will also investigate the possible simultaneous transfer of moisture and hydrophobic substances along temperature gradients that typically exist during wildfire conditions.

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