Fire-Induced Water-Repellent Soils: An Annotated Bibliography

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ABSTRACT

The development and nature of water-repellent, or hydrophobic, soils are important issues in evaluating hillslope response to fire. The following annotated bibliography was compiled to consolidate existing published research on the topic. Emphasis was placed on the types, causes, effects and measurement techniques of water repellency, particularly with respect to wildfires and prescribed burns. Each annotation includes a general summary of the respective publication, as well as highlights of interest to this focus. Although some references on the development of water repellency without fires, the chemistry of hydrophobic substances, and remediation of water-repellent conditions are included, coverage of these topics is not intended to be comprehensive. To develop this database, the *GeoRef, Agricola*, and *Water Resources Abstracts* databases were searched for appropriate references, and the bibliographies of each reference were then reviewed for additional entries.

REFERENCES

Adams, Susan, Strain, B.R., and Adams, M.S., 1970, Water-repellent soils, fire, and annual plant cover in a desert scrub community of southeastern California: Ecology, v. 51, p. 696-700.

This was the first study to be conducted on fire-related water repellency in deserts. Researchers examined the vegetation mosaic that resulted from hydrophobic soils in a desert scrub community of Southern California, four years after fire. Large hummocks of soil supported various shrubs, but were devoid of the annual plants that resided between the hummocks. Results of the study suggested that hydrophobic soil layers within the hummocks were responsible for the observed vegetation patterns. Fire appeared to intensify the hydrophobic properties of the soil, and to increase the depth at which these layers were found. Researchers also noted that the three different types of shrubs appeared to cause varying degrees of water repellency on their respective hummocks.

Almendros, G., Gonzalez-Vila, F.J., and Martin, F., 1990, Fire-induced transformation of soil organic matter from an oak forest - an experimental approach to the effects of fire on humic substances: Soil Science, v. 149, no. 3, p. 158-168.

This study describes the effects of fire on the organic matter from a Dystric Xerochrept under oak forest. In laboratory experiments designed to simulate the effects of fire on isolated humic fractions, several physicochemical characteristics are described in the heated samples, as well as in humic substances extracted from samples of control and post fire soil areas. The study describes an irreversible dehydration and decarboxylation of the humus colloids, which the authors suggest may play an important role in fire-induced water repellency. Although other authors have suggested that fire-induced translocation and fixation of hydrophobic compounds are responsible for the formation of water-repellent soils, the results of this study suggest that the changes in surface properties of the humus substances may also greatly increase the hydrophobicity of soils after burning. The thermal loss of the oxygen-containing functional groups turn the surface of the humus macromolecules hydrophobic.

Barrett, Gary, and Slaymaker, Olav, 1989, Identification, characterization, and hydrological implications of water repellency in mountain soils, Southern British Columbia: Catena, v. 16, p. 477-489.

This study evaluated and identified hydrophobic soils at various sites within the mountains of British Columbia. Contrary to many other studies, these water-repellent soils were fine-grained (one site was clay-silt lacustrine deposits). Researchers found that all sites in the subalpine-alpine ecotone exhibited water-repellent or difficult-to-wet layers. These layers (no more than a few centimeters thick) occurred at or near the surface, and were found in locations of accumulated organic matter. The results strongly indicated that the water repellency was associated with the accumulation of organic matter, specifically that derived from vegetation in the alpine-subalpine ecotone. The authors noted that the repellency appeared to be a "permanent" feature, in that it did not degrade with exposure to water. They also reported that water-repellent layers graded into gradually less repellent (or "transient") layers below.

Bashir, S.M., 1969, Hydrophobic soils on the east side of the Sierra Nevada: Reno, University of Nevada, M.S. thesis, 97 p.

The occurrence of water repellency on the east side of the Sierra Nevada was evaluated with respect to a variety of soil and cover types. Three general soil textures were evaluated in the study, including sandy, loamy, and fine loamy soils. In addition to bare soils, the four cover types included Jeffrey pine, manzanita, snow brush, and bitter brush. The results showed that water-repellent conditions occurred in all major soil types under litter, and that there was no good correlation between the nature of repellency and litter depth. Texture, burn-intensity, and the presence of fungi influenced the degree of water repellency, but no differences were found between the four cover types. Sandy soils also had deeper water-repellent layers than fine loams or loams. This study found that in all cases (even in burned areas), water repellency began at the mineral surface. This is in contrast to other studies that have described the occurrence of post-fire water-repellent layers 1 or 2 inches below the surface (beneath a wettable layer). Fire in this case did, however, induce repellency, or intensify existing repellency. The author notes that the results of the capillary rise technique used by Emerson and Bond (1963) to measure the degree of water repellency, were unreliable when used on soils containing high percentages of silt, clay, and organic matter. The literature review contains historic information on various causes of water repellency, including findings from some European literature that relate iron to wetting resistance in soils.

Bisdom, E.B.A., Dekker, L.W., and Schoute, J.F.Th., 1993, Water repellency of sieve fractions from sandy soils and relationships with organic material an soil structure: Geoderma, v. 56, p. 105-118.

Researchers investigated the relationship between water repellency and soil constituents of agricultural and uncultivated sandy soils in the southwestern Netherlands. The study offered insight into the variables affecting water repellency in sandy soils and compared results to the proposed causes of repellency found in other literature. While other investigations have attributed water repellency primarily to “coatings” on soil particles, this study found interstitial material to be the dominant factor. These findings were supported with electron microscopy photographs of sand grain surfaces which showed very little organic material remaining after soil samples were washed with water (thus removing the interstitial material and rendering samples wettable). Researchers also determined that fresh and partly decomposed organic matter had higher water-drop penetration times than more degraded fragments. The authors concluded that further studies are needed to establish the role of biota in water repellency.

Boelhouwers, J.C., De Graaf, P.J., and Samsodien, M.A., 1996, the influence of wildfire on soil properties and hydrological response at Devil’s Peak, Cape Town, South Africa: Zeitschrift fur Geomorphologie, Suppl.-Bd. 107, p.1-10.

This paper describes the results of a series of field sprinkling experiments on burned and unburned hillslopes near Cape Town, South Africa. The study focused on the infiltration patterns, and the influence of water-repellency, of the two sites. On the unburned sites all the simulated rain entered into the soil, regardless of the intensity of application. No water repellency was observed at the unburned plots. In contrast, for any rainfall intensity applied, overland flow stayed consistent after 2-4 minutes on the burned plots. In this case, a pronounced water-repellent zone was detected between 20 and 100mm beneath the surface.

Accelerated erosion was observed from the burned plots following two moderate rainfall events.

Booker, F.A., 1998, Landscape and management response to wildfires in California: University of California, Berkeley, MS thesis, 436 p.

Bond, R.D., 1968, Water repellent sands, *in* 9th International Congress of Society of Soil Science, Adelaide, Australia, 1968, Transactions, v.1, p. 339-347.

This paper presents some preliminary research into the phenomenon of water-repellent soils in Australia. Research was directed toward the evaluation of sandy, water-repellent pastures in two districts of South Australia. Trenches excavated during the growing season revealed that dry, water-repellent sections of the profile corresponded to patches devoid of vegetation on the surface. Conversely, wet areas were occupied by vegetation. Repellency, in some instances, was as deep as two feet. Two techniques were employed to measure the repellency. One approach was to measure the contact angle of water drops from enlarged photograph prints. The other method involved use of the capillary rise technique for indirect measurement. In an attempt to remedy water repellency in some agricultural soils, the vegetation was replaced with another group of plants. Repellency decreased, but only temporarily. Within a few years, the condition had returned to the same degree of severity.

Bond, R.D., 1969a, Factors responsible for water repellence of soils, *in* DeBano, L.F., and Letey, John, eds., Water-repellent soils: University of California, Riverside, May 6-10, 1968, Proceedings, p. 259-264.

This author attributes water repellency of sand in Australia to organic films produced by fungi growing in the soil. The composition of these organic films is unknown, but they are not oil nor waxes. The effect of the films is reduced by dilute acid and alkali. The intensity of repellency in the field varies with the species of fungi in the soil, and with the season when the soil is tested.

Bond, R.D., 1969b, The occurrence of water-repellent soils in Australia, *in* DeBano, L.F., and Letey, John, eds., Water-repellent soils: University of California, Riverside, May 6-10, 1968, Proceedings, p. 1-6.

This paper introduces some of the factors that affect water repellency in Australian soils. The author suggests that a low clay content is the most important soil condition to have naturally occurring water repellency (usually less than 7% in Australian soils). In fact, the discussion summary that follows the paper mentions laboratory burning experiments in which sand became water repellent more readily than soils having clay contents of 10% to 15%. The author also states that the total organic matter content has no effect on the degree of water repellency, but that plant residue must be present for the condition to develop.

Bond, R.D., and Hammond, L.C., 1970, Effect of surface roughness and pore shape on water repellence of sandy soils: Soil and Crop Science Society of Florida Proceedings, v. 30, p. 308-315.

This investigation determined the relationship between real contact angles on individual sand grains and the apparent contact angle resulting from a collective mass of sand grains. The paper included SEM images of contrasting surfaces on wettable and water repellent sand grains, as well as water drop and menisci shapes. Contact angles on water-repellent sand grains were usually found to be less than 60°, implying that the 120° contact angles noted on water-repellent sand masses were the result of porosity. Researchers concluded that, in view of the low contact angles observed on individual sand grains, substances do not need to be highly water repellent in order to impart a significant repellency to a soil or sand mass. Consequently, a much larger range of organic substances have the potential to cause water repellency.

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: Australian Journal of Soil Research, v. 2, p. 111-122.

Contrary to some previous research, this investigation found evidence that fungal activity tended to support the formation of water-stable soil aggregates. The paper also reported on other contributions of soil microflora to structural characteristics. In reference to water repellency, research was still preliminary and didn't appear to offer much new information. Results were inconclusive as to the specific source of fungal water repellent substances, but the authors noted that basidiomycetes appeared to be significant.

Bozer, K.B., Brandt, G.H., and Hemwall, J.B., 1969, Chemistry of materials that make soils hydrophobic, *in* DeBano, L.F., and Letey, John, eds., Water-repellent soils: University of California, Riverside, May 6-10, 1968, Proceedings, p. 189-204.

This paper discusses some of the structural characteristics of various hydrophobic substances and their associated degree of water repellency. The authors state that many of the materials causing water repellency in soils are made up of organic compounds with both hydrophobic and hydrophilic characteristics. The permanence of water repellency is related to the strength of the hydrophilic portion of the compound, since this is the part that bonds to soil particles. The hydrophobic portion of the molecule influences the degree of water repellency.

Brandt, G.H., 1969, Water movement in hydrophobic soils, *in* DeBano, L.F., and Letey, John, eds., Water-repellent soils: University of California, Riverside, May 6-10, 1968, Proceedings, p. 91-114.

A series of water-flow experiments were performed on untreated, medium to coarse-textured soil cores, and on cores treated with a hydrophobic substance known as 4-t-butyl catechol (TBC). Infiltration into the cores was evaluated under a variety of conditions, including different heads, compaction rates, and soil textures. Results showed that equilibrium flow rates were reached more rapidly in treated (water-repellent) cores than in untreated ones. Although dry treated cores hindered water flow, in saturated, treated cores, flow was actually accelerated. To explain the observed effects on infiltration, the author proposed that TBC causes particles to "collect in small hydrophobic aggregates or bridges," thus reducing additional pore plugging and stabilizing the matrix to water flow. This is in contrast to untreated cores, which allow both coarse and fine particles to move during water flow, and restrict permeability.

Burcar, S., Miller, W.W. Tyler, S.W, and Johnson, D.W., 1994, Seasonal preferential flow in two Sierra Nevada soils under forested and meadow cover: Soil Science Society of America Journal, v. 58, p. 1555-1561.

This study illustrated the effects of water repellency on infiltration under various soil, temporal, and plot cover conditions. Researchers evaluated infiltration, runoff and preferential flow in a sandy soil derived from granitic parent material (Marla), and a finer-grained, loamy soil derived from weathered andesitic lavas (Umpa). Measurements were made in the spring and fall (corresponding to high and low antecedent moisture conditions, respectively), and under forest (accumulations of pine litter) and meadow (little surface organic debris) vegetative covers. Results indicated that vegetation in the Sierra Nevadas is extremely important in determining the spatial distribution of water repellency, in that forested plots tended to have greater water repellency than meadow areas. They also found that repellency in the Sierras is seasonal and has a major impact on infiltration properties. Contrary to other literature which suggests that coarser textured soils tend to be more water repellent, this study found water repellency to be more persistent in the finer-textured volcanic soil. In the fall, the coarser-textured soil exhibited higher infiltration rates, as expected, but in the spring, the forested Umpa soil actually had higher infiltration rates, despite its finer texture. This behavior was explained by the fact that, in the spring, the persistent water repellent nature of the Umpa enabled deep, well established preferential flow paths to form, whereas high antecedent moisture conditions in the course-textured Marla soil caused preferential flow paths to dissipate, thus forcing slower matrix flow to be the dominant infiltration process. In the fall, however, low antecedent moisture conditions resulted in less conductive flow paths in the Umpa, and thus, significantly lower infiltration rates.

Burch, G.J., Moore, I.D, and Burns, J., 1989, Soil hydrophobic effects on infiltration and catchment runoff: Hydrological Processes, v. 3, p. 211-222.

Results of this investigation illustrate the difficulty of predicting how water-repellent conditions will affect a watershed. Eucalypt forest catchments at two sites in southeastern Australia showed strikingly different responses to precipitation events, following the development of drought-induced, water-repellent soils. At the first site, water repellency (when present) significantly interfered with infiltration, as was evidenced by a comparison of runoff generation in a forest and grassland catchment. At this site, the grassland catchment consistently produced more runoff than the forested catchment when soils were wettable. However, the scenario was reversed during an isolated, summer storm, when the forested catchment (which had developed water- repellent soils) generated significantly higher runoff than the grassland catchment. In contrast, a second forested site, also exhibiting drought-induced water repellency, generated minimal runoff in response to precipitation events. This discrepancy was attributed to the dense network of macropores present at the second site, which enabled the water repellent soils to maintain high infiltration rates via preferential flow.

Campbell, R.E., Baker, M.B., Jr., Ffolliot, P.F., Larson, F.R., and Avery, C.C., 1977, Wildfire effects on a ponderosa pine ecosystem– an Arizona case study: Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo., U.S.D.A. Forest Service Research Paper RM-191, 12 p.

This was a comprehensive study that evaluated various effects of wildfire on a southwestern forest ecosystem. The investigation was conducted following a 1972 wildfire in a ponderosa pine forest in north-central Arizona. Soils were derived from the Kaibob limestone formation. Researchers established three watersheds representing severe and moderate burns and an unburned control, to study the effects of the fire. Burned areas exhibited significantly reduced rates of infiltration, which were attributed to fire-induced water repellency and to sealing of unprotected surface soil. Water repellency in the soil was evaluated by placing drops of distilled water on fresh soil cores. Data from these tests was extremely variable and inconsistent between sampling dates, possibly due to variations in soil moisture. Overall, however, researchers found that water repellency was the most prevalent in severely burned areas. Although unburned sites also contained water-repellent layers, the repellency was only a surface phenomenon, whereas in burned sites, the water-repellent layer occurred below a wettable area. Water repellency was generally found to be inversely related to soil moisture content (particularly in unburned areas). Some water repellency persisted four years after the fire in severely burned areas. Repellency also persisted more in the sandy loam soils than in finer-textured soils. In addition to information on water-repellency, this paper also provides the results of soil moisture and infiltration monitoring over the course of four years after the fire.

Cory, J.T., and Morris, R.J., 1969, Factors restricting infiltration rates on decomposed granitic soils, *in* DeBano, L.F., and Letey, John, eds., Water-repellent soils: University of California, Riverside, May 6-10, 1968, Proceedings, p. 149-161.

The purpose of this investigation was to determine the extent and nature of water repellency in the Carson Range of the Sierra Nevadas. Granitic (coarse-textured) soils were taken from burned and unburned, brushland and pine-covered areas and subjected to various heat treatments. Although the first set of experiments did not simulate natural conditions (no temperature gradients were produced) they did provide information with respect to temperature and time effects on water-repellent properties. Researchers found that temperatures over 600°C destroyed water repellency when maintained for one hour. Repellency reached a maximum at 200°C. In experiments that simulated natural conditions (intact samples were heated from the top only), researchers observed that longer heating times caused water-repellent layers to move deeper into the soil and increase in thickness. These changes were also associated with a decrease in water repellency. Attempts to identify hydrophobic compounds were inconclusive.

Crockford, H., Topalidis, S., and Richardson, D.P., 1991, Water repellency in a dry sclerophyll eucalypt forest– measurements and processes: Hydrological Processes, v. 5, p. 405-420.

This study examined the water repellency at numerous sites in an Australian eucalypt forest over a period of four years. Field measurements were supplemented with lab experiments that attempted to identify some of the processes taking place. Results indicated that several weeks of cool, wet weather were required for water repellency to break down, and a much shorter period of hot, dry weather for it to be reestablished. Three possible explanations were proposed as to the mechanism of breakdown during prolonged wetting: 1) clay aggregates may disaggregate and expose wettable surfaces; 2) litter may swell and enlarge water entry paths; or 3) hydrophobic compounds may undergo chemical transformations. The authors also note that water repellency in pine forests was due to fungal hyphae (a surface phenomenon), and was consequently reduced during mixing for lab preparations, whereas the repellency of eucalypt forest samples resulted from organic matter and was not so easily disrupted.

DeBano, L.F., 1969a., Observations on water-repellent soils in western United States, *in* DeBano, L.F., and Letey, John, eds., Water-repellent soils: University of California, Riverside, May 6-10, 1968, Proceedings, p. 17-29.

This paper describes the theory behind water repellency and discusses the implications with respect to soil-moisture relationships. Figures of moisture retention and evaporation curves for water-repellent and wettable soils are included The paper also discusses infiltration and diffusivity, with accompanying tables and wetting curves. Experimental results suggest that water repellency will alter unsaturated flow (both during evaporation and infiltration), and thus needs to be taken into account when modeling water movement. The author proposes that the capillary changes resulting from differences in apparent liquid-solid contact angles explain some of the effects of hydrophobic substances. He also suggests that moisture transfer in water-repellent soils may be dominated by vapor flow, whereas liquid flow is probably more important in wettable soils.

DeBano, L.F., 1969b., Water movement in water-repellent soils, *in* DeBano, L.F., and Letey, John, eds., Water-repellent soils: University of California, Riverside, May 6-10, 1968, Proceedings, p. 61-89.

This paper provides an introduction to some basic concepts involving water repellency and the effects on water movement. It includes information on relationships between soil moisture and tension, and soil-moisture distribution, in repellent and wettable soils. Also included are infiltration curves for conditions in layered and unlayered soils.

DeBano, L.F., 1969c., The relationship between heat treatment and water repellency in soils: *in* DeBano, L.F., and Letey, John, eds., Water-repellent soils: University of California, Riverside, May 6-10, 1968, Proceedings, p. 265-279.

This paper describes the results of two types of burning experiments that were used to study the relationship between water repellency in brushland soils and heat treatment. The experiments lead the authors to propose a model for water repellency before, during and after fire. Before fire, hydrophobic substances accumulate in the litter layer and mineral soil immediately beneath it. When the fire burns the vegetation litter layer, the hydrophobic substances move downward along temperature gradients. After the fire, a water-repellent layer is located below and parallel to the soil surface on the burned area.

DeBano, L.F., 1971, The effect of hydrophobic substances on water movement in soil during infiltration: Soil Science Society of America Proceedings, v. 35, no. 2, p. 340-343.

Infiltration experiments were conducted on wettable and water-repellent soils using both vertical and horizontal soil columns. Soil samples were collected from the San Gabriel Mountains of southern California, from a burned area that had formerly been covered with chaparral vegetation. Results showed that hydrophobic substances significantly reduced infiltration, especially at the lower water contents. Repellent soils had horizontal infiltration rates that were 25 times slower than those in wettable soils, and more diffuse wetting fronts with significantly lower water contents.

DeBano, L.F., 1981, Water repellent soils: a state-of-the art: Pacific Southwest Forest and Range Experiment Station, Berkeley, Calif., U.S.D.A. Forest Service General Technical Report PSW-46, 21 p.

This paper provides a comprehensive overview of water-repellent soils that addresses the distribution, chemistry, effects on water movement, and classification (measurement) of water repellency, as well as the factors that affect it. The benefits, problems, and research needs of water repellency are also addressed. For each topic, the author includes a discussion of previous research, and concludes with current knowledge of the subject.

DeBano, L.F., and Krammes, J.S., 1966, Water-repellent soils and their relation to wildfire temperatures: Bulletin of the International Association of Scientific Hydrology, v. 11, no. 2, p. 14-19.

A previous (1965) paper by the same authors is one of the first to describe the relationship between fire and soil-water repellency. As part of an ongoing investigation, this study attempted to determine the significance of temperature and duration of heating. Naturally water-repellent soil samples were collected from the San Gabriel Mountains of Southern California, and heated between 300°F and 900°F for up to 20 minutes. Intense water repellency resulted from the milder treatments, whereas extreme temperatures (800-900°F applied for 20 minutes) completely destroyed repellency. Although these experiments did not realistically simulate natural conditions (samples were heated in a muffle furnace rather than from the surface, as would occur in a forest fire), the results still provided some data on time-temperature relationships, and confirmed the role of heating in some forms of water repellency.

DeBano, L.F., and Letey, J., eds., 1969, Water-repellent soils: University of California, Riverside, May 6-10, 1968, Proceedings, 354 p.

The papers listed below are those included in this symposium. Only those marked with asterisks have been annotated, and occur as individual entries throughout this document. In addition to the papers listed, this publication summarizes a general discussion at the end of the meeting in which the use of terminology was discussed. It was concluded that the term, "water-repellent", is more appropriate than the term, "hydrophobic", when referring to soil properties. However, the latter can be used to describe substances that affect a soil's wettability.

Session I – Distribution of Water-Repellent Soils:
*Bond, R.D. The occurrence of water-repellent soils in Australia.
Van't Woudt, B.D. Resistance to wetting under tropical and subtropical conditions.
Jamison, V.C. Wetting resistance under citrus trees in Florida.
*DeBano, L.F. Observations on water-repellent soils in western United States.
*Holzhey, C.S. Water-repellent soils in Southern California.

Session II – Characterizing Soil Water Repellency:
*Letey, J. Measurement of contact angle, water drop penetration time, and critical surface tension.
*Hammond, L.C., and Yuan, T.L. Methods of measuring water repellency of soils.

Session III – Water Movement in Water-Repellent Soils:
*DeBano, L.F. Water movement in water-repellent soils.
*Brandt, G.H. Water movement in hydrophobic soils.
Gardner, H.R. Effects of hexadecanol and organic matter extract on soil.

*Hussain, S.B., Skau, C.M., Bashir, S.M., and Meeuwig, R.O. Infiltrometer studies of water-repellent soils on the east slope of the Sierra Nevada.

Session IV – Modification of Soil Wettability -- Increasing Soil Wettability:
Black, W. Basic chemistry of surface-active agents
Valoras, N. Surfactant adsorption by soil materials
*Cory, J.T. and Morris, R.J. Factors restricting infiltration rates on decomposed granitic soils.
Watson, C.L. Hydraulic conductivity of soil as influenced by surfactants.
Mustafa, M.A. Nonionic surfactant effect upon soil aggregate stability.
*Krammes, J.S. and Osborn, J. Water-repellent soils and wetting agents as factors influencing erosion.

Session V – Modification of Soil Wettability – Decreasing Soil Wettability:
*Bozer, K.B., Brandt, G.H., and Hemwall, J.B. Chemistry of materials that make soils hydrophobic.
Brandt, G.H. Soil physical properties altered by adsorbed hydrophobic materials.
Fink, D.H., and Myers, L.E. Synthetic hydrophobic soils for harvesting precipitation.
Savage, S.M. Contribution of some soil fungi to water repellency in soils materials.

Session VI – Natural Causes of Water Repellency in Soils:
*Bond, R.D. Factors responsible for water repellence of soils
*DeBano, L.F. The relationship between heat treatment and water repellency in soils.
*Holzhey, C.S. Soil morphological relationships and water repellence.
Adams, Susan, Strain, B.R., and Adams, M.S. Water-repellent soils and annual plant cover in a desert scrub community of southeastern California.

Session VII – The Effect of Soil Water Repellency and Wetting Agents on Plant Growth:
Osborn, J.F. The effect of wetting agents and water repellency on the germination and establishment of grass.
Parr, J.F. Effects of surfactants on plant growth and considerations in their use.
Endo, R.M. The deleterious effects of two nonionic surfactants on the germination and growth of various grasses.
Shaw, E. Molecular physics and related properties of water in connection with phenomena of wetting.
Waddington, D.V. Observations of water repellency on turfgrass areas.

DeBano, L.F., Mann, L.D., and Hamilton, D.A., 1970, Translocation of hydrophobic substances into soil by burning organic litter: Soil Science Society of America Proceedings, v. 34, p. 130-133.

Researchers investigated the relationships between soil texture, surface material, and heat-induced water repellency. Four different soil types were evaluated in burning experiments with two different surface materials (sugarbush plant litter, and a water-repellent soil). The soils that were tested included a pure sand, and three samples with varying amounts of sand, silt (12-42%) and clay (1-13%). Researchers observed that hydrophobic substances translated down into the soil during burning and formed water-repellent layers. The thickest and most intense layers occurred under conditions of burned litter as plant top material, and with pure sand as the underlying soil. The results are attributed to the fact that the coarse-textured soils had a smaller surface area to volume ratio. The authors also noted a general increase in water repellency with an increase in translated organic matter, but no direct relationship was found.

DeBano, L.F., and Rice, R.M., 1973, Water-repellent soils– their implication in forestry: Journal of Forestry, v. 71, p. 220-223.

This paper offers an extensive summary of information on water-repellent soils (both biologically and fire-induced), and provides a good base of information on the causes, effects, characteristics, and the interdependence of various factors. Although more current research has since added to the findings presented in this paper, it is still a comprehensive account of previous research on the topic. The authors do, however, neglect to mention some alternative hypotheses regarding the mechanism of formation (e.g. Savage, et al., 1969 and 1972).

DeBano, L.F., Rice, R.M., and Conrad, C.E., 1979, Soil heating in chaparral fires: effects on soil properties, plant nutrients, erosion, and runoff: Pacific Southwest Forest and Range Experiment Station, Berkeley, Calif., U.S.D.A. Forest Service Research Paper PSW-145, 21 p.

In an attempt to determine the effects of prescribed burning on chaparral environments, researchers studied prescribed burns and one wildfire in Southern California between 1968 and 1975. Data on wildfire temperatures (including temperature gradients and durations of heating) and descriptive information on vegetation and soils were used to generate stylized soil heating curves representing different burn intensities. These curves, in turn, enabled researchers to estimate the direct effects of fire on plants, litter, and soil (including chemical, physical, and biological properties), and the long-term effects on erosion, surface runoff, and hydrology. Although published research supplemented the results of this investigation, the authors note that historical measurements of maximum soil and fire temperatures do not adequately characterize heat pulses and time-temperature relationships. Information pertaining to water repellency in this paper is limited to a summary of previous research on the topic.

DeBano, L.F., Savage, S.M., and Hamilton, D.A., 1976, The transfer of heat and hydrophobic substances during burning: Soil Science Society of America Journal, v. 40, no. 5, p. 779-782.

This investigation addressed the role of soil moisture in fire-induced water repellency. Pine litter was burned over wet and dry sand for 5 and 25-minute trials. Out of the four treatment types, the 5-minute burning over dry sand produced the thickest and most intense water-repellent layer. The next most intense repellency developed in the 25-minute burn over wet sand. Although hydrophobic substances traveled the deepest in dry sand after 25 minutes, high temperatures destroyed some of the repellency in the upper layer. Water repellency was concentrated close to the surface in the wet sand trials, and was even shallower for the shorter burn period. Temperatures, however, did not get high enough to destroy repellency at the surface when sands were wet. The paper supplies information on the sequential development of temperature gradients at various depths within the sand profiles, and on the subsequent intensities and depths of water repellency. Results of the analysis of organic matter and carbon content appeared to support the hypothesis (Savage, 1974) of natural fractionation of organic compounds with depth during burning. The authors also note that the presence of soil moisture appeared to interfere with this process. Thus, both polar compounds and extremely water-repellent substances were left near the surface of the wet sand, resulting in intense water repellency. The authors propose that the results suggest that in areas where water repellency is a problem, prescribed burning should be done when the soil is moist.

DeByle, N.V., 1973, Broadcast burning of logging residues and the water repellency of soils: Northwest Science, v. 47, no. 2, p. 77-87.

This investigation focused specifically on water-repellent soils in northern coniferous forests, before and after the burning of logging residues. As a result, the information presented offers a contrast to studies conducted in chaparral settings. The introduction describes occurrences of water-repellent soils in unburned settings resulting from vegetation, microorganisms in the soil, and organic matter. It also discusses prior research on water repellency intensified by fire, including temperatures and durations of heating that enhanced or destroyed the condition. In this study, researchers observed that dry, deciduous litter was very water repellent, but that the mineral portion of the soil exhibited only sporadic repellency. This water repellency was only found to increase in intense fire situations (i.e. wildfires and "jackpot" slash burns), and was temporary. The author speculated that the water repellency (when it existed) was short-lived due to the fine-textured nature of soils in the study area, and that the general lack of repellency following prescribed burns was the result of high soil moisture conditions. He suggested that wildfires produce more repellency because they tend to occur when the soil is relatively dry (thus creating extreme temperature gradients), and that repellency under slash piles results from the high temperatures and long durations of burning that subsequently evaporate soil water. Similarly, chaparral fires result in more extensive water repellency due to the higher burn intensities and lower soil-moisture conditions associated with chaparral settings. The latter also tend to occupy coarser-textured soils, thus enhancing water repellency.

Dekker, L.W., and Ritsema, C.J., 1994, How water moves in a water repellent sandy soil– 1. Potential and actual water repellency: Water Resources Research, v. 30, no. 9, p. 2507-2517.

The first in a series of papers by Dekker and Ritsema analyzing fingerlike wetting patterns in water-repellent soils. This "finger flow", as it is referred to, describes the pattern of infiltration whereby a soil becomes wet in only a few places, and the rest remains dry. It is significant because it indicates the process of preferential flow through the wetted zones, causing surface waters to reach the groundwater more rapidly than by homogeneous wetting. Although finger flow has been described in other situations (i.e. layered soils), this study examines the phenomenon specifically in water-repellent soils (dune sands). It also introduces the concept of "potential" and "actual" water repellency. Potential water repellency refers to measurements performed on oven-dried samples, while actual water repellency refers to field-moist samples. The introduction contains a literature review summarizing the causes of water repellency in soils. Also included in this paper is a brief discussion on the relationship between liquid-solid contact angle and surface tension.

Dekker, L.W., and. Ritsema, C.J., 1995, Fingerlike wetting patterns in two water-repellent loam soils: Journal of Environmental Quality, v. 24, p. 324-333.

This study examined the occurrence of finger flow in water-repellent soils (specifically in a silt loam and silty-clay loam). The results indicated that fingered flow occurred even in places with a relatively low degree of water repellency, and that "fingers" in fine-textured soils were wider than in sandy soils.

Dekker, L.W., and Ritsema, C.J., 1996a, Uneven moisture patterns in water repellent soils: Goderma, v. 70, p.87-99.

In the Netherlands, naturally-occurring water-repellent soils are widespread and they often show irregular moisture patterns, which lead to accelerated transport of water and solutes to the groundwater and surface water. Under grasscover, spatial variability in soil-moisture content is high due to fingered flow, in arable land vegetation and microtopography play a dominant role. Examples are given of uneven soil moisture patterns in water-repellent sand, loam, clay and peat soils with grasscover, and in cropped water-repellent sandy soils. In addition, the influence of fungi in inducing soil-moisture patterns is illustrated.

Doerr, S.H., 1998, On standardizing the 'water drop penetration time' and the 'molarity of an ethanol droplet' techniques to classify soil hydrophobicity - a case study using medium textured soils: Earth Surface Process and Landforms, v.23, p. 663-668.

The 'water drop penetration time' (WDPT) and 'molarity of an ethanol droplet' (MED) methods for assessing soil hydrophobicity are evaluated to determine 1) how well measurements taken on air-dried and sieved laboratory samples reflect the hydrophobicity of and undisturbed, *in situ* soil surface in the field; 2) to examine the reproducibility of hydrophobicity results in the laboratory, and 3) to determine the compatibility of the MED and WDPT test results. Using air-dried soils with a broad particle size and hydrophobicity range, this study shows that a high representativeness and replicability of results can be achieved. A close relationship between the two sets was found for highly, but not for moderately hydrophobic soils. Guidelines are suggested to increase representativeness, replicability, and comparability of results in future studies.

Doerr, S.H., Shakesby, R.A., and Walsh, R.P.D., 1998, Spatial variability of soil hydrophobicity in fire-prone Eucalyptus and pine forests, Portugal: Soil Scince, v. 163, no.4, p. 313-324.

This paper assess the *in situ* severity and spatial variability of hydrophobicity of surface soils in dry summer conditions in burnt and unburnt *Pinus pinaster* and *Eucalyptus globulus* forests in Portugal. The molarity of ethanol droplet (MED) technique was used for the evaluation. The average severity of hydrophobicity in both long-unburnt and recently burnt forests is among the highest recorded. The authors concluded that burning in the study area had little impact on surface hydrophobicity. This is attributed to 1) preburn hydrophobicity already so severe that the organic compounds released from the litter during the burning contribute no detectable additional hydrophobic effects; and 2) fire temperatures were insufficient to destroy surface hydrophobicity. Spatial variability of hydrophobicity is generally low for all land types. The authors content that the relative spatial uniformity is induced by the planting of *P. pinaster* and *E. globulus* ; the litter layers of both species, and the root zone in the case of *E. globulus* , are identified as the sources of hydrophobic substances. Extreme hydrophobicity in *E. globulus* stands is found to develop within 2 years of planting on previously hydrophilic plowed terrain.

Doerr, S.H., Shakesby, R.A., and Walsh, R.P.D., 1996, Soil hydrophobicity variations with depth and particle size fraction in burned and unburned *Eucalyptus globulus* and *Pinus pinaster* forest terrain in the Águeda basin, Portugal: Catena, v. 27, p. 25-47.

The evidence presented in this paper suggests that soil hydrophobicity in the Águeda Basin exhibits three characteristics that conflict with the findings of previous studies in other localities. First, burning in the study area was not found to enhance hydrophobicity, as unburned and old burn soils are just as water repellent as newly burned soils. Second, hydrophobicity is characteristic of soils from the surface down to close to the Cw horizon rather than confined to a near-surface layer sandwiched by surface and subsurface hydrophilic layers. Third, hydrophobicity is associated with the finer rather than the coarser size fractions of the soils. The authors conclude that the enhanced overland flow effects found in post-burn land in the study may be more the result of plugging of pre-burn gaps in an already existing near-surface hydrophobic layer with fine hydrophobic material, than of creation or translocation of a hydrophobic layer because of burning. Soils on unburned land and old-burn land experience little overland flow despite their hydrophobic character when dry because of their numerous routeways provided by roots and soil faunal activity through the hydrophobic aggregates of the soil. And lastly, the authors describe hydrophobicity that tends to disappear when the soils become wet.

Dyrness, C.T., 1976, Effect of soil wettability in the high Cascades of Oregon: Pacific Northwest Forest and Range Experiment Station, Portland, Oregon, U.S.D.A. Forest Service Research Paper PNW-202, 18 p.

Researchers studied fire-related impacts over the course of six years following a wildfire in the Willamette National Forest in Oregon. Vegetative cover consisted of lodgepole pine stands, and soil textures ranged from loamy-sands to sandy-loams. Results showed a considerable variation in water repellency with depth in burned area soils compared to unburned controls. Similar to other studies, the surface inch of soil was usually wettable after the fire, but deeper layers (1-6 inches) exhibited significant water repellency. This condition persisted up to five years after the fire, and was negligible by the sixth. Wettability of lightly burned soils recovered faster than in heavily burned areas during the third and fourth years. Results also indicated that infiltration rates in burned soils decreased three-fold. The author notes that contact angle measurements of water repellency tended to be more reliable and consistent than water drop tests. The use of a wetting agent (Aqua-Gro) did little to alleviate water repellent conditions.

Emerson, W.W., and Bond, R.D., 1963, The rate of water entry into dry sand and calculation of the advancing contact angle: Australian Journal of Soil Research, v. 1, no. 1, p. 9-16.

This study used the rate of capillary rise of a wetting front in a vertical column of sand to calculate the advancing contact angle. The method differs from a similar study by Letey, Osborn, and Pelishek (1962), where the contact angle was calculated by measuring the downward rate of wetting front infiltration.

Everett, R.L., Java-Sharpe, B.J., Scherer, G.R, Martin, W.F., and Ottmar, R.D., 1995, Co-occurrence of hydrophobicity and allelopathy in sand pits under burned slash: Soil Science Society of America Journal, v. 59, no. 4, p. 1176-1183.

Researchers examined the development of allelopathic and water-repellent layers with respect to fire under broadcast and piled slash. The paper cites research describing some environmental conditions under which allelopathic substances form. These conditions are similar to those which result in natural water repellency. Experimental plots consisted of sand pits under slash. Following fire, water-repellent layers developed between zero and eight-centimeter depths, and were up to eight centimeters thick. Moderate water repellency was found to extend to greater depths and thicknesses than severe repellency. In addition to water-repellent layers, slash burning produced underlying allelopathic layers. Researchers observed a higher occurrence of water repellency and allelopathy under burned slash piles than under broadcast slash. With respect to vegetation, allelopathic effects appeared to be limited to unsaturated soil conditions. Water-repellent layers were also found to decrease seed emergence and development. The authors conclude that the experimental results imply the potential for severe erosion following fires, due to the combined difficulty of vegetative reestablishment, and complications with water repellency.

Fink, D.H., 1970, Water repellency and infiltration resistance of organic-film-coated soils: Soil Science Society of America Proceedings, v. 34, p. 189-194.

This research evaluated the effects of various soil textures and organic films on water repellency and infiltration resistance. The author concludes that the effective contact angle is independent of soil chemical and physical properties. Instead, he suggests that it is related to the proportion of soil surface covered with organic material, and to the structure of the hydrophobic group.

Fink, D.H., and Mitchell, S.T., 1975, Freeze-thaw effects on soils treated for water repellency, *in* Hydrology and Water Resources in Arizona and the Southwest: American Water Resources Association, Hydrology Section, Arizona Section, Arizona Academy of Sciences, Tempe, Ariz., April 11-12, 1975, Proceedings, v. 5, p. 79-85.

This study was initiated by the failure (little to no runoff production) of a water harvesting catchment in Arizona that had been treated with paraffin wax in order to make the soil water repellent. Researchers hypothesized that this failure was the result of freeze-thaw processes that destroyed the artificially-induced water repellency of the soil. They performed a series of lab experiments on various soils and found that coarser-textured soils tended to withstand freeze-thaw cycling better than finer-textured soils. Results also indicated that since smoother plots retained less ponded water, they would be less likely to suffer freeze-thaw damage. However, the investigation concluded that water repellency breakdown in the water harvesting catchment was not due to freeze-thaw processes, but to shrink-swell properties of the soil.

Foggin, G.T., and DeBano, L.F., 1971, Some geographic implications of water-repellent soils: Professional Geographer, v. 23, p. 347-350.

This review paper includes general discussions of the nature of naturally-occurring and fire-induced water repellency, factors causing repellency, and geographic and geomorphic implications of water repellency. Water repellency of soils affects the runoff cycle of a watershed. A repellent layer will promote surface runoff by reducing infiltration rates. On burned plots, precipitation saturates only the thin, overlying soil, which may lead to sheet erosion and rill and gully formation. Intense and concentrated infiltration may occur where burrow holes, tension cracks and root channels breach the repellent layer. This may allow surface runoff and near surface lateral flow to enter the deeper soil. Increased surface runoff also adds to storm flow within the drainage network, removing material stored in the channels as well as contributing to channel scour. This increase in both discharge and sediment yield produces downstream flooding.

Franco, C.M.M., Tate, M.E., and Oades, J.M., 1995, Studies on non-wetting sands. I. The role of intrinsic particulate organic matter in the development of water-repellency in non-wetting sands: Australian Journal of Soil research, v.33, p.253-263.

Giovannini, G., and Lucchesi, S., 1983, Effect of fire on hydrophobic and cementing substances of soil aggregates: Soil Science, v. 136, no. 4, p. 231-236.

Researchers performed an experimental burn within the Sardinian Regional Forest in Italy, to study the effects of fire on some factors related to soil erodibility. The burn covered an area of approximately 100m^2 in a chaparral-vegetated watershed. Soils derived from Paleozoic schists and sandstones exhibited a slight natural repellency prior to burning, which the authors suggest was due to the incorporation of intensely hydrophobic organic matter into the mineral fraction. Fire destroyed this water repellency in the surface horizons, and caused a decrease in organic matter content and aggregate stability. In contrast, post-fire aggregate stability in the B horizons increased, due to inputs of translocated organic matter. However, unlike other studies (e.g. DeBano, et al, 1970) which have attributed post-fire, subsurface water repellency to translocated organic matter, this investigation found that the underlying horizons remained wettable. The authors suggest that, in this case, fine-textured soils may have interfered with the development of water repellency.

Giovannini, G., and Lucchesi, S., 1984, Differential thermal analysis and infrared investigations on soil hydrophobic substances: Soil Science, v. 137, no. 6, p. 457-462.

The differential thermal analysis (DTA) of a water-repellent soil collected in a coastal pine forest was characterized by two exothermic peaks in the temperature range of 220 to 550^{0}C. Extraction of the soil with benzene resulted in suppression of the second exothermic peak as well as the nonwettable property. The DTA coupled with IR spectrophotometry suggested that the soil's water-repellency may be due to a fraction or organic material with a low degree of humification. The IR investigation and fractionation by absorption chromatography of the extracted substances show a great complexity; the only hypothesizable compound arrangement was an ester between phenolic acids and polysaccharide substances. The complete combustion curve of the soil's water repellent substances suggested that only temperatures above 550^{0}C can destroy the nonwettable property in the soil.

Giovannini, G., Lucchesi, S., and Cervelli, S., 1983, Water repellent substances and aggregate stability in hydrophobic soil: Soil Science, v. 135, no. 2, p. 110-113.

This study examined the correlation between soil water repellency and aggregate stability. Researchers suggested that less polar compounds were more hydrophobic. These substances were extracted from a water-repellent soil using benzene, and then applied to soil aggregates from a wettable soil. The authors concluded that hydrophobic substances increased aggregate stability by behaving as cementing substances. In a wettable soil, increased aggregation usually improves infiltration and thus reduces erosion. However, this paper suggested that in a hydrophobic soil, water-repellent aggregates would lead to more erosion than in a wettable soil.

Giovannini, G., Lucchesi, S., and Giachetti, M., 1987, The natural evolution of a burned soil: a three-year investigation: Soil Science, v. 143, no. 3, p. 220-226.
Fire-induced physicochemical changes in a soil were evaluated three years after an experimental burn in Italy. In order to determine the effect of time, the same parameters were evaluated in this investigation as in a previous study of the same area (Giovannini and Lucchesi, 1983). Results showed that the A horizon had experienced a decrease in organic matter, destruction of water repellency, and a decrease in the water stability index values of soil aggregates immediately following the fire. All of these parameters increased after the burn, and reached pre-fire levels by the third year. Although the B1 and B horizons exhibited an increase in organic matter following the fire, these levels did not change during the three years of subsequent monitoring.

Hammond, L.C., and Yuan, T.L., 1969, Methods of measuring water repellency of soils, *in* DeBano, L.F., and Letey, John, eds., Water-repellent soils: University of California, Riverside, May 6-10, 1968, Proceedings, p. 49-60.
This paper presents and discusses the capillary and dynamic capillary rise methods for determining an apparent advancing soil-water contact angle as a measure of water repellency. These two approaches allow for the incorporation of wetting time in the measurement, and provide an essentially instantaneous determination of water repellency. The authors point out that the current renewed interest in the nature and consequences of water repellency in soils demands new and improved methods for both assessing water repellency, and understanding it. They conclude that the complexity of water-repellent behavior in soil will require several parameters to be characterized.

Harper, R.J., and Gilkes, R.J., 1994, Soil attributes related to water repellency and the utility of soil survey for predicting its occurrence: Australian journal of Soi Research, v. 32, p. 1109-1124.

Henderson, G., 1981, Physical and chemical aspects of water repellent soils affected by slash burning at Vancouver, British Columbia [abs.]: Vancouver, University of British Columbia, Faculty of Forestry, M.S. thesis, p. ii-iii.
This study used water drop penetration time and contact angles to characterize soil water repellency in a Vancouver watershed subjected to slash burning. Hydrophobic extractions were also analyzed for functional groups using infrared absorption chromatography. Results indicated that slash burning caused water repellency to increase, with repellent conditions persisting up to six years after fire. The majority of extracted hydrophobic compounds were non-polar. Furthermore, infrared absorption analysis revealed that the hydrophobic substances had both hydrophilic and hydrophobic components. The author suggested that the hydrophilic end of the organic molecule bonds to soil particles, leaving the hydrophobic end exposed. When these extracts were added to wettable sand, heat treatments of 250°C for 10 minutes caused repellency to increase. The sand again became wettable when heated to 350°C. The author also noted that the method of using water drop penetration time was more reliable and consistent than the contact angle method to indicate the presence of soil water repellency.

Henderson, G.S., and Golding, D.L., 1983, The effect of slash burning on the water repellency of forest soils at Vancouver, British Columbia: Canadian Journal of Forest Research, v. 13, p. 353-355.

This study compared the water repellency of soils from slash burn clearcuts of various ages, with those in unburned clearcuts, and uncut control plots. Soil textures were predominantly sands, sandy loams, loamy sands, and gravely sands. Burned plots tended to exhibit more repellency than unburned plots, especially in younger (one or two year-old) burns. The most intense repellency occurred in the upper four centimeters of the soil, and decreased with depth. Humus samples exhibited severe water repellency. In contrast to other studies, researchers generally did not observe a surface hydrophilic condition or severe erosion. The reduced longevity of repellency was attributed to the high precipitation of the region. However, the authors also caution that repellency may be a chronic feature once established, since hydrophobic substances are not easily degraded.

Hillel, D., and Berliner, P., 1974, Waterproofing surface-zone soil aggregates for water conservation: Soil Science, v. 118, p. 131-135.

Naturally occurring soil aggregates from the Mediterranean region of Upper Galilee were treated with water-repellent silicone to determine the effects upon infiltration and evaporation. When a soil surface was covered with a layer of these small (0.2-0.5mm), water repellent aggregates, infiltration was reduced. The largest (2-5mm) aggregates had the opposite effect, in that infiltration increased. Aggregates remained dry as water moved through interaggregate voids. Larger, water repellent aggregates were also found to reduce evaporation losses, in contrast to hydrophilic aggregates which appeared to have no significant effect.

Holzhey, C.S., 1969a, Water-repellent soils in southern California, *in* DeBano, L.F., and Letey, John, eds., Water-repellent soils: University of California, Riverside, May 6-10, 1968, Proceedings, p. 31-41.

This paper provides a summary of the nature and distribution of water-repellent soils in southern California. The author differentiates between seasonal and year-round water repellency. The former is characterized by water-repellent horizons immediately below decomposing woody litter. In this situation, repellency is most pronounced in dry soils, but breaks down when soils become moist in the winter. Repellency is then reestablished upon drying. In contrast, soils that are water repellent year round are wettable when extremely dry, but become repellent following rain in the fall. The latter soils contain little or no woody plant litter. The author states that the type of repellency is related to the nature of the associated plant communities, which in turn reflects one of three climatic regimes (desert, mountain, and marine). The climatic patterns themselves also affect the expression of water repellency. Seasonal repellency is dominant in the lower elevations, while year-round repellency is found in mountain areas and mountain-lowland transitions. The paper includes a discussion on the distribution of water repellency as determined by vegetation type, along with a chart depicting the relative water repellency of soils beneath various woody species.

Holzhey, C.S., 1969b, Soil morphological relationships and water repellence, *in* DeBano, L.F., and Letey, John, eds., Water-repellent soils: University of California, Riverside, May 6-10, 1968, Proceedings, p. 281-288.

Water repellency in southern California soils is discussed with respect to various physical attributes and soil morphologies. The author notes that herb-dominated communities primarily exhibit seasonal water repellency, whereas year round water repellency is often found in surface horizons with littered forest soil morphologies.

Hubbel, D.H., 1988, Developmental aspects of water-repellency of sandy soils: Soil Science Society of America Journal, v. 52, p. 1512-1514.

In contrast to studies where water-repellent soils were reported to break down under wet conditions, this paper described the occurrence of a water-repellent soil in which repellency (related to microbial growth) was intensified by high humidity conditions. The investigation originally attempted to transfer the latter form of repellency from a water-repellent, Florida sand, to other wettable materials. Direct contact between materials was ineffective in transferring repellency. During the course of the experiment, researchers discovered that repellency was actually suppressed when another variety of Florida soil (Eustis fine sand) was mixed with the repellent sand. This elicited another investigation into the mechanism of suppression, which determined that an organism (apparently a *Bacillus* species) in the Eustis sand produced a volatile product capable of suppressing the water repellency.

Hudson, R.A., Traina, S.J., Shane, W.W., 1994, Organic matter comparison of wettable and nonwettable soils from bentgrass sand greens: Soil Science Society of America Journal, v. 58, no. 2, p. 361-366.

Unlike previous studies that have only analyzed organic matter associated with water-repellent soils, this research included organic matter analysis of wettable soils from the same site. Researchers compared the alkaline extractable and lipid fractions of wettable and nonwettable soils from creeping bentgrass sand greens. Soil samples of each type were taken from two sites and subjected to a series of extraction sequences. At the first site, the hydrophobicity appeared to be the result of physical or structural differences, rather than differences in organic matter. However, methanol extractions on samples from the second site did reveal the presence of some qualitative differences. The introduction includes a literature review of previous research on the nature of hydrophobic substances.

Hussain, S.B., Skau, C.M., Bashir, S.M., and Meeuwig, R.O., 1969, Infiltrometer studies of water-repellent soils on the east slope of the Sierra Nevada, *in* DeBano, L.F., and Letey, John, eds., Water-repellent soils: University of California, Riverside, May 6-10, 1968, Proceedings, p. 127-131.

Simulated rainfall experiments were used to evaluate runoff with respect to various soil characteristics (e.g. initial soil moisture, bulk density, and organic matter), and six different cover treatments. The study area, located approximately 20 miles south of Reno, Nevada, was dominated by gravely-loamy sands, and covered by chaparral vegetation and stands of pine. Researchers found that pine litter significantly decreased wettability of the soil. However, they found that although the pine litter imparted water repellency to the soil, it also appeared to result in a better-structured soil, capable of holding more moisture. As many other researchers have found, burning caused a water repellent layer to form below the surface, leaving a wettable layer on top. The burned plots exhibited higher bulk densities than plots where pine litter had been manually removed from the surface. Despite this characteristic, the burned plots still had higher rainfall retention.

Imeson, A.C., Verstraten, J.M., van Mulligen, E.J., and Sevink, J., 1992, The effects of fire and water repellency on infiltration and runoff under Mediterranean type forest: Catena, v. 19, p. 345-361.

Researchers performed a series of rainfall simulation experiments on burned and unburned soils in the Selva region of Catalonia, Spain, to determine the relationship between hillslope hydrology and forest fires. The study found infiltration patterns to be similar for burned and unburned soils due to the presence of macropores (illustrated with photographs) in the vicinity of vegetation. These macropores rapidly conducted water to lower soil horizons, thus bypassing a water-repellent layer near the surface, and preventing high rates of hillslope runoff from occurring. In unburned locations, water was intercepted from litter and throughflow above water-repellent AE or E horizons, while in burned areas the macropores intercepted overland flow from a water-repellent surface. Although runoff from burned slopes was higher over short distances due to the loss of surface litter (and detention storage), the number of macropores also increased in burned soils, thus providing more conduits for infiltration. Consequently, infiltration rates were high following forest fires. However, burned soils also showed the potential to degrade over time and reduce porosity. In light of this, the paper concluded that more research is needed to study post-fire changes in soil properties.

Jex, G.W., Bleakley, B.H., Hubell, D.H., and Munro, L.L., 1985, High humidity-induced increase in water repellency in some sandy soils: Soil Science of America Journal, v. 49, p. 1177-1182.

The degree of resistance to water penetration of diverse water-repellent soils was found to be controlled by their moisture states. Repellency was found to increase sharply when samples of a hyperthermic, uncoated Typic Quartzipsamment soils were incubated at 100% relative humidity and to decline when wetted or incubated at humidities less than 90%. A soil which was not water repellent in the field did not become repellent at 100% relative humidity. Repellency increase in the soils was temperature dependent and could be eliminated by gamma irradiation, indicating a biological nature of the process. Application of antibiotics prior to incubation suggested that prokaryotic organisms were essential to repellency increase. A dilution study of the soil incubated at 100% relative humidity for various periods revealed that the actinomycete population correlated best with repellency increase. Actinomycetes were found to dominate the visual field when the incubated soil was examined by electron microscopy. A model for repellency increase and decline, based on soil humidity, is offered.

John, P.H., 1978, Heat-induced water repellency in some New Zealand pumice soils: New Zealand Journal of Science, v. 21, p. 401-407.

This paper discusses temperature-time combinations that produce varying degrees of (and destruction of) water repellency in volcanic soils. The author notes that only surface soils beneath stands of *Pinus radiata* and scrub produced repellency when heated, while sands of low organic content beneath pasture land exhibited no repellency after heat treatment. Also discussed are methods of measuring repellency and advantages of these methods, based on the paper by Watson and Letey (1970).

Jungerius, P.D., and de Jong, J.H., 1989, Variability of water repellence in the dunes along the Dutch Coast: Catena, v. 16, p. 491-497.

This study describes a naturally-occurring water repellency in soils developed on sand dunes. Some soil types are more sensitive to erosion by slope wash than erosion by wind due to water repellency that is apparent when the sand is dry. Water repellence of the dune soils can best be measured with the Water Drop Penetration Time (WDPT) test. A high temporal and spatial variability of the WDPT values is described. There is a complex relationship between water repellence and organic matter content - the age of the organic matter appears to be more important than the type of vegetation cover.

King, P.M., 1981, Comparison of methods for measuring severity of water repellence of sandy soils and assessment of some factors that affect its measurement: Australian Journal of Soil Research, v. 19, p. 275-285.

This paper includes a comprehensive investigation and discussion of water repellency measurement. The study evaluated three quick field methods of assessing water repellency in sandy soils, including an ethanol drop test (modified from Watson and Letey, 1970), a water drop penetration test, and the infiltration rate of water into soil from a small ring infiltrometer. The purpose of the experiments was to determine the effectiveness of these tests (by comparing them against each other and to contact angle measurements derived from the capillary rise technique), and to determine factors that may have an impact on repellency measurements, such as soil temperature, soil abrasion (due to sieving and pouring), and soil moisture. Results showed that intense sieving dramatically reduced water repellency, but that the effects of light sieving were negligible. However, it was also recommended that tests be conducted on lightly sieved samples, rather than on undisturbed ones, because a greater variability of repellency will result from the latter (due to root channels and the uneven distribution of organic matter). Furthermore, since different moisture contents produced significantly variable results, the author recommended that samples should be air- or oven-dried prior to testing. Temperature was also found to have a significant effect on water repellency, especially in South Australian soils. The author suggested that this temperature sensitivity may have been responsible for the decreased winter infiltration rates in South Australian soils described by Bond (1969), rather than an increase in fungal activity.

Krammes, J.S., and Osborn, J., 1969, Water-repellent soils and wetting agents as factors influencing erosion, *in* DeBano, L.F., and Letey, John, eds., Water-repellent soils: University of California, Riverside, May 6-10, 1968, Proceedings, p. 177-187.

These workers hypothesized that a wetting agent treatment could reduce surface runoff and erosion from areas having water-repellent soils after wildfires. The results of several plot studies in Southern California generally support the hypothesis. In most case the treatment significantly reduced surface runoff and erosion, and in one case not only reduced total debris yield but also aided in reducing dry-creep erosion. On some plots, however, the treatment was beneficial only for decreasing surface runoff, and on others it showed no significant result. The authors concluded that the water-repellent wetting agent treatment resulted in a very favorable benefit to cost ratio, although the high cost of the treatment requires data on runoff and erosion to identify potential treatment areas. The authors argued for selective application of wetting agents to highly erodible areas.

Krammes, J.S., and DeBano, L.F., 1965, Soil wettability: a neglected factor in watershed management: Water Resources Research, v. 1, no. 2, p. 283-286.

This represents one of the first studies to investigate the formation of water-repellent soils and their effects on runoff processes. Researchers used the method of water drop penetration time (rather than contact angle) to rapidly assess water repellency in the field. The authors distinguish between the water repellency of extremely dry soils (caused by the formation of impenetrable air films at the water-soil interface) which transmit water after being moistened, and soils that maintain water-repellent properties at fairly high moisture contents (caused by hydrophobic substances on the mineral grains). Water-repellency of the former can be overcome by application of water to the soil under a vacuum, but in the latter, such treatment will not significantly affect water uptake. Water-repellent soils of the second type were identified in the San Dimas Experimental Forest of Southern California, a chaparral environment, by water drop tests in the field and laboratory. The condition was more prevalent in coarse-textured soils, and appeared to be related to temperature. The author also noted that the water-repellent soils were covered by saturated layers, and had underlying layers that were wet where roots or other channels were present. This is a frequently cited paper that forms the foundation for later research.

Kutiel, P., and Inbar, M., 1993, Fire impacts on soil nutrients and soil erosion in a Mediterranean pine forest plantation: Catena, v. 120, p. 129-134.

Leitch, C.J., Finn, D.W., and van de Graff, R.H.M., 1983, Erosion and nutrient loss resulting from Ash Wednesday (Feb. 1983) wildfires; a case study: Australian Forestry, v. 46, p. 173-180.

Letey, John, 1969, Measurement of contact angle, water drop penetration time, and critical surface tension, *in* DeBano, L.F., and Letey, John, eds., Water-repellent soils: University of California, Riverside, May 6-10, 1968, Proceedings, p. 43-47.

This paper describes various techniques of characterizing water repellency, including measurement of contact angles, water drop penetration time, and the potential use of critical surface tension. The author reviews the concepts involved in his 1962 publication on measurement of liquid-solid contact angles, and explains that since the contact angle is difficult to measure directly on rough surfaces, the apparent contact angle can be calculated instead by measuring the rate of water flow through a soil column, or the height of capillary rise. This paper is often cited for the method of using water drop penetration time (WDPT) to rapidly assess water repellency, although it has been used in prior research as well. Letey emphasizes that WDPT does not necessarily indicate contact angle, but rather, the persistence of water repellency. At best, one can assume that at some point the contact angle is greater than 90° if water beads up on the surface. This paper presents the preliminary stages of using critical surface tension to characterize water repellency. The method is further developed in later research (Watson and Letey, 1970), and then slightly modified by King (1981).

Letey, John, Osborn, J., and Pelishek, R.E., 1962a., Measurement of liquid-solid contact angles in soil and sand: Soil Science, v. 93, no. 3, p. 149-153.

This paper is often cited for its explanation of contact angle measurement and characterization of water repellency. The model applies Poiseuille's approximation of flow in capillary tubes. Since ethanol has a zero contact angle and wets all solids, infiltration tests with ethanol were used to calculate the effective pore radius and in turn, the contact angle for other solutions. However, the model did not work well for pure sand, possibly due to the retention of trapped air within the pores. The authors also suggest that water drop tests have limitations in defining water repellency, especially when comparing soils of different textures or aggregations.

Letey, John, Osborn, J., and Pelishek, R.E., 1962b., The influence of the water-solid contact angle on water movement in soil: Bulletin of the International Association of Scientific Hydrology, v. 7, p. 75-81.

Researchers investigated the effect of contact angle on capillary rise, moisture retention, saturated hydraulic conductivity, and evaporation. The paper includes water infiltration curves that sharply contrast those normally observed for a wettable soil. Water infiltration was slower and evaporation rates were lower in the water-repellent samples than in the wettable soils. Water-repellent soils also drained at a lower suction than wettable ones.

Mallik, A.G. and Rahman, A.A., 1985, Soil water repellency in regularly burned Calluna heathlands; comparison of three measuring techniques: Journal of Environmental Management, v.20, p. 207-218.

Mansell, R.S., 1970, Infiltration of water into soil columns which have a water-repellent layer: Proceedings, Soil and Crop Science Society of Florida, Proceedings, vol. 29, p. 92-102.

The object of this paper was to provide a physical analysis for the influence of a layer of water-repellent soil upon infiltration into an otherwise wettable profile. Green and Ampt's equation for infiltration velocity was used to analyze infiltration of water into a soil profile that has a subsurface layer of water-repellent soil. A comparison of infiltration for vertically downward, horizontal, and vertically upwards cases revealed that the relative decrease in velocity due to the presence of a water-repellent layer was the greatest for the upward case, the least for the downward case, and intermediate for the horizontal case. This a water-repellent soil layer should be most effective in reducing surface evaporation by decreasing upward capillary flow, less effective in reducing lateral water flow to plant roots, and least effective in reducing downward flow during rainfall or irrigation. However, on sloping surfaces a layer of soil that is even marginally water-repellent effectively reduces downward infiltration, and, consequently, increases surface runoff. Experimental results from infiltration into a horizontally positioned soil column showed that a water-repellent layer located behind wettable soils does significantly reduces the infiltration velocity.

Ma'shum, Mansur, and Farmer, V.C., 1985, Origin and assessment of water repellency of a sandy South Australian Soil: Australian Journal of Soil Research, v. 23, p. 623-626.

This paper addresses the variations in water repellency resulting from different extraction and drying procedures. The study tested samples of a sandy lucerne pasture soil from South Australia, and found that water repellency can be falsely removed with one treatment (i.e. hot water extraction), but reestablished with subsequent chloroform treatment, indicating that the water repellent substances were not removed. It also shows that different drying procedures result in different degrees of water repellency (i.e. air-dried soil was less repellent than oven-dried soil). This variability was attributed to changes in the molecular conformation of organic matter. Further tests on the effects of agitation on water repellency led to the conclusion that the water repellency of the original soil was due to both coatings on sand particles and inter-mixed, partially decomposed plant remains.

Ma'shum, Mansur, Tate, M.E., Jones, G.P., and Oades, J.M., 1988, Extraction and characterization of water-repellent materials from Australian soils: Journal of Soil Science, v. 39, p. 99-110.

Researchers used organic solvent systems to extract hydrophobic organic materials from Australian soils. Organic materials extracted with a mixture of isopropanol/ammonia were shown to be long chain polymethylene waxes. The extractions indicated that water repellency was not covalently linked to the surface of sand grains. This report includes technical detail on structures and types of compounds in hydrophobic organic materials. It is useful if one is interested in bonding and the chemical makeup of these compounds, or in methods of extraction from soils.

Ma'shum, Mansur, Oades, J.M., and Tate, M.E., 1989, The use of dispersible clays to reduce water-repellency of sandy soils: Australian Journal of Soil Research, vol. 27, p. 797-806.

The work presented in this paper deals with the role of surface area in determining water-repellency in soils, and the effects if intermixing small amounts of finely particulate materials, including clays, upon the water repellency. Water-repellency induced by organic compounds such as cetyl alcohol on acid-washed sand is a function of both the concentration of the hydrophobic materials and the surface area of the sand. Sands with low surface area are easily rendered hydrophobic. The admixture of dispersible clays with water-repellent soils was found to be particularly effective in alleviating water-repellency. The ability of clays to disperse and thus spread over the hydrophobic surfaces of the sand grains was found to be important. This ability is related to both their sodicity and particle shape, which is primarily determined by mineralogy. Because of their microstructures, kaolinite and illite are shown to be more effective in decreasing hydrophobicity than montmorillonite.

McGhie, D.A., 1980, The contribution of the mallet hill surface to runoff and erosion in the Narrogin region of Western Australia: Australian Journal of Soil Research, v. 18, p. 299-307.

Runoff and erosion were compared among five different land classes in the Great Southern area of Western Australia. The results showed that the mallet hill surface (an Australian land class) yielded the highest runoff. This characteristic was attributed to several factors, including water repellency and a "heavier textured" (higher clay content) soil. Forested and harvested areas of the mallet hills land class exhibited the most severe water repellency (persistent even at 10-15 cm depth), which was related to comminuted surface litter in the soil. A decrease in repellency with time (in cleared areas) was attributed to the removal of topsoil, rather than weathering of organic matter. Researchers also noted, however, that the effect of water repellency on runoff in forested areas of mallet hills was mitigated by the presence of surface litter.

McGhie, D.A., and Posner, A.M., 1980, Water repellence of a heavy-textured Western Australian surface soil: Australian Journal of Soil Research, v. 18, p. 309-323.

This study evaluated the degree and cause of water repellency in virgin mallet hill soil near Narrogin, Western Australia. The occurrence of water repellency in this case was unusual, since the soils contained more than 20% clay. The authors attributed this anomaly to the presence of clay aggregates in the soil, which allowed water repellency to persist, despite the texture. Results of the investigation indicated that severe water repellency only developed where litter was present. Fungi (*Aspergillus* and *Penicillium*), however, did not contribute to water repellency, and in some instances, appeared to decrease it. Extractions with aqueous solvents removed water repellency, while subsequent treatments with non-polar solvents restored it.

McGhie, D.A., and Posner, A.M., 1981, The effect of plant top material on the water repellence of fired sands and water repellent soils: Australian Journal of Agricultural Research, v. 32, p. 609-620.

This study examined the effects of a variety of soil amendments on the water repellency of fired sands. Researchers evaluated a range of finely ground plant species, suites of fungal cultures, and different crop and pasture rotations. Results indicated that cereal crops tended to reduce repellency, and that continuous pasture led to severe repellency. The authors suggest that growing wettable species in water-repellent areas may be one option to help reduce water repellency in the soil.

McNabb, D.H., Gaweda, F., Froehlich, H.A., 1989, Infiltration, water repellency, and soil moisture content after broadcast burning a forest site in southwest Oregon: Journal of Soil and Water Conservation, v. 44, no. 1, p. 87-90.

This paper describes the results of broadcast burning of a harvested site in a Mixed Evergreen Forest Zone of the eastern Siskiyou Mountains in southwest Oregon. Parent material is loam or fine-textured soil. Increased water repellency was observed for a period of five months after the burn. The water repellency then decreased rapidly as fall rains recharged the soil profile. Measuring water repellency by apparent contact angle produced a closer correlation with change in infiltration capacity than did the water-drop-penetration-time test in the field. Water repellency measured using the water-drop-penetration-time test gradually declined after burning. But when measured using the contact-angle method, water repellency increased slightly during the summer. A relation between the apparent contact angle and field moisture content is defined. These workers also concluded that because even decreased infiltration capacity due to water repellency is still two to three times greater than that which would occur in a 100-year storm, the potential for broadcast burning to result in overland flow from intense, short-duration storms is low. Prolonged storms of low intensity which locally saturate the soil profile are more likely to result in overland flow in a broadcast burn area.

Meeuwig, R.O., 1971, Infiltration and water repellency in granitic soils: Intermountain Forest and Range Experiment Station, Ogden, Utah, U.S.D.A. Forest Service Research Paper INT-111, 20 p.

Natural water repellency in the Carson Range of the Sierra Nevada was evaluated with respect to its impact on runoff and infiltration patterns in granitic soils. The study correlated measurements of water repellency under different plant covers with data from infiltrometer tests and rainfall simulators to determine the net effects of the respective vegetation types. The soils involved were sands and sandy loams with clay contents ranging from 2.4-4.5 %. Eight general types of wetting patterns were noted, based on visual observations from hand-dug trenches. These wetting patterns (illustrated with cartoons) tended to be associated with characteristic runoff values. Results indicated that water repellency was most intense beneath pine litter at higher elevations. However, the author suggested that, in most cases, the presence of an understory (with its associated root channels) and soil fauna activity, broke up the continuity of the water-repellent layer, and thus, mitigated the impermeability of the soil. In contrast, water repellency beneath chaparral vegetation was found in patches, rather than a continuous layer, and did not appear to impede infiltration.

Megahan, W.F., and Molitor, D.C., 1975, Erosional effects of wildfire and logging in Idaho, *in* Watershed Management Symposium: American Society of Civil Engineers, Irrigation and Drainage Division, Logan, Utah, August 11-13, 1975, p. 423-444.

A very hot wildfire over both clearcut and uncut watersheds provided the setting for an evaluation of erosion following wildfires. Sandy loam to loamy sand soils overlie moderately fractured bedrock of the Idaho batholith. Vegetation (before the fire) was typical of the seral stage of the Douglas-fir/ninebark habitat type with an overstory of ponderosa pine, and lesser amounts of Douglas-fir and Engelman spruce with an understory of small Douglas fir, ninebark and huckleberry. The authors found that the percent frequency of occurrence of water repellency was about equal on both the harvested and uncut watersheds. However, both the average thickness and the maximum thickness of the water-repellent layer was greater on the clearcut watershed. The average and maximum thickness of repellent layers tended to decrease with time on both watersheds. Paradoxically, the frequency of sites exhibiting water-repellent soils increased on both study watersheds after one year. Based on erosion pin data, there was a tendency for greater erosion from the clearcut area, specifically from areas with thicker water-repellent layers.

Morris, S.E., and Moses, T.A., 1987, Forest Fire and the natural soil erosion regime in the Colorado Front Range: Annals of the Association of American Geographers, v. 77, no. 2, p. 245-254.

This paper evaluates post-fire sediment yields along the Colorado Font Range, and in particular, includes information relating to the occurrence and duration of water-repellent soils following forest fires. The study looked at sediment flux rates from five forested catchments that included vegetation communities of Ponderosa pine/Douglas fir, lodgepole/aspen, and Engelman spruce/subalpine fir. The sites spanned chronological times of burning, from new to four years old, and a fifth site which had not burned in several decades. Researchers found that erosion rates declined rapidly after burning. Since other variables between sites (i.e. vegetation cover, slope angle, and textural characteristics of undisturbed soil) were similar, a decrease in soil water repellency was considered to be a major factor in the decreased sediment flux. This was supported by tests of water repellency at the various sites.

Morris, R.J., and Natalino, M., 1969, The chemical nature of the organic matrix believed to limit water penetration in granitic soils: Reno, University of Nevada System, Center for Water Resources Research, Desert Institute, Project Report No. 1313 p.

This research was directed toward the identification of some of the compounds in forest litter responsible for water repellency in granitic soils. Ethanol was used to extract tar-like substances from species of pine, snowbrush, and manzanita. These extractions were then processed, and the products analyzed, using thin layer, column, and gas-liquid chromatography, qualitative analysis, and infrared spectrophotometry. The study was inconclusive as to the exact nature of individual substances, but researchers determined that the organic material consisted of partially unsaturated aliaphatic carboxylic acids and side chain attachments of simple sugars (mainly pentose and hexose sugars).

Osborn, J., Letey, John, DeBano, L.F., and Terry, E., 1967, Seed Germination and establishment as affected by non-wettable soils and wetting agents: Ecology, v. 48, no. 3, p. 494-497.

The purpose of this study was to see how germination and vegetative establishment were affected by water-repellent soils and by wetting agents applied to the soil. Researchers used a naturally occurring, nonwettable sandy loam derived from granitic parent material. The soil had previously been occupied by a moderately dense stand of chaparral, burned in a 1960 fire. They found that, on sloping profiles, water-repellent soil samples had much lower rates of germination, due to less available infiltrated moisture. On level profiles, water-repellent soils yielded reduced rates of vegetative establishment. Wetting agents increased both germination and vegetative establishment on these samples by increasing the amount of available moisture. However, on wettable sand, wetting agents appeared to have a toxic effect on seed germination. This characteristic was less evident when wetting agents were applied to a wettable soil, possibly due to interactions with colloidal surfaces and ash.

Osborn, J.F., Pelishek, R.E., Krammes, J.S., and Letey, J., 1964, Soil wettability as a factor in erodibility: Soil Science Society of America Proceedings, v. 28, p. 294-295.

This investigation illustrates some of the potential effects of water repellency on erosion. The study focused on an area adjacent to the San Dimas Experimental Forest in Glendora, California, which was burned over by a wildfire in July of 1962 (the previous summer). Prefire vegetation consisted of moderately dense chaparral that mantled a shallow, sandy loam derived from granitic parent material. The fire covered hillslopes with half an inch of wettable ash, overlying a 2- to 3-inch layer of very hydrophobic, partially ashed and decomposed material. Researchers measured the amount of material yielded after eight rainstorms (between January and April) from slopes that had been treated with a wetting agent, and compared it to results on untreated slopes. They found that significantly more erosion occurred on the untreated (water-repellent) plots. Photographs illustrate the intense rilling that developed in these areas. Analysis of vegetative status showed that slopes remained relatively bare until April, and that the treated plots had much higher rates of vegetative establishment than untreated plots. The author notes that, although the area studied was water repellent, there was also ash and soil outside of the study area that was wettable.

Parks, D.S., and Cundy, T.W., 1989, Soil hydraulic characteristics of a small southwest Oregon watershed following high-intensity wildfire, *in* Berg, N.H., ed., Symposium on Fire and Watershed Management: Pacific Southwest Forest and Range Experiment Station, Sacramento, Calif., October 26-28, 1988, Proceedings, General Technical Report PSW-109, p. 63-67.

This investigation was initiated following the Angel Fire in September, 1987, northeast of Grant's Pass, Oregon, to determine fire effects on hydrological response and erosion in a small watershed. Researchers evaluated infiltration capacity, saturated hydraulic conductivity, soil-moisture characteristics, and soil-water repellency in an area with steep topography that experienced a high intensity burn. Vegetation prior to burning consisted of Douglas fir and mixed pine, with grasses, ferns, forbes and shrubs in the understory. The soils were described as stony clay loams derived from serpentine bedrock. The results indicated that fire had little effect on the hydrological response of the watershed, and that the occurrence of water repellency was minimal. The authors suggest that future runoff patterns in the area will likely be dominated by subsurface flow.

Poff, R.J., 1989, Distribution and persistence of hydrophobic soil layers on the Indian burn, *in* Berg, N.H., ed., Symposium on Fire and Watershed Management: Pacific Southwest Forest and Range Experiment Station, Sacramento, Calif., October 26-28, 1988, Proceedings, General Technical Report PSW-109, p. 153.

This report describes the occurrence of water-repellent soils in the Tahoe National Forest, following the Indian fire in September, 1987. Approximately 250 ha contained severely water-repellent layers up to 38 centimeters thick, but 5- to 10- centimeter thicknesses were more common. The deepest and most intense layers were found beneath stands of white fir. Areas without duff, however, did not exhibit water repellency, suggesting that the amount and type of litter present before the burn contributed to the development of fire-induced water repellency. The thickness of the A horizon and fire intensity also appeared to affect the nature of repellency. Mechanical disturbance of thick water-repellent layers proved ineffective in mitigating hydrophobic conditions, but did appear to improve conditions where thinner layers existed.

Prosser, I.P. and Williams, Lisa, 1998, The effect of wildfire on runoff and erosion in native *Eucalyptus* forest: Hydrological Processes, v.12, p.251-265.

This paper describes a comparison of runoff and erosion rates measured from burnt and unburned sites for 10 months following a moderately intense fire. At the scale of the hillslope plots, rates of runoff and sediment transport were increased. The authors attribute these increases to soil hydrophobicity, the presence of which was enhanced by the wildfire, and reduced ground cover. Removal of ground cover lowered the threshold for initial sediment movement. Both runoff and sediment transport were localized, resulting in little runoff or sediment yield after the fire at the hillslope catchment scale. The authors conclude that rainfall events of greater than one year recurrence interval are required to generate substantial runoff and sediment yields from mild burns.

Richardson, J.L., and Hole, F.D., 1978, Influence of vegetation on water repellency in selected western Wisconsin soils: Soil Science Society of America Journal, v. 42, p. 465-467.

Soil wettability was assessed with respect to various soil types and plant communities in western Wisconsin. Three criteria were used to characterize the water repellency, including wetting angle, water drop penetration time (WDPT), and 90° surface tension. Researchers found that water repellency appeared to be linked to fungi under plant communities with red pine (*Pinus resinosa*) or hemlock (*Tsuga candensis*). They also found that burning prairie grass resulted in increased soil-water repellency.

Ritsema, C.J., Dekker, L.W., Nieber, J.L., and Steenhius, T.S., 1998, Modeling and field evidence of finger formation and finger recurrence in a water repellent sandy soil: Water Resources Research, v. 34, no. 4, p. 555-567.

With prolonged rainfall, infiltrating wetting fronts in water repellent soils may become unstable, leading to the formation of high-velocity flow paths, the so-called fingers. In this paper, field evidence of the process of finger formation and finger recurrence is given for water repellent sandy soil. In this case, water repellency is considered to be a plant-induced soil property. Theoretical analysis and model simulations indicate that finger formation results from hysteresis in the water retention function, and the character of the formation depends on the shape of the main wetting and main drainage branches of that function. Once fingers are established, hysteresis causes fingers to recur along the same pathways during following rain events. Leaching of hydrophobic substances from these fingered pathways makes the soil within the pathways more wettable than the surrounding soil.

Ritsema, C.J., Dekker, L.W., and Heijs, A.W.J., 1997, Three-dimensional fingered flow patterns in a water repellent sandy field soil: Soil Science, v. 162, no. 2, p. 79-90.

This paper describes water flow and transport through the vadose zone of water-repellent soils along preferred flow paths. Again, the water repellency is considered to be plant-induced. In a series of soil blocks defined in a water repellent sandy field, fingered flow patterns were distinct after rain events. Fingers were found at places where the degree of potential water repellency in the upper part of the soil was low. Soil block samples between rain events showed only remnants of fingerlike wetting patterns as a result of continuing processes like drainage, redistribution, and evaporation.

Ritsema, C.J., and Dekker, L.W., 1994, How water moves in a water repellent sandy soil– 2. Dynamics of fingered flow: Water Resources Research, v. 30, no. 9, p. 2519-2531.

The companion paper to Dekker and Ritsema (1994), this one focuses on the dynamics of finger flow. Researchers found that the width of the "fingers" in the field would expand or shrink in diameter, depending on weather conditions. They also found that water contents in the fingers were higher in the top soil, and became drier with depth. Finger flow was found to be an important process in grass-covered, water- repellent, sandy soils.

Ritsema, C.J., and Dekker, L.W., 1995, Distribution flow- a general process in the top layer of water repellent soils: Water Resources Research, v. 31, no. 5, p. 1187-1200.

This investigation attempts to quantify the effects of "distribution flow", a term introduced in the 1993 paper by Ritsema, et al. The authors describe several soil factors that facilitate the formation of distribution flow, including the presence of a water-repellent layer. They conclude that modeling of distribution flow must be done in two or three dimensions.

Ritsema, C.J., Dekker, L.W., Hendrickx, J.M.H., and Hamminga, W., 1993, Preferential flow mechanism in a water repellent sandy soil: Water Resources Research, v. 29, no. 7, p. 2183-2193.

This research analyzed flow processes in a water-repellent, sandy, field soil of the western Netherlands using boron and bromide tracers. Results of the tracer applications alluded to the development of vertical flow paths with interstitial "dry soil bodies" that were extremely water repellent. These flow patterns are illustrated with graphs, cartoons and photographs. The term, "distribution flow", was introduced to describe the process of horizontal flow in the wet topsoil, where water was laterally distributed toward zones of vertical preferential flow. The investigation also confirmed the presence of divergent flow from the bottom of these vertical flow paths, and then subsequent uniform movement of tracer fronts below the divergent zone. The spatial variability in water content was thus, greatest in the upper part of the soil profile, and decreased with depth as the soil became more wettable and less conducive to preferential flow. The authors suggest that laboratory experiments involving preferential flow do not account for divergent flow, and may actually overestimate flows under field conditions.

Roberts, F.J., and Carbon, B.A., 1971, Water repellence in sandy soils of south-western Australia. I. Some studies related to field occurrence: Field Station Record, CSIRO Division of Plant Industries (Australia), v.10, p. 13-20.
Field observations and four laboratory experiments revealed some characteristics of the water-repellent, agricultural soils in south-western Australia. Researchers discovered that more than half of the soil organic matter occurred in particulate form, and could be removed by winnowing or flotation. The rest of the organic matter formed "skins" around the mineral particles, and could not be removed by mechanical means (e.g. shaking) when dry. The latter form appeared to be the most significant in terms of water repellency, since removing the particle form failed to make the soil wettable. Organic matter contents of 1-10%, and an acidic pH appeared to be associated with the most severe repellency. Results of laboratory experiments indicated that water repellency became less severe with increasing sand grain surface area. Fine-textured samples remained wettable after treatment with hydrophobic substances. Field observations also found water repellent soils to be limited to course-textured soils, although other studies (e.g. McGhie and Posner, 1980) have noted the occurrence of water repellency in fine-textured soils.

Roberts, F.J., and Carbon, B.A., 1972, Water repellence in sandy soils of south-western Australia. II. Some chemical characteristics of the hydrophobic skins: Australian Journal of Soil Research, v. 10, p. 35-42.
The goal of this study was to determine the nature of hydrophobic coatings ("skins") found on sand grains in Southern and Western Australia. Water-repellent sands were subjected to a series of extractions, most of which did not completely remove the hydrophobic substances. Only treatments with dilute alkaline solutions removed the "skins" easily, in the form of suspended particles. These extracts restored water repellency to wettable sands, unless the extracts were filtered. Researchers determined that the hydrophobic skins on sand grains represented organic materials derived from the stable humic acid complex. Results also indicated that substances responsible for water repellency could potentially come from plants or soil microbes.

Robichaud, P.R., 1996, Spatially-varied erosion potential from harvested hillslopes after prescribed fire in the interior northwest: Moscow, University of Idaho, Ph.D. dissertation, 219 p.
A section of this dissertation is devoted to the study of water-repellent soils, as part of a broader investigation into the effects of post-fire, spatially-varied surface conditions on erosion. Included is a comprehensive literature review on water repellency, as well as the author's own investigation into the formation of water-repellent conditions with respect to texture and moisture content at the time of burning. The study consisted of exposing four textures of soils to four levels of heating at low and high moisture contents, and then measuring the resultant water repellencies at various depths. Unlike most research on water-repellent soils, this study included experiments using volcanic ash-derived soils; a topic that the author notes, has received little attention. Results were quite variable.

Salih, M.S.A., Taha, F.K., and Payne, G.F., 1973, Water repellency of soils under burned sagebrush: Journal of Range Management, V.26, no.5, p. 300-331.

Results of laboratory and field testing demonstrates that the burning of sagebrush produces water repellency in soils. Field tests indicate that water repellency is produced as a result of the burning of the sagebrush leaf mulch under the shrub, rather than the burning of the live plant material. Maximum repellency occurs at soil temperatures between 1400 and 1800 degrees F.

Savage, S.M., 1974, Mechanism of fire-induced water repellency in soil: Soil Science Society of America Proceedings, v. 38, p. 652-657.

Chaparral (manzanita) litter from the Red Mountain area in southern California was subjected to two types laboratory burn experiments over a sand column. In the first experiment, the burned litter remained on the surface of the sand, while in the second experiment, the litter was removed after burning to prevent heat in the litter from moving into the sand. The latter resulted in lower maximum soil temperatures and less severe water repellency. Following burn treatments, materials were extracted from the water-repellent sand and subjected to fractionation analysis. Results indicated that molecules of the hydrophobic substances showed a decrease in polarity with depth in the sand column. The author concludes that organic substances from the litter layer probably move into the underlying sand during the fire, and confer a mild repellency as they condense on cooler soil particles at a shallow depth. Subsequent heat from the litter layer (after burning) moves into the sand and "fixes" the polar hydrophobic substances in place, while the less polar ones migrate deeper into the soil, thus increasing the thickness of the water-repellent layer. The author points out that this process, which is controlled by the intensity of the heat moving down into the soil profile, governs the thickness of the water-repellent layer (along with soil texture, as reported by other researchers). The author also suggests that the amount of hydrophobic substances initially produced by the litter depends on the duration and intensity of the fire and the quantity of litter in the soil. The introduction includes a literature review of previous research into the causes of fire-related water repellency.

Savage, S.M., Martin, J.P., and Letey, John, 1969a., Contribution of some soil fungi to natural and heat-induced water repellency in sand: Soil Science Society of America Proceedings, v. 33, p. 405-409.

One of the earlier studies attempting to understand water-repellent soils, this paper offers some alternate explanations on the mechanism of water-repellency after heating. In particular, it suggests that heat-induced repellency is the result of a chemical reaction (pyrolosis), rather than physical vaporization and subsequent condensation on cooler soil particles, as proposed by DeBano (1966). It also indicates that condensed materials must be heated *in situ* to confer a high degree of water repellency to a soil, and demonstrates the importance of soil fungi (rather than litter alone) in producing water-repellency after heating.

Savage, S.M., Martin, J.P., and Letey, John, 1969b., Contribution of humic acid and a polysaccharide to water repellency in sand and soil: Soil Science Society of America Proceedings, v. 33, p. 149-151.

Researchers evaluated the effects of microbially-generated polysaccharides, humic acids, and their metal salts, on water repellency in sand and soil. Of all the substances tested, only one humic acid caused water repellency. The repellency in this instance was found to be pH dependent. Results also indicated that a larger amount of the hydrophobic substance was needed in the soil than in the sand, presumably because of the larger surface area of the soil. Researchers concluded that the contribution of polysaccharides and humic acids to water repellency is minimal.

Savage, S.M., Osborn, J., Letey, John, and Heaton, C., 1972, Substances contributing to fire-induced water repellency in soils: Soil Science Society of America Proceedings, v. 36, p. 674-678.

This investigation attempted to identify the source and chemical nature of materials moving from a heated soil, and to determine if these materials were capable of causing water repellency. Water-repellent soil was taken from the Red Mountain area in southern California, where chamis chaparral brush is the dominant vegetation type. Researchers concluded that the processes responsible for causing fire-induced water repellency began between 300° and 400°C, in contrast to DeBano et al. (1967) who reported that soils reach a maximum repellency at around 300°C. They also found the most effective substances causing fire-induced water repellency to be aliphatic hydrocarbons, and determined the source of these compounds to be surface soil litter. Results further indicated that the mechanism involved in producing water repellency after heating was probably a structural change in the substances, rather than simple condensation of volatilized material on cooler soil particles. The authors also concluded that *in situ* heating of these materials was necessary to cause repellency.

Scholl, D.G., 1971, Soil wettability in Utah juniper stands: Soil Science Society of America Proceedings, v. 35 no. 2, p. 344-345.

This study investigated the wettability of soils in a stand of Utah juniper with respect to ground-cover zones, upper profile soil horizons, the amount of organic matter, and moisture conditions in the soil. The results indicated that wettability was closely related to organic matter, and that the O horizon was far more resistant to wetting than others below it. Results also showed an increased resistance to wetting with decreased moisture content, as expected. The exception to this trend was zone three (the bare soil in an open area beyond the canopy), where the opposite occurred. The paper explained that the latter was probably a wettable soil, according to the classification proposed by DeBano (1966), causing the water drop penetration time to decrease with a decrease in moisture content. Another exception was that water repellency no longer increased above the 15-bar level. The author explained that this was most likely due to the presence of montmorillonite in the soil, which caused cracking and exposure of the more wettable portions.

Scholl, D.G., 1975, Soil wettability and fire in Arizona chaparral: Soil Science Society of America Proceedings, v. 39, no. 2, p. 356-361.

The author examined the effects of field and lab fires of variable intensities on the water repellency of soil layers in Arizona chaparral. Although soils were water repellent before and after fire events, the hot fires resulted in water repellency at greater depths and decreased repellency at the surface. Tests also indicated that the water-repellent layers were destroyed at approximately 270°C. The introduction notes other research which indicates that sandy soils tend to cause the most severe water repellency problems due to the small surface area to volume ratio of the grains (thus requiring less material to coat the grains).

Scott, D.F., 1993, The hydrological effects of fire in South African mountain catchments: Journal of Hydrology, v. 150, p. 409-432.

The results of this study illustrate the complexity with which variables interact to produce various hydrological responses to fire. Four South African mountain catchments were monitored following fire events to determine the effects on streamflow, storm-flow, and sediment yield. Two of the catchments were covered with scrub vegetation prior to burning, a third with eucalypt forest, and the fourth with pine. Included in the experimental design were tests for water repellency and experimental plots to measure overland flow. In the scrub catchments, researchers observed no increase in storm flow or sediment yield, and increases in annual flow were within model predictions. In contrast, storm flows and sediment yields in the forested catchments increased significantly. Soils in the latter were found to be highly water repellent, although the eucalypt catchment was already naturally water repellent prior to burning. The author attributed the hydrologic response of the forested catchments to large increases in overland flow, resulting from water-repellent soils. The relatively moderate response of the scrub catchments was explained by the fact that the water repellency in these areas was patchy, so although overland flow occurred on steeper slopes, it was able to infiltrate into the soil before reaching streams, and thus, did not affect storm flow. The author also suggests that the nature of water repellency in the catchments was the result of vegetation type and burn intensity (which in turn was affected by fuel loading, soil moisture and fuel moisture conditions at the time of burning, and the type of vegetative cover).

Scott, D.F., and Van Wyk, D.B., 1990, The effects of wildfire on soil wettability and hydrological behaviour of an afforested catchment: Journal of Hydrology, v. 121, p. 239-256.

This study reported some of the complex hydrological responses that resulted during the first year after a high intensity wildfire on a South African research catchment in the Jonkershoek State Forest. Prior to burning, approximately half of the catchment was vegetated with fynbos (the indigenous scrub vegetation of South Africa) and the remainder afforested with *Pinus radiata* for timber harvesting. Soils were characterized by friable, sandy to silty loams (with approximately 10% clay content), derived from sandstone colluvium, minor shale lenses, and deeply weathered granite. Researchers evaluated pre-fire and post-fire stream flow and sediment data in conjunction with tests for water repellency in the burned catchment and in an unburned control. Widespread repellency after the fire occurred primarily below the surface. Some shallow, post-fire repellency occurred in areas of fynbos vegetation, whereas strongly repellent conditions (up to 150mm in depth) were found in burned soils of the pine plantation (the deepest and most severe repellency occurred beneath slash piles). Prior to burning, the latter soils also exhibited some mild, infrequent water repellency associated with deep litter accumulations and fungal mycelia. Although weekly stream flow values increased very little, quick flow volumes and peak flow rates increased by 201% and 290%, respectively. "Pulses of rain" as small as 5mm generated surface runoff during low intensity storms of long duration. This runoff occurred as saturation overland flow in wettable soils with subsurface water-repellent layers. Four-fold increases in bedload and suspended sediment yields were attributed to the increased stream energy and overland flow. The author concluded that the nature of fire-induced water repellency was related to vegetation type and soil heating. He also noted that, in contrast to previous studies of burned South African fynbos catchments, post-fire sediment yields in this study were much higher. He suggested that these differences were due to variations in burn intensity and parent material of the soils. The lower sediment yields occurred following low intensity prescribed burns in catchments dominated by granite-derived soils, whereas the this study involved a high intensity wildfire on sandstone derived soils.

Scott, D.F., and van Wyk, D.B., 1992, The effects of fire on soil water repellency, catchment sediment yields and streamflow: *in* van Wilgen, B.W., Richardson, D.M., Kruger, F.J., and van Hensbergen, H.J., eds., Fire in South African mountain fynbos, Ecological studies, v. 93, Springer-Verlag, Berlin, p. 216-239.

This paper examines the hypothesis that fire would induce the development of water repellency in the soil, which would increase the probability of overland flow, causing increased stormflows and water yield, and would be associated with increased sediment yields. Investigations were conducted at three different scales: 1) streamflow, stormflow and sediment yield were analyzed to assess the response of the whole catchment to fire; 2) rain-generated overland flow was measured on small plots as a measure of infiltration rate; and 3) soils were tested for water repellency before and after the fire. The researchers found that there was considerable water repellency in the soils before the fire, and the fire reduced repellency in the upper 15 mm of soil. Little serious heating of the soil by the fire occurred, and the ground litter was only partially consumed. No effects of the fire were detected at the catchment level, and the authors thus concluded that the fire had little effect on the catchment's hydrological behavior.

Sevink, J., Imeson, A.C., and Verstraten, J.M., 1989, Humus form development and hillslope runoff, and the effects of fire and management, under Mediterranean forest in NE-Spain: Catena, v.16, p. 461-475.

This paper describes two different types of humus forms that develop on distinct soil configurations. The observations indicate that mor type humus forms develop on soil with a lithic contact at shallow depth or with an abrupt textural change, and consist of an ectorganic layer abruptly overlying a generally water-repellent layer. This form limits root penetration and moisture supply. Moder type humus develops under more favorable rooting and soil moisture conditions. Rainfall simulator experiments showed that in mor type humus forms the storage capacity of an unburned ectorganic layer is relatively high, which reduces the probability of hillslope runoff. However, if the soil is dry, runoff may be generated during rainstorms because of the presence of the water-repellent mineral top soil, but the dense root structure in the ectorganic layer will strongly reduce erosion risks. If moist or wet, the soils are not water repellent. Because of the shallow lithic contact or an argillic B horizon, a perched water table is frequently present on many slopes during wet periods and under such conditions throughflow and saturated overland flow occur extensively. Moder type profiles have a high infiltration capacity and are unlikely to generate hillslope runoff, even during rainstorms. The perched water table and throughflow observed at the mor sites were not observed at the moder sites. Fire leads to the complete or partial destruction of the ectorganic layer, and the authors speculate that this results in a lower storage capacity of the remaining ectorganic layer. As a result, hillslope runoff will sharply increase.

Teramura, A.H., 1973, Relationships between chaparral age and water repellency: Fullerton, California State University, M.A. thesis, 18 p.

The purpose of this study was to examine the effects of stand age upon water repellency in the chaparral of Southern California. Particular emphasis was placed upon the contribution of incorporated organic material in the soil to the intensity of water repellency with respect to dominant shrub species forming the vegetative cover. Results of water drop penetration time testing indicated an increase in water penetration times with increasing stand age. The author indicates that this naturally-occurring repellency may accumulate over time, and is directly related to the plant cover and the time between fires. Two explanations for this phenomenon, one based on microbial degradation of litter and the other based on plant physiology with maturity, are proposed. Further, the author indicates that the amount of incorporated organic matter beneath the canopy in comparison to the water drop penetration time remains relatively uniform between species and between sites. Therefore, water repellency cannot be explained by simply expressing the total amount of incorporated organic matter in the soil. Although organic matter may be the primary source of hydrophobic substances, only a small amount of the total oxidizable organic matter contains substances capable of inducing water repellency.

Terry, J.P., and Shakesby, R.A., 1993, Soil hydrophobicity effects on rainsplash–simulated rainfall and photographic evidence: Earth Surface Processes and Landforms, v. 18, p. 519-525.

Video cameras and still photography were used in conjunction with rainfall simulation experiments to investigate the erosional effects of rainsplash on water-repellent soils. The experiments used sandy loam soil samples from the Agueda Basin in north central Portugal. Although not explicitly stated, the water repellency appeared to be fire-related. Splash ejection droplets from water-repellent soils were larger, slower, and carried more sediment than drops from wettable soils. The mechanism of detachment (illustrated with cartoons) also differed, in that rainfall on water-repellent samples exposed the underlying dry soil to splash detachment by subsequent drops, whereas wettable samples developed a "cohesive surface layer" that reduced soil loss. As a result, splash losses were consistently greater on water-repellent samples. The implications of these results are discussed with respect to erosion of water-repellent soils (particularly in burned areas).

Tillman, R.W., Scotter, D.R., Wallis, M.G., and Clothier, B.E., 1989, Water-repellency and its measurement by using intrinsic sorptivity: Australian Journal of Soil Research, v. 27, p. 637-644.

The authors use the concept of sub-critical water repellency to describe soil water absorption that is less than expected. Measurements of non-repellent and sub-critical repellent behavior in the laboratory suggest that the ratio of the apparent intrinsic sorptivity of ethanol to that of water is a useful index of sub-critical repellency. The authors suggest that overt water-repellency is observed only exceptionally, so it is regarded as an interesting if somewhat esoteric phenomenon in soil physics. The authors suggest that sub-critical repellency may be more widespread and significant.

Topalidis, S., and Crockford, R.H., in press, Water Repellency in a dry schlerophyll eucalypt forest - runoff generation: Hydrologic Processes.

Rainfall-induced runoff characteristics were investigated in a small, eucalypt catchment near Canberra Australia. The study combined information from tensiometers and piezometers with measurements of surface hydraulic conductivities to help explain the occurrence of anomalously low runoff values for precipitation events. Despite the presence of intensely water-repellent soils and observations of overland flow, instruments recorded very little surface runoff in the catchment. Researchers concluded that runoff was negligible because macropores enabled water to bypass the water-repellent soils at the surface and infiltrate to lower layers. Most of the water moved through macropores less than 1mm in diameter, although larger macropores resulting from burrows and channels adjacent to tree roots, also provided conduits for infiltration. This was another case in which the water-repellent soils had an unusually high clay content (20-40%).

Tschapek, M, 1984, Criteria for determining the hydrophilicity-hydrophobicity of soils: Zeritscrift für Pflanzererährung und Bodenkunde, v. 147, no. 2, p. 137-149.

Van Dam, J.C., Hendrickx, J.M.H., Van Ommen, H.C., Bannink, M.H., Van Genuchten, M.Th., and Dekker, L.W., 1990, Water and solute movement in a coarse textured water-repellent field soil: Journal of Hydrology, v. 120, p. 359-379.

This paper provides a method for simulating unstable water flow in naturally water-repellent soils. A numerical model based on Richards' equation for unsaturated flow and Fickian-based convection-dispersion equation for solute transport is presented. Water repellency is accounted for by defining a factor equal to the volumetric fraction of the soil occupied by preferential flow paths.

van't Woudt, B.D., 1954, On factors governing subsurface flow in volcanic ash soils, New Zealand: American Geophysical Union Transactions, v. 35, no. 1, p. 136-144.

This paper presents observations on the hydrology in response to storm events of soils derived from rhyolitic ash on the North Island of New Zealand. The author identifies three factors that restricted vertical flow into the soil at various depths, resulting in lateral subsurface flow. One of the factors was a form of water repellency in which the soil was difficult to wet after desiccation, but would eventually become wettable at higher moisture contents. This condition resulted in a thin layer of lateral flow near the surface, over a drier, underlying layer. The thickness of the conducting layer increased with continued precipitation. Other factors that led to subsurface flow included a lower permeability of the B horizon relative to the A horizon, and an increase in particle size with depth in the soil. The paper also described the effect of topography on soil water repellency and subsequent storm flow. Soil on the upper half of the slope dried out more quickly between storm events, and consequently maintained its water-repellent qualities, in contrast to soil on the lower portions of the slope, which generally maintained higher moisture contents that reduced the frequency of water repellency. As a result, lateral flow was observed on the upper portion of the hillside, but not on the lower half. The author does not mention the effects of this runoff pattern on erosion, but a previous (1952) paper discusses some implications with respect to soil fertility.

Wallis, M.G., Scotter, D.R., and Horne, D.J., 1991, An evaluation of the intrinsic sorptivity water repellent index on a range of New Zealand soils: Australian Journal of Soil Research, v. 29, p. 353-362.

This paper provides an evaluation of the intrinsic sorptivity repellency index (RI) developed by Tillman et al., (1989) as a method for measuring water repellency in soils. The RI is used to determine if water repellency is a widespread condition in New Zealand soils, and is compared with existing techniques for water repellency measurement. Values for the RI indicate that 14 New Zealand soils with a wide range of textures were naturally water repellent. No mention of fire-induced repellency is made in the paper. The authors conclude that the RI is more sensitive than the Molarity of Ethanol Droplet (MED) and Water Drop Penetration Time (WDPT) test for soil water repellency, and is therefore particularly useful for evaluating soils with low degrees of water repellency. Other advantages described of the RI over the MED and WDPT tests are that the RI is a physically significant parameter which can be used to calculate actual and potential short-time water infiltration. The RI can be measured *in situ* or on undisturbed cores at either field-moist or air-dry conditions.

Ward, P.R., and Oades, J.M., 1993, Effect of clay mineralogy and exchangeable cations on water-repellency in clay-amended sandy soils: Australian Journal of Soil Research, v. 31, p. 351-364.

This investigation explored the interaction between clays and water-repellent Australian soils. The introduction cites previous studies that have observed reductions in water repellency with the addition of fine particles, such as clays, but notes that these studies have proved inconclusive as to the mechanism involved. This research attempted to resolve some of the discrepancies. A series of tests were performed on a naturally water-repellent Australian sand, and two wettable sands treated with hydrophobic substances (one with cetyl alcohol, the other with organic matter extracts). Additions of dry clays (both Na^+- and Ca^+ -saturated clays) had no effect on water repellency. However, when sand-clay mixtures were subjected to a wetting and drying cycle, repellency was significantly reduced. Researchers concluded that clays reduced repellency by physically "masking" the hydrophobic surfaces of sand grains. The effectiveness of a clay in reducing water repellency was determined, not by its dispersibility, but by its ability to remain dispersed over the surface of sand grains during the drying process. This corresponded to clays that had a "low, but significant charge." Kaolinite was found to be more effective in reducing water repellency than montmorillonite, and the authors suggested that it could potentially be used to remedy problems with water-repellent field soils.

Watson, C.L., and Letey, John, 1970, Indices for characterizing soil-water repellency based upon contact angle-surface tension relationships: Soil Science Society of America Proceedings, v. 34, p. 841-844.

This investigation used the relationship between surface tension and apparent liquid-solid contact angle to develop indices for characterizing soil-water repellency. Two indices were proposed. The first involved a water drop test with a series of ethanol solutions to determine the degree of water repellency. The second test evaluated the persistence of water repellency by measuring the time required for a drop of water to be absorbed by the soil. The paper notes that both of these indices are important in classifying water-repellent materials, since a high degree of repellency is not necessarily indicative of persistence. The introduction also provides a summary of other techniques used to characterize and measure the degree of repellency, and discusses some of their drawbacks or advantages.

Wells, C.G., Campbell, R.E., DeBano, L.F., Lewis, C.E., Fredriksen, R.L., Franklin, E.C., Froelich, R.C., Dunn, P.H., 1979, Effects of fire on soil– a state-of-knowledge review: Washington DC, U.S. Department of Agriculture Forest Service, General Technical Report WO-7, 34 p.

This paper summarizes the state-of-the-art for the following fire and soil topics: (1) soil temperature and heating; (2) chemical properties and nutrient cycling; (3) soil microfauna; (4) soil physical properties; (5) erosion; and (6) effects of fire on range soils. A section defining knowledge gaps, research scope and priorities is included, in addition to an extensive bibliography. A discussion of water repellency is included in the section on soil physical properties. This section describes work presented in DeBano, 1974 and 1966, DeBano et al., 1967 and 1976, Savage, 1974 and Savage et al., 1972 and Scholl, 1975. This work includes a description of a wetting-resistant ash dust layer which results in runoff and erosion. The thickness of water-repellent layers is described as being a function of fire intensity, soil-water content and soil physical properties. Deeper layers result from hotter fires, a dry pre-fire soil results in a thicker layer, and water repellency is more likely to develop in coarser soils. Water-repellent soils are described as forming due to wildfires in chaparral in Southern California and Arizona, lodgepole pine in Oregon (Dyrness, 1976), and ponderosa pine in Arizona (Campbell et al., 1977). Broadcast burning of logging residue in Montana did not produce appreciable water repellency over medium-to-fine textured soils. However, slash piles burned over coarse-textured soils did produce water repellency.

Wells, W.G., II., 1981, Some effects of brushfires on erosion processes in coastal Southern California, *in* Erosion and Sediment Transport in Pacific Rim Steeplands: Christchurch, New Zealand, International Association of Hydrological Science, no. 132, , p. 305-342.

This paper reports on some of the effects of fire on erosion processes in chaparral settings. In the discussion on water repellency, the author describes the implications of an intensely repellent subsurface layer on soil movement. He emphasizes that the presence of such a confining layer effectively reduces the storage capacity of the soil mantle by 20 times or more, limiting hydrologic activity to the upper 5 cm. Photographs depict the wettable bed and surface soils of a levee-bordered rill, overlying a nonwettable soil. The author points out that in areas with water-repellent soils, these miniature debris flow types of rills tend to predominate over other rill formations. He suggests that the rills form as a result of increased pore pressure above the water-repellent layer, which reduces the intergranular stress and shear strength of the soil mass, and ultimately leads to failure in the form of a small debris flow. Evidence from several storm events is provided, but the author notes that further testing is needed to confirm the process.

Wessel, A.T., 1988, On using the effective contact angle and the water drop penetration time for classification of water repellency in dune soils: Earth Surface Processes and Landforms, v. 13, no. 6, p. 555-561.

This paper compares and contrasts various methods used to classify water repellency. The methods used in this study involved measuring the water drop penetration time (WDPT) and the effective or observed solid-liquid contact angle, α', rather than the contact angle α. The investigation determined that water repellency in dune soils was best characterized by water drop penetration time, because it subdivided water-repellent soils and was easy to measure. It was also found to be a better indicator of the erosion potential of soils, since the time required for infiltration of precipitation is related to the amount of surface runoff.

Williams, C.L., 1991, Post-fire sediment yield from the chaparral vegetation zone, Ash Creek drainage basin, Arizona: Fort Collins, Colorado State University, M.S. thesis, 138 pp.

The objective of this study was to determine and investigate the factors controlling sediment yield for two areas in the Ash Creek drainage basin which was burned in 1959. The author concludes that lithology is probably the most significant factor affecting post-fire sediment yield. Immediately following fire on chaparral-vegetated hillslopes, hydrophobic soil conditions and barren hillslopes caused a dramatic rise in hillslope runoff.

Witter, J.V., Jungerius, P.D., and ten Harkel, M.J., 1991, Modeling water erosion and the impact of water repellency: Catena, v. 18, p. 115-124.

Measurements of surface runoff and sediment yield from coastal dune plots in the Netherlands were used to develop a regression model for water erosion. Water repellency was expressed differently in the two catchments studied, and subsequently resulted in very different responses to precipitation. The more water-repellent catchment yielded runoff that was an order of magnitude higher than the wettable catchment. However, sediment yield was an order of magnitude less. The authors attributed this anomaly to presence of moss vegetation in the less wettable catchment. Although moss induced water repellency in the dune sands, it also acted to stabilize the soil surface, and thus countered the effects of higher runoff. Since soil moisture conditions were found to significantly influence the expression of water repellency (and hence, runoff parameters), the author suggested that antecedent moisture should be taken into account when modeling water erosion in dune environments.
Note: This study observed higher pH values in the more water-repellent soils, in contrast to Roberts and Carbon (1971), who determined that an acidic pH was associated with severe repellency.

Ziernolz, Christoph, Hairsine, Peter, and Booker, Fred, 1995, Runoff and soil erosion in brushland following the Sydney brushfires: Australian Journal of Soil and Water Conservation, v.8, no. 4, p. 28-37.

Zwolinski, M.J., 1971, Effects of fire on water infiltration rates in a ponderosa pine stand, *in* Hydrology and Water Resources in Arizona and the Southwest: Arizona Section American Water Resources Association and the Hydrology Section Arizona Academy of Sciences, Tempe, Arizona, April 22-23, 1971, Proceedings, v. 1, p. 107-112.

This study evaluated the infiltration capacity of a silt loam in an unburned, lightly burned (soil temperatures <200°F) and heavily burned (soil temperatures 350-550°F) ponderosa pine stand in east-central Arizona. Soils in the study area were derived from volcanic cinders and basalt slag. Infiltrometer plots revealed that both burn treatments caused significant decreases in infiltration capacity immediately after fire. However, these differences could not be detected during the second and third summers. The author notes that most of the hydrographs exhibited a depression 5 to 15 minutes after the initial water application, and attributes this characteristic to water repellency in the soil.