WATER-REPELLENT SOILS: WHAT THEY ARE AND WHY THEY ARE IMPORTANT

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Awareness of water-repellent soils began with an observation made during a soil organic matter investigation at the beginning of this century. There was mainly academic interest in water-repellent soils until the 1960s, at which time it was realized that this unique soil property had far-reaching implications in the management of agricultural and wildland ecosystems. Since the 1960s, interest in these soils has expanded both geographically and scientifically. The importance of water-repellent soils was the theme for a conference held in September 1998 in Wageningen, the Netherlands. Speakers at this conference came from throughout the world to report on a wide range of topics related to soil water repellency. Specific topics included the origins of water repellency, assessment of water repellency, occurrences and consequences of water repellency, water flow and transport in water-repellent soils, and the amelioration of water-repellent soils. This paper reviews the evolution of the interest in these soils and some of the major findings reported at the Netherlands conference.

Normally, dry soils have an affinity for adsorbing liquid and vapor water. This occurs because there is strong attraction between the mineral soil particles and water. Not all soils, however, display these wettable characteristics; some repel water instead. For example, when water droplets are placed on the surface of an air-dry soil that is water repellent, the droplets bead up. Water will not penetrate because the mineral soil particles are coated with hydrophobic substances that repel water. The degree of water repellency is related to the contact angle between the water droplet and the water-repellent soil surface. Also, a so-called effective contact angle has been calculated for soils using a version of the capillary rise equation.

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Chemically, hydrophobic substances have no polarity and therefore do not attract water. This resistance to wetting affects water movement into and through soils, as will be discussed in detail in a second paper on this issue (DeBano 1999). The discussion here, however, is limited to the general nature of soil water repellency, the historical activities and attention focused on water repellency, the problems arising from this unique soil condition, and the various remedial treatments used to ameliorate water repellency. Other topics that captured interest at a recent international workshop on water repellency in soils are also discussed.

The Nature of Water Repellency

The cause of water repellency in soils is related to organic matter. Water repellency can result from the following processes involving organic matter: (a) an irreversible drying of the organic matter (e.g. the difficulty encountered when rewetting dried peat materials); (b) production of leachates, which coat mineral soil particles (e.g. coarse-grained materials easily made water repellent by plant leachates); (c) coating of soil particles with hydrophobic microbial byproducts (e.g. fungal mycelium); (d) intermixing dry mineral soil particles and dry organic matter; and (e) vaporization of organic matter and condensation of hydrophobic substances on mineral soil particles during fire (e. g. heat-induced water repellency).

Attempts have been made to characterize water repellency chemically. The chemistry, however, is complex and elusive and it appears that numerous organic compounds are responsible for producing water repellency. These compounds can be either synthesized in nonfire environments by microorganisms or formed during soil heating by fires. Many chemicals have been proposed as sources of water repellency: a mixture of aliphatic hydrocarbons, aromatic compounds, esters, polysaccharides, humic and fulvic acids, fatty acids, and polymethylenes (Wallis and Horne 1992). The severity of water repellency depends not only on the organic matter, but also on soil texture, soil water content, and fire severity.

Historical Interest

Water repellency has been a concern of both scientists and land managers for well over a century. During this time, the interest in water repellency has evolved from an isolated scientific curiosity to an established field of science that is recognized worldwide.

Interest in water-repellency phenomena began during the nineteenth century, when it was reported as being associated with organic matter and its decomposition, particularly by fungi. Reports on fungal decomposition of organic matter by Waring in 1837 (Bayliss 1911) were probably the first publications describing the effect of mycelium growth on water absorption by soil. Wetting resistance was associated with a phenomenon known as fairy rings. The term "fairy ring" was used by these early investigators to describe the arrangement of plants (usually grass or crop plants) in an approximate circular form where plant growth on the inside of the circle was stimulated. This inner circle of healthy plants was surrounded by circles of bare ground or concentric zones of withered plants. In many cases fairy ring phenomena were so abundant that they materially affected the yield of grasslands and agricultural crops.

The interest in organic matter, and specifically humic substances, continued into the earlier part of the twentieth century. In 1908, Schreiner and Shorey (1910) reported studying a soil "that could not be wetted, either by man, by rain, irrigation or movement of water from the subsoil." Shortly thereafter it was reported that in eastern Colorado, grassland soils infected with fleshy fungus (*Agaricus tabularis*) had lower soil water contents than bare areas and the inner and outer vegetated rings, particularly in the surface soil early in the growing season (Shantz and Piemeisel 1917). Papers describing water-repellent soils began appearing in scientific journals during the 1940s and 1950s. Studies in Florida reported wetting resistance in citrus orchards (Jamison 1947). Elsewhere in the world, water repellency was reported in New Zealand and Germany.

The 1960s witnessed the beginning of national and international interest in soil water repellency. Several noteworthy activities occurred during this decade. First, a large number of papers were published on water repellency, primarily by scientists in Australia and the United States. For example, between 1960 and 1970, more than 90 publications dealing with various aspects of water repellency were published. A second significant landmark was reflected in two publications: one describing the measurement of liquid-solid contact angles in soil and sand (Letey et al. 1962a) and a second describing the influence of water-solid contact angles on water movement in soil (Letey et al. 1962b). The third milestone was the summarization and synthesis of all available knowledge on water repellency at the first international conference on water repellency held in June 1969 at the University of California, Riverside (DeBano and Letey 1969). Also during the 1960s, excessive postfire erosion following wildfires was shown to be related to the water-repellency of soils formed during fires (Krammes and DeBano 1965). This discovery stimulated a search for a better understanding of the chemical properties of hydrophobic substances and the use of nonionic wetting agents for remedial treatments.

Following the 1968 conference, the interest in water repellency expanded both nationally and internationally. Not only were land managers in the United States interested in water repellency, but it was reported in Italy, Spain, Portugal, Greece, Poland, Taiwan, Egypt, India, New Zealand, Australia, South Africa, Chile, Germany, the Netherlands, and Belgium.

Associated with this expanding interest were the applications of emerging scientific knowledge in several fields, particularly in soil physics, where water movement into and through soils was being characterized as a "fingering" process. Understanding the fingering process depended upon having a knowledge of the physics of water movement through heterotrophic systems with unsteady saturated and unsaturated flow processes occurring simultaneously, heterogeneous horizontal layers (e.g. soil horizons or other subsurface strata), preferential and lateral flow pathways, and hysteresis.

Management and Amelioration

Water repellency in soil created management problems almost from its initial identification early in the twentieth century. The attention received by water repellency in soils, however, has evolved from what was previously an isolated academic curiosity in the early twentieth century to present-day worldwide concern among scientists and managers of both agricultural lands and wildlands. Approaches for ameliorating water repellency also evolved concurrently as the effect of water repellency on water movement processes became better understood.

The first descriptions of difficult-to-wet soils were reported as incidental observations during an organic matter study in California (Schreiner and Shorey 1910) and a study of fungal infection of grasslands in Colorado (Shantz and Piemeisel 1917). However, specific examples of decreased productivity of citrus orchards were first reported in the 1940s (Jamison 1947), and the adverse effect (dry patch) of water repellency on the productivity and aesthetics of golf greens began attracting serious attention during the 1960s (Morgan et al. 1966). Also during the 1960s, water repellency was reported to reduce productivity of pastures in Australia (Bond 1964). Also, the role of water-repellent soils in erosion and postfire management of chaparral areas in California that had been burned by wildfires was attracting attention during the 1960s (DeBano et al. 1967).

Since the 1970s, the interest in water-repellent soils has continued to grow. It was estimated in the early 1990s that about 5 million hectares of land in Australia and New Zealand were adversely affected by water repellency, resulting in a financial loss of more than 150 million dollars. In the Netherlands, not only do water-repellent soils affect productivity, but they accelerate the movement of contaminants (e.g. fertilizers, pesticides) into the groundwater tables via preferential water flow. As a consequence, a widespread interest has developed in creating models that can be used to describe the transport of chemicals through soils under field conditions (Flüher et al. 1996). Soil classification systems are now being developed to reflect the susceptibility of soils to the rapid transport of water and associated chemicals into groundwater (Quisenberry et al. 1993).

Fire-induced water repellency remains a present-day concern following both wild and prescribed fires. Attempts are currently being made to develop infiltration models that will account for the effect of water-repellent soils. Water repellency also is being recognized as an important factor in erosional processes in nonfire environments, particularly in sand dunes along the west coast of the Netherlands (Witter et al. 1991). Concerns are being focused on the spatial variability of fire-induced water repellency (Doerr et al. 1998) and the relationship between the spatial distribution of water repellency and erosion potential produced during prescribed burning (Robichaud 1996).

Several other, less widespread concerns about water repellency have been reported during the last 30 years. For example, localized areas of highly water repellent soils are created by oil spills, requiring intensive remedial efforts (Roy and McGill 1998). Furthermore, water repellency is becoming recognized as a key mechanism responsible for the self-cleaning features of plant surfaces (Neinhuis and Barthlott 1997). The diminished aesthetics and playing qualities of golf greens that are afflicted with the age-old problem of "dry patch" continue to be a concern to golf green supervisors (Hudson et al. 1994).

An increased interest in water repellency has also been focused on wildland soils, in both fire and nonfire environments. Water-repellent soils have been reported in several wildland environments, including dry sclerophyll eucalyptus in Australia (Crockford et al. 1991), eucalyptus forests in South Africa (Scott 1991), eucalyptus and pine forests in Portugal (Doerr et al. 1996), and windbreaks in Taiwan (Lin et al. 1996). Also, the fire-induced water repellency described above continues to have its primary impact on soil-water relationships in wildland ecosystems.

The first remedial treatments used for water repellency were wetting agents (or surfactants). Considerable research was conducted by the scientists at the University of California, Riverside, on the effectiveness of specific surfactants for treating water repellency in soils. Nonionic wetting agents were rapidly identified as being chemicals that could readily wet-up highly water repellent soils (Letey et al. 1975; Miller and Wilkinson 1977). Water-repellent thatch material on golf courses was effectively treated with these wetting agents. Wetting agents were also tested as a treatment for ameliorating heat-induced water repellency in brushland soils burned during wildfires. Although anionic wetting agents effectively reduced erosion on small burned plots, an effort to use operational-level wetting agent treatments to reduce soil erosion on burned watersheds was not successful (Rice and Osborn 1970). Another technique used to ameliorate water repellency in dry-patch turf areas of Australia consisted of mixing loamy soil with naturally occurring water-repellent sands to improve their wettability (Bond 1978).

Coping with water-repellent soils continues to present a challenge to managers of agricultural and pasture lands worldwide into the 1990s (Capriel 1997). Interest has continued in the usefulness of wetting agents as a remedial treatment for water repellency (Effron et al. 1990), although this treatment does not capture as much interest as it did during the 1960s and 1970s. Wetting agents have also been used to increase the effectiveness of irrigation (Wallis et al. 1990).

Remedial treatments other than wetting agents are being tested extensively at present in Australia and New Zealand (Blackwell et al. 1993). These treatments include direct drilling, wide furrow sowing, and the use of microorganisms and fertilizers to stimulate microbial breakdown of water repellency. Soil claying, a treatment that involves mixing large amounts of clay in the upper water-repellent layer, has received widespread use in Australia (Carter and Hetherington 1997). High pH soil treatments have also been used to improve the wettability of soils supporting golf greens (Karnok et al. 1993).

An International Workshop on Soil Water Repellency

During the week of 1 September 1998, a 3-day international workshop was held, titled "Soil Water Repellency: Origins, Assessment, Occurrence, Consequences, Modeling, and Amelioration" at the SC-DLO Winand Staring Centre for Land, Soil and Water Research, in Wageningen, the Netherlands. The conference was planned to be held 30 years after the first International Conference on Water Repellency at Riverside, California in 1968 (DeBano and Letey 1969). An important part of the 1998 workshop was to review the progress and changes in the field that had occurred during the past 30 years.

The increased interest in water repellency since the 1968 conference was demonstrated by the large number of scientists from many parts of the world who presented papers at the Wageningen workshop. The 1998 workshop was attended by about 70 scientists from 14 countries: Australia, Belgium, Canada, Denmark, Germany, Greece, the Netherlands, New Zealand, Portugal, Russia, South Africa, Spain, the United Kingdom, and the United States. In contrast, only scientists from Australia, England, and the United States participated in the earlier conference at Riverside.

The subject material at the two conferences was somewhat similar. In 1968, the major areas of interest were characterizing water repellency, movement of water through water-repellent soil systems, use of wetting agents as remedial treatments, fire-induced water repellency, hydrophobic compounds that produced water repellency, and the effect of water-repellent soils on plant growth. However, during the Wageningen workshop, entire sessions were devoted to origins and assessments of water repellency, occurrence and consequences of water repellency, flow and transport in water-repellent soils, and amelioration of water-repellent soils.

Significant advances in many areas were apparent during the past 30 years, though some age-old problems remain unsolved. For example, substantial progress in soil physics during the past 30 years has provided a much better understanding and characterization of water movement through water-repellent soil systems. Along with progress in scientific theory came the development of improved technology, now capable of more thoroughly analyzing the composition of organic matter and of measuring soil water changes continuously under field conditions. Considerable progress has been made in developing specific mechanical and agronomic techniques for ameliorating water-repellent soils, particularly in Australia and New Zealand. Chemical treatments, such as wetting agents, still remain important but are sharing the limelight with physical approaches (e.g. claying or furrowing). The processes involved in creating fire-induced water repellency are understood better now than 30 years ago, but effective postfire remedial treatments are still lacking. The century-old problem of fairy rings, dry patch, or thatch accumulation still remains a high priority in the management of golf greens. The most important impression obtained when reviewing the progress during the past 30 years is that water repellency in soils has evolved from a limited scientific curiosity to a full-fledged field of science that has attracted the efforts of scientists and managers worldwide.

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