Journal of Scientific Research & Reports
3(8): 1003-1037, 2014; Article no. JSRR.2014.001

SCIENCEDOMAIN *international*
www.sciencedomain.org

Soil Hydrophobicity: An Overview

Idowu Ezekiel Olorunfemi[1*], Temitope Akinwale Ogunrinde[1]
and Johnson Toyin Fasinmirin[1]

[1]Department of Agricultural Engineering, Federal University of Technology, Akure, Nigeria.

Authors' contributions

This work was carried out in collaboration among all authors. Author IEO wrote the protocol and wrote the first draft of the manuscript. Authors TAO and JTF managed the literature searches. All authors collaborated on the revision and improvement of the article. All authors read and approved the final manuscript.

Review Article

Received 2nd October 2013
Accepted 8th February 2014
Published 7th March 2014

ABSTRACT

Water is the most precious resource to Agriculture. The occurrence of soil hydrophobicity has drastically reduced the amount of water available for plant growth and crop production. Hydrophobicity is a phenomenon that reduces the affinity of soils for water. It occurs when the soil is not completely wettable. This paper presents a brief review of the method/characterization, impacts and amelioration/treatment of soil hydrophobicity. It also reviews the general causes and characteristics of soil hydrophobicity: organic matter decomposition, heating of the soils by wildfires, fungal and microbial activities, growth of particular vegetation species and soil characteristics. Adequate knowledge of these causes will be valuable in providing means of treating and cushioning the effects of soil hydrophobicity.

Keywords: Hydrophobicity; organic matter; agriculture; water repellency; fungi; soil.

1. INTRODUCTION

Hydrophobicity (Soil water repellency) is a reduction in the rate of wetting and retention of water in the soil caused by the presence of hydrophobic coatings on soil particles [1,2]. Soils that repel water are considered hydrophobic and these soils which have hydrophobic properties tends to resist or retard surface water infiltration [3] and increase water runoff

---

**Corresponding author: E-mail: olorunfemiidowu@gmail.com;*

rates, creating extreme soil erosion potentials. It is one of the most important physical properties of soils found all over the world, and it may have significant effects on the eco-hydrological processes of land ecosystems. Hydrophobicity in soils was first described by Schreiner and Shorey [4], who found that some soils in California could not be wetted and thereby were not suitable for agriculture [5]. They described a soil in California that "could not be wetted, either by man, by rain, irrigation, or the movement of water from the subsoil" [6]. During the 1990s, the occurrence of water repellency continued to be reported in a wide range of natural and agricultural environments and as a result was fast becoming an important component in the management and productivity of soils worldwide with problems on agricultural lands being the most frequently reported [7]. The findings point to the fact that hydrophobicity is not an isolated curiosity as it can be found in soils all over the world [8–12] and has also been reported under a range of crops and cropping systems [13]. In agricultural lands, variability of soil texture, soil structure and the other physical and chemical properties which affects soil hydrophobicity has been reported [14]. These variabilities have appreciable effects on water infiltration/wetting process and its related parameters [15–16]. Different studies have exhibited different spatial correlation structures for soil hydraulic properties such as saturated/unsaturated hydraulic conductivity, saturated and residual soil water content, sorptivity and pore-size distribution parameter [16,17–20]. All of these earlier studies indicated the importance and the need for proper characterization of the spatial variability of soil parameters.

Hydrophobicity has been reported in varying proportions of soil particles [21–22], sandy soils Fig. 1 because of their low particle surface area-to-volume ratio are especially prone to being hydrophobic [21,23] as compared to the fine-grained soil [24] because little organic matter is required to coat the surfaces [25]. However earlier reviews [25–27] showed that fine textured soils are also characterized by high level of hydrophobicity. Generally, soils high in organic matter and soils that dry out frequently are more susceptible to water repellency. Greater drying of soils is making them less able to retain water due to the fact that drying accentuates the movement of organic solutes to soil surfaces and if critical water content is reached, a water repellent barrier can limit the rate and capacity of water absorption [2,13, 28]. Soils in fields or forests that have been burned also tend to exhibit water repellency. In an extremely water repellent soil, sorptivity and capillary rise will be 0 and drops of water will form on the soil surface and they will often evaporate before infiltrating [2]. The increasing dry climate and a reduction in the availability of irrigation water has led to a situation where soil water repellency has emerged as an issue facing gardeners, farmers, land managers, hydrologists and soil scientists.

Soil hydrophobicity can also be caused by fungal and microbial activity, growth of particular vegetation species, organic matter, heating of the soils by wildfires and soil characteristics [25,29]. Soil Scientists have been concerned with spatial variation of soil properties (texture, moisture contents, organic matter content etc which contribute to the occurrence of soil hydrophobicity) for many years [30,31]. From the variable nature of the numerous factors stated above as being the major causes of hydrophobicity, one can expect hydrophobicity itself to vary with space and time.

Hardie et al. [32] reported that water repellency has been associated with increased erosion, poor seedling establishment, uneven crop growth, reduced irrigation efficiency and accelerated leaching of solutes including pesticides and fertilizer [33,34]. For crop production, water repellency can stress plants resulting in poorer yield quality [2]. It can also cause waterflows to develop preferential pathways - this can lead to greater infiltration through the profile, taking water away from the root zone and runoff which can cause loss of nutrients and soil erosion. Water doesn't stick to hydrophobic soil particles as readily as hydrophilic soil particles, water tends to bead up on hydrophobic soil surfaces Fig. 1 instead of going into the soil (poor infiltration). This causes localized dry spots in some places resulting in plant stress and deep percolation in others resulting in poor irrigation efficiency and crop performance [35].

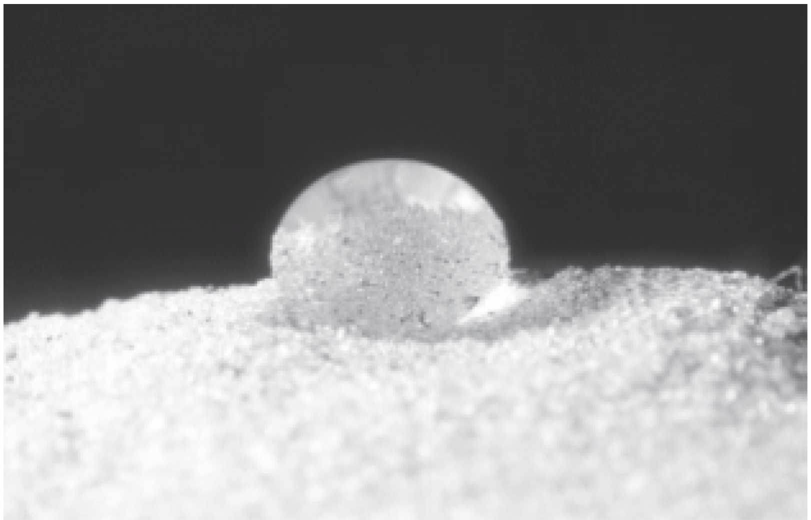

Fig. 1. Water repellent sandy soil with a water droplet (adapted from Moore and Blackwell, [80])

1.1 Origin of Hydrophobicity

Naturally, soil, a porous media is expected to have high affinity for water due to intermolecular attraction between soil particles and the water molecules (adhesion) but numerous literatures have proven otherwise. Some soils exhibit a reduced, or no affinity to water (hydrophobicity or water repellency) at the surface and within the root zone making hydrophobic in nature. This phenomenon is due to the presence waxy organic substances. Schreiner and Schorey [4] were amongst the first to document soil water repellency. This was the result of a series of studies which actually commenced in 1908 to identify organic chemicals contained in a California soil. Also, Bayliss [36] validated that soils containing mycelium were difficult to wet and cited an example where rain did not penetrate the soil in mycelia infested areas but penetrated to a depth of 10 cm in the adjacent non-mycelial areas.

For close to two decades (1920 – 1939), only two publications on hydrophobicity were found [7]. The first publication was a report of resistance to wetting in sands by Albert and Kohn [37] while the second report by Kenyon [38] described the creation of "ironclad" or artificial catchments. Another early study associated soil hydrophobicity with the reduced productivity of citrus groves in Florida [39]. Also, about that time both Robinson and Page [40] and Hedrick and Mowry [41] discovered that soil aggregates, which had been stabilized by adding organics to the clay fraction, became slightly water repellent. Other published papers reporting observations on water-repellent soils include the results of an investigation on difficult-to-wet soils in The Netherlands as reported by Domingo [42]. Van't Woudt [43] also in the New Zealand reported the effects of organic particle coatings on the wettability of soils.

Starting from 1960, interest in soil hydrophobicity increased rapidly which led to substantial increase in the knowledge about hydrophobicity in soils sand related fields. Over 90 publications dealing with various aspects of hydrophobicity were published between 1960 and 1970 [7]. These publications paid considerable attention to the following areas: use of wetting agents to increase infiltration and enhance water movement in water-repellent soils [44,45]; usefulness of wetting agents for irrigating hydrophobic soils [46]; evaluation of the longevity of wetting agents [47] and their use for reducing postfire erosion [48] and enhancing turfgrass growth [49]. Other advances in the study of hydrophobicity till the 1970s include the development in the relationships among organic matter, soil microorganisms, and hydrophobicity, characterization of hydrophobic soils, hydrophobic soils used for water harvesting, reducing evaporation, and laboratory and field measurement methods were also developed [7].

During the 1970s, more understanding of fire-induced water repellency [50,51] and its importance in postfire erosion on watersheds [52] were subjects of active research. Fire-induced hydrophobic soils also received worldwide attention [7]. Numerous other examples of soil water repellency in unburned areas can as well be found in the literatures [25] and during the 1990s and early 2000s it became evident that soil water repellency is widespread and not restricted to burned areas or a narrow set of other conditions [6].

1.2 Occurrence of Hydrophobicity

Soil hydrophobicity has been known for many years. It is a phenomenon that occurs in different soils worldwide under variety of climatic conditions and may occupy large areas [10, 24]. About 5 million hectares of agricultural land in Western Australia are susceptible to water repellency [53]. Hydrophobicity is usually recognised in soils that dry out frequently, difficult to wet and not cultivated. Hydrophobicity is not restricted to some specific, seasonally dry environments, but is much more widespread than previously considered [25]. It is also important to note that the occurrence of soil water repellency is not limited to any particular soil type [1,2,26]. In most parts of the world, the phenomenon of soil hydrophobicity has been recognized [7,10] and has been observed in sand, sandy loam, loam, clay, peaty clay, clayey peat and sandy peat soils [26] as well as in heavy clay soils with grass cover [54]. Hydrophobicity is most pronounced in coarse textured soils and is common in sandy soils supporting turf or pasture grasses, where it often results in management problems of the Turfgrass [55,56]. However earlier reviews by Doerr et al. [25]; Dekker et al. [26] showed that fine textured soils are also characterized by high level of hydrophobicity [27].

In many parts of the world hydrophobic soil has been found and reported: Nepal [57], Egypt [58], Mali [59], United States [5,60], Australia [61,62,63], Great Britain [64], Japan [65], Poland [66], Canada [67,68], The Netherlands [69,70], Italy [71,72], Portugal [73,74], New Zealand [75], Nigeria [76], Columbia [10], Spain [77], South Africa [78] and Germany [79].

1.3 Distribution and Variation of Hydrophobicity

The heterogeneity of soils is extreme. Each soil has unique properties that differentiate it from others as no two parcels of land are the same. Several of these soil properties affect the severity of soil hydrophobicity one way or the other. Some of these factors include organic matter content, soil texture, soil moisture content, fire intensity etc. These factors (such as soil moisture content, organic matter content, soil pH, soil texture) vary spatially and temporarily and so variations of soil hydrophobicity can also either be spatial variation (changes with depth) or temporal variation (changes with time). The spatial variations of these soil properties and many others have been the concern of soil scientists for many years [30,31]. Regalado and Ritter [81] reported that hydrophobicity varies spatially and temporally according to the conditions of the climate. Doerr et al. [25] also reported a general increase in soil water repellency during dry weather, and a reduction or complete elimination after prolonged and/or heavy precipitation. Temperature and/or soil moisture conditions may be the reason for this seasonal variation. Several studies have found an inverse relationship between hydrophobicity and soil moisture [82], noting that increased soil moisture levels results in decreased hydrophobicity. Drier soils tend to be more hydrophobic [10,83] showing that the degree of hydrophobicity is a function of the soil water content and also a threshold water exists where hydrophobicity disappears [84] temporarily [85]. However, experiment by Dekker et al. [86] to measure hydrophobicity in sand dunes in the laboratory after drying the soil samples at varying temperatures reveal that a relatively low moisture content does not necessarily express strong hydrophobicity [87,88].

In agricultural lands, soil texture, soil structure and other physical and chemical properties have been reported to vary severely and their variabilities affect infiltration processes and its related parameters appreciably [15,16]. Numerous researches have reported that soil texture, the proportions of different particle sizes (sand, silt and clay) in a soil, influences the degree of hydrophobicity. Although hydrophobicity or water repellency is found in all soil textures, stronger hydrophobic layer is formed in soil with higher percentages of sand. The surface roughness of the soil also influences the gravity of hydrophobicity as increased roughness is linked to greater repellency [89]. Furthermore, the severity of soil hydrophobicity varies with the soil profile as it is most severe at shallower soil depths. Clothier et al. [90] reported that hydrophobicity varies with space and is mostly pronounced within the top 5 – 10 cm of the soil profile while according to Karnock and Tucker [85] the most severe water repellency usually occurs in the top 1 to 2 inches of the profile; however studies have shown that on occasion it can also be found at 6 – inch soil depths.

1.4 Hydrophobicity and Contact Angle

Soils which have hydrophobic properties (also called water repellent soils) can resist or retard surface water infiltration [3]. Water droplets in contact with these soils tend to form beads Fig. 5.

A distinctive contact angle (θ), which is a quantitative measure of the wetting of a solid by a liquid, forms between the drop of water and soil surface, which for water repellent soils is >90º [2]. It is the angle that a small drop of liquid makes as it meets the surface or interface of another phase, usually a solid [91]. Fig. 5 shows that low values of θ indicate that the liquid spreads, or wets well, while high values indicate poor wetting. If the angle θ is less than 90º the liquid is said to wet the solid, with a contact angle of zero representing complete wetting. If it is greater than 90° it is said to be non-wetting. The critical angle will be greater than 90º, if the energy required to create the solid-liquid interface is greater than that required for creation of a solid-gas interface. In other words, the liquid will bead up on the surface to minimize the solid-liquid interfacial area. The low contact angle generally indicates that the surface of the substrate is hydrophilic and has a high surface energy/ good wetting property. Conversely a high contact angle generally indicates that the surface is hydrophobic and has a low surface energy/ poor wetting property [92]. Most soils have a certain level of water resistance, where water will infiltrate but at a slower rate than expected as demonstrated by Tillman et al. [93]. These soils have contact angles between 0º and 90º. However a contact angle of 30º is not uncommon in soils [21]. Fig. 5 shows the forms of water repellency in soil based on the contact angle between water and soil. Contact angle is commonly used as the most direct measure of wetting and the primary focus of its studies is in assessing the wetting characteristics of solid/liquid interactions.

2. MEASUREMENT AND CHARACTERIZATION OF SOIL HYDROPHOBICITY

Soil hydrophobicity can be measured both in field and by laboratory experiments. The field technique is known to be generally more reliable than laboratory techniques as recent studies have shown that drying samples by air and oven are not indicative of field conditions [94,95,96,97,98]. Numerous techniques have been developed to measure and classify hydrophobicity of soil some of which are the water drop penetration time (WDPT) test [43], which is based on the time taken for a drop of water to infiltrate into soil [94]; The molarity of ethanol droplet (MED) test (also known as the ‘Percentage Ethanol’ or ‘Critical Surface Tension’ test) [99] is an extension of the WDPT test [7] and uses different concentrations of ethanol to alter the surface tension of the liquid; direct measurement of contact angle by the capillary rise method [24] and determination of the Index of soil water repellency, R, from the sorptivities of 95% ethanol and water using the minidisk infiltrometer [100]. Others include the Wihelmy plate method, Sessile drop method, Du Noüy ring method and modified capillary rise method [101]. We shall examine them thoroughly citing their advantages and disadvantages.

2.1 Water Droplet Penetration Time (WDPT)

This is one of the simplest and most common methods of classifying soil hydrophobicity. It is based on the time taken for a drop of water to infiltrate into soil [94]. It involves placing a drop of water on the soil and measuring the time for it to penetrate or determining the time the water droplet takes to be absorbed by the soil sample. If the soil is hydrophobic, the water droplet will not penetrate into the soil but will tend to “ball up” and remain on the soil surface for measured period of time. This varied period of time for which the water droplet remain on the soil surface is called the water droplet penetration time (WDPT) and is depended upon the degree of hydrophobicity exhibited by the soil [102]. The longer the duration it takes the water droplet to remain on the soil surface, the stronger the hydrophobicity, and as such the WDPT is best characterized as measuring the Persistence of soil hydrophobicity or water repellency as proposed by Watson and Letey [103]. While Wander [104] used the penetration time of more than 10 seconds, other researchers like Bond and Harris [105], Krammes and DeBano [106] and Letey [107] employed penetration time of more than 5 seconds as the limit for classifying soils as being hydrophobic [102] and whereas the likes of Watson and Letey [103], King [83], Dekker and Ritsema [70] and Bachmann et al. [101] have all reported WDPT values under five seconds as water repellent [98]. WDPT test separates soils which are classified as being hydrophobic from those which are wettable.

A wetting angle distinguishes these two types of soils (hydrophobic and wettable). If the wetting angle is greater than 90 degrees, the water droplet will remain on the surface until it evaporates; if the angle is less than 90 degrees, pore capillary forces will pull the water into the soil. So for a hydrophobic soil, wetting angle is >90 whole for a wettable soil, wetting angle is <90. The water droplet penetration time (WDPT) method is easy and very useful for quick determination of soil hydrophobicity especially when numerous samples are to be analysed. The limitations of this methods are that it takes considerable time in hydrophobic soil, has no physical meaning and the penetration time of the water droplet can be influenced by other factors like surface roughness, pore geometry etc. [108]. Also, WDPT values are not easily reproduced and it gives only qualitative information on the stability of the hydrophobicity, but does not provide quantitative measurement of the contact angle [102].

Based on the WDPT method, different classifications of WDPT have been done Table 1. Dekker and Jungerius [109] described and distinguished seven classes of repellency ranging from wettable with WDPT less than 5 s to extremely water repellent with WDPT of more than 6h while king [83], Bisdom et al. [69] and Doerr [110] also distinguished varying classes of soil hydrophobicity/repellency as in Table 1.

Table 1. Classes of water droplet penetration time (WDPT) test

Notation	**King [83]**	**Dekker and Jungerius [109]**	**Bisdom et al. [69]; Doerr [110]**
Time Range (s)	Time Range (s)	Time Range (s)	Time Range (s)
Non repellent	≤1	0 – 5	≤5
Slightly repellent	1 – 60	5 – 60	5 – 10 10 – 30 30 – 60
Strongly repellent	60 – 600	60 - 600	60 – 180 180 – 300 300 – 600
Severely repellent	600 – 3600	600 – 3600	600 – 900 900 – 3600
Extremely repellent	≥ 3600	3600 – 10800 10800 – 21600 ≥21600	3600 – 18000 ≥18000

Adapted from: Hunter [98]

2.2 Molarity of an Ethanol Droplet (MED) Test

The molarity of ethanol droplet (MED) test also known as the ‘Percentage Ethanol’ or ‘Critical Surface Tension’ test [99] is an extension of the WDPT test [7] and uses different concentrations of ethanol to alter the surface tension of the liquid [2]. The molarity of ethanol droplet (MED) test quantifies hydrophobicity as the least ethanol concentration that can permit penetration of a drop of water within 5 s [70] or alternatively, the 90° liquid surface tension of the infiltrating droplet [111]. In the MED test, drops with an increasing concentration of ethanol are applied to the soil in order to indirectly measure the apparent surface tension [112]. This effectively determines how strongly the water is repelled, and this property is best reported as the strength or severity of soil hydrophobicity or water repellency [99]. The concept that a liquid can only completely enter the soil if θ is less than 90^o is employed in this procedure [99]. A similar procedure as the surface tension approach was proposed by King [83] except that he recommended measuring the molarity (rather than surface tension) of ethanol in a droplet of water required for soil infiltration within 10 s. King [83] proposed a classification where soils with a MED index<1 are not significantly hydrophobic and soils with a MED index >2.2 are severely hydrophobic [99]. Dekker and

Ritsema [70] in their study used a procedure that reported the results of the ethanol drop test in terms of the volumetric ethanol percentage. All of these procedures have a relationship between them with which a value of one of them can be easily converted to another [99]. The MED test is simple and quick as less time is needed in its observation but it may give a poor representation of soil infiltration rates and wetting behavior across intervals of measurement.

2.3 Capillary Rise Method (CRM)

Capillary rise method is a method used in the determination of liquid-solid contact angle as described by Letey et al. [113] by measuring the rate of rise of water in a sand column Fig. 2. The fact that a liquid rise in a capillary tube and that the height of the liquid, depends on interfacial tension is employed in the capillary rise method to determine wettability of soils (a porous material) [114,115,116]. The principle of measuring the liquid-solid contact angle through the capillary rise method is described in the equation (1):

$$\gamma = \frac{\Delta\rho g h r}{2\cos\theta} \tag{1}$$

Where

γ is the surface tension of liquid (dyn m^{-1}), $\Delta\rho$ is the change in density of the liquid (kg m^{-3}), g is the acceleration due to gravity (m s^{-1}), h is the height of capillary rise (m), r is the effective pore radius (m) and θ is the liquid – solid contact angle (or wetting angle).

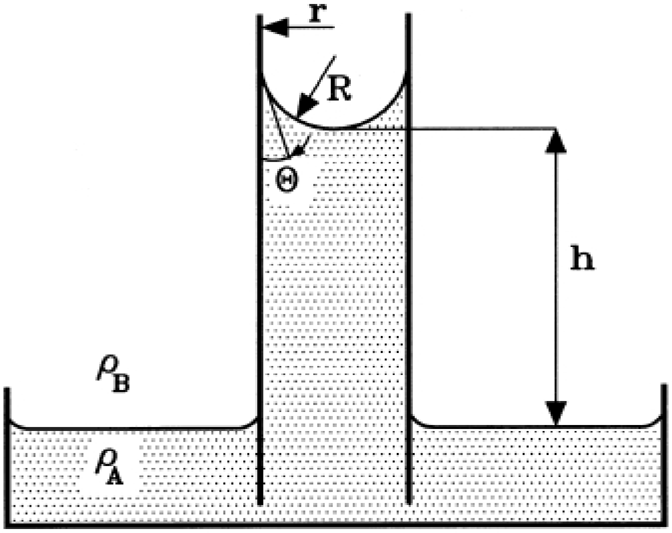

Fig. 2. Capillary rise method (Adapted from Drelich et al. [117])

The effective pore radius (r) and liquid-solid contact angle θ are not known. The assumption that ethanol has the same contact angle value (0) for all soil materials was used to calculate the effective pore radius (r). The contact angle θ for water can then be calculated [98]. The capillary rise technique is not a good procedure for measuring θ when θ is greater than 90°

[99]. To overcome this limitation, Bachmann et al. [101] modified the capillary rise method to account for contact angle between 0 – 180º [98].

2.4 Wihelmy Plate Method

The Wihelmy plate method Fig. 3 is another method employ in the determination of the contact angle if the surface tension of the fluid is known [118]. Similarly, if the contact angle for the given solid-liquid pair is known, surface tension of the liquid can be obtained with this method. It operates based on the principle proposed by German chemist, Ludwig Wihelmy [119] that the weight of a solid plate immersed into a liquid is subjected to gravitational force acting vertically downwards; the buoyancy acting vertically upwards and the surface force acting along the liquid - vapour interface directly at the three phase line [116]. The method depends on the change in force after a rectangular plate, hanging vertically from a microbalance, meets a liquid – air surface [120]. The Wilhelmy plate is a thin plate that is used to measure equilibrium surface or interfacial tension at an air – liquid or liquid – liquid interface [121]. The Wilhelmy plate consists of a thin plate usually on the order of a few square centimeters in area and it is often made from filter paper, glass or platinum which may be roughened to ensure complete wetting [121]. The metal plate must be cleaned from organic contaminants by an organic solvent and then flamed in a Bunsen burner before the experiment. Both roughening and cleaning of the plate surface are used to maintain good wetting of the plate by the test liquid [117].Since the equation for the Wilhelmy technique does not depend on the geometry of the solid surface, as long as the walls of the solids are parallel and normal to the liquid surface, the method is not only applicable to plates, but also to rods, capillary tubes, wires and fibers [122] and also notable is the fact that materials such as glass, mica, and steel [123,124] have been used. In fact, the results of the experiment are irrelevant of the material used, as long as the material is wetted by the liquid [125].

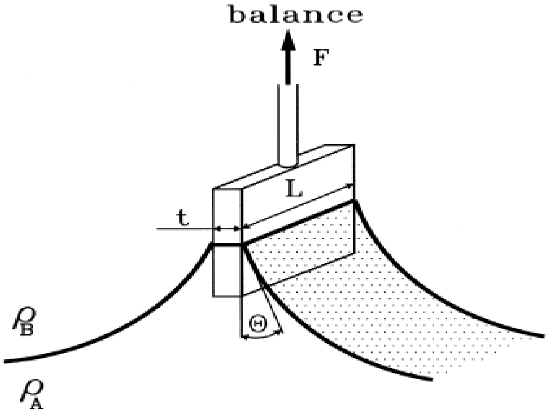

Fig. 3. A schematic of the Wilhelmy Plate Method (Adapted from Drelich et al. [117])

In this method, the plate is oriented perpendicular to the interface Fig. 4. When the plate is brought in contact with the liquid, the change in its weight is detected by a microbalance [118]. The force applied to the plate is equal to the weight (measured by a microbalance) of the liquid meniscus uplifted over the horizontal surface or the plate is dipped into the liquid whose surface tension is to be measured, as shown in Fig. 4 and the vessel containing the liquid is gradually lowered and the force measured by the balance at the point of detachment (F) is noted. Another approach in which the Wilhelmy plate can be used is to raise liquid level until it just touches the hanging plate. The force recorded on the microbalance is then noted.

This force, measured by the microbalance, is used to calculate the interfacial tension by using the Wilhelmy equation (2):

$$\gamma = \frac{F}{P \cos\theta} \tag{2}$$

Where *P* is the wetted perimeter of the plate (m) and θ is the contact angle measured for the liquid meniscus in contact with the object surface.

Cleaning of the metal plate from organic contaminants by an organic solvent and flaming in a Bunsen burner before each experiment reduces the contact angle values to near-zero values (so that the liquid wets the plate completely). If the contact angle is close to zero, Equation (2) simplifies to equation (3):

$$\gamma = \frac{F}{P} \tag{3}$$

The Wilhelmy plate method's benefit is that it may be automated, allowing for easy replication of many samples. However, the cost of equipment may be prohibitive. Another important advantage of the Wilhelmy plate method is that it theoretically covers the whole θ range between 0 and 180° and that the measurement is comparably fast. Also the task of measuring an angle is reduced to the measurements of weight and length, which can be performed with high accuracy and without subjectivity. While some of the drawbacks of this method is the Adsorption of organic compounds from the laboratory environment or test solutions which can be a major source of experimental error when measuring surface tensions using the Wilhelmy plate method. The solid sample also must be produced with a uniform cross section in the submersion direction. Rods, plates, and fibers with known perimeters are ideal samples, but it is sometimes difficult to measure the perimeter and the wetted length precisely.

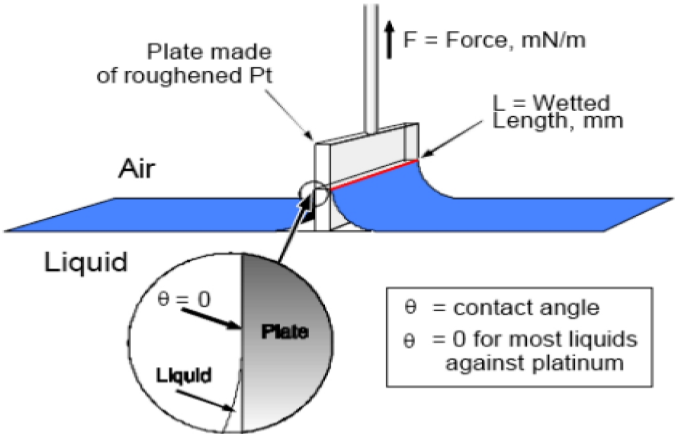

Fig. 4. Wilhelmy plate method for measuring surface tension

2.5 Du Noüy Ring Method

The Du Noüy method uses a platinum ring which is submerged in the test liquid to measure equilibrium surface or interfacial tension at air-liquid or liquid-liquid interfaces instead of a thin plate as used in the Wihelmy method. The Du Noüy method is a common method of measuring surface and interfacial tension and the apparatus used is called the Du Noüy ring tensiometer. In this method, the force necessary to remove the platinum ring from the test liquid is related to the interfacial tension. This force is measured as the ring is pulled out of the liquid.

The total force needed to detach the ring is given by the equation (4):

$$\gamma = \frac{F}{P\cos\theta} f \tag{4}$$

Where *F* if the force measured, *P* is the wetted perimeter of the three-phase contact line (m), θ is the contact angle measured for the liquid meniscus in contact with the object surface and f is the correction factor and varies from about 0.75 to 1.05 [117]. Here the surface tension is multiplied by 2 because it acts on the two circumferences of the ring (inside and outside ones) i.e. *P* = 2(2r).

2.6 Sessile Drop Method

The Sessile drop method is based on the analysis of the profile of the drop sitting on a solid substrate. It involves placing a liquid droplet on the surface of the solid and measuring the contact angle simply by aligning a tangent to the drop profile at the point where the three interfaces meet i.e. the drop's base Fig. 5. The contact between both liquid and solid surface interface will exert a force on each other. The surface energy of the solid surface and surface tension of the liquid determines the type of force exerted and this may be attractive or repellent force. The results will include contact angle which is the angle formed between the liquid/solid interface and liquid/vapour interface, and a deduction of the surface's wetting capability. The liquid used for such experiments is referred to as the probe liquid. The nature of the contact angle formed is first described by Thomas Young [126]. The Young's equation (5) defines the contact angle of a liquid drop on an ideal solid surface by the mechanical equilibrium of the drop under the action of three interfacial tensions [127].

$$\gamma_{sv} = \gamma_{sl} + \gamma_{lv} cos\theta_y \tag{5}$$

Where γ_{sv}, γ_{sl}, and γ_{lv} represent the solid-vapor, solid-liquid and liquid-vapor interfacial tensions, respectively, and θ_y is the Young's contact angle.

The Sessile drop method involves measuring the contact angle directly using a Goniometer Fig. 6, which allows the user to measure the contact angle visually. Surface scientists use a Contact Angle Goniometer Fig. 6 to measure contact angle, surface energy and surface tension. The static sessile method employs the use of a microscope to analyze and determine the contact angle of a probe liquid which is deposited on a surface by means of a syringe [128]. In the dynamic sessile method which is similar to the static method described above, the drop of liquid which is deposited on a surface is modified. The droplet's volume is changed dynamically without increasing its solid-liquid interface area and this maximum angle is the advancing angle. Volume is then removed to produce the smallest possible angle, which is called the receding angle. The difference between the advancing and receding angles is called contact angle hysteresis [128]. Drop shape analysis is a convenient way to measure contact angles and thereby determine surface energy. Also only small amounts of liquid (a few microliters) and small surface substrates (a few square millimeters) are required [127]. On the other hand, the accuracy of the measurement is dependent on the subjective impression of the user/operator which can lead to errors or a set of detection rules of software used.

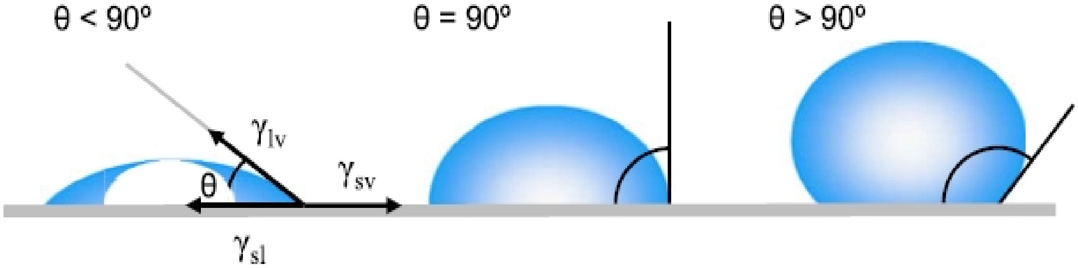

Fig. 5. Diagram of contact angles formed by sessile liquid drops on a smooth homogeneous solid surface showing the surface energies of the involved interfaces (Adapted from Yuan and Lee [127])

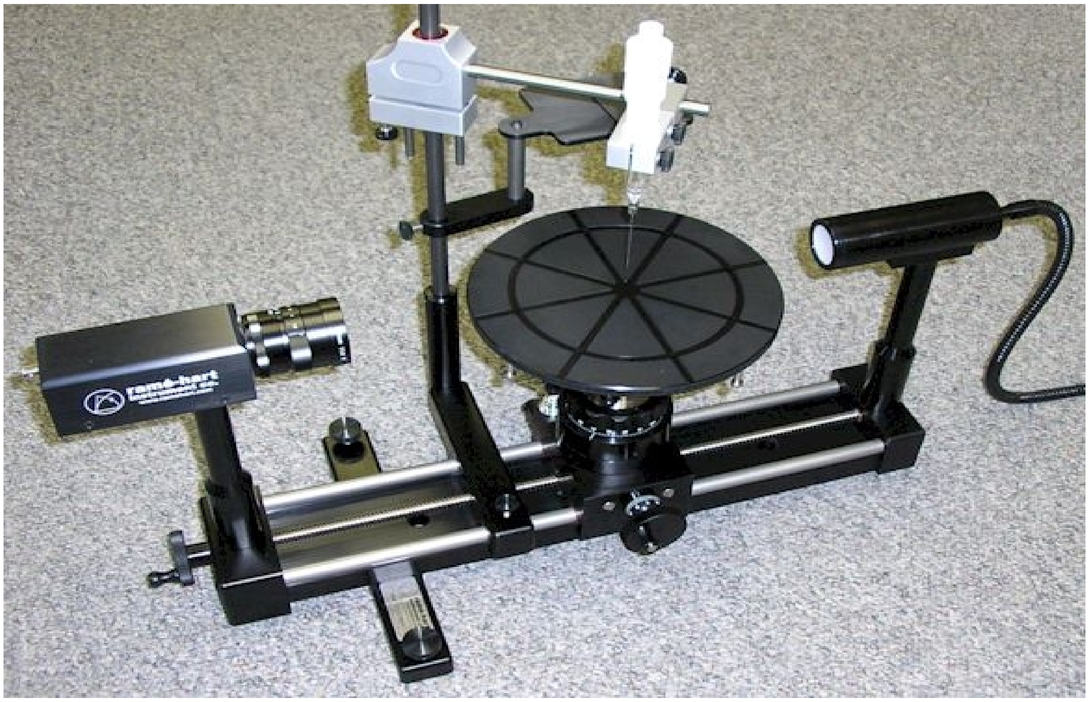

Fig. 6. A Contact Angle Goniometer by Rame Hart Instrument Company, New Jersey, USA

2.7 Water Repellency Index (RI)/ Intrinsic Sorptivity Method

The soil water repellency index (RI) compares hydraulic behavior of water and ethanol in soil [98]. An Index of soil water repellency, *R*, can be determined from the sorptivities of 95% ethanol and water, two different liquids with different angles of contact, densities and viscosities [129]. The sorptivity calculated from the unsaturated flow rate in soil is determined using the Minidisk Infiltrometer Fig. 7 [100], a hand-held field instrument for rapidly assessing soil infiltration capacity. It consists of a plastic tube, 22.5 cm long and 3.1 cm in outside diameter, marked with milliliter gradation (0 to 100 mL), a rubber stopper placed in the top, and a styrofoam-looking base that holds the tension. One-half centimeter above the base is an air-inlet tube. The Infiltrometer Fig. 7 is constructed of a polycarbonate tube with a semi-permeable stainless steel sintered disk (4.5cm dia., 3 mm thick).

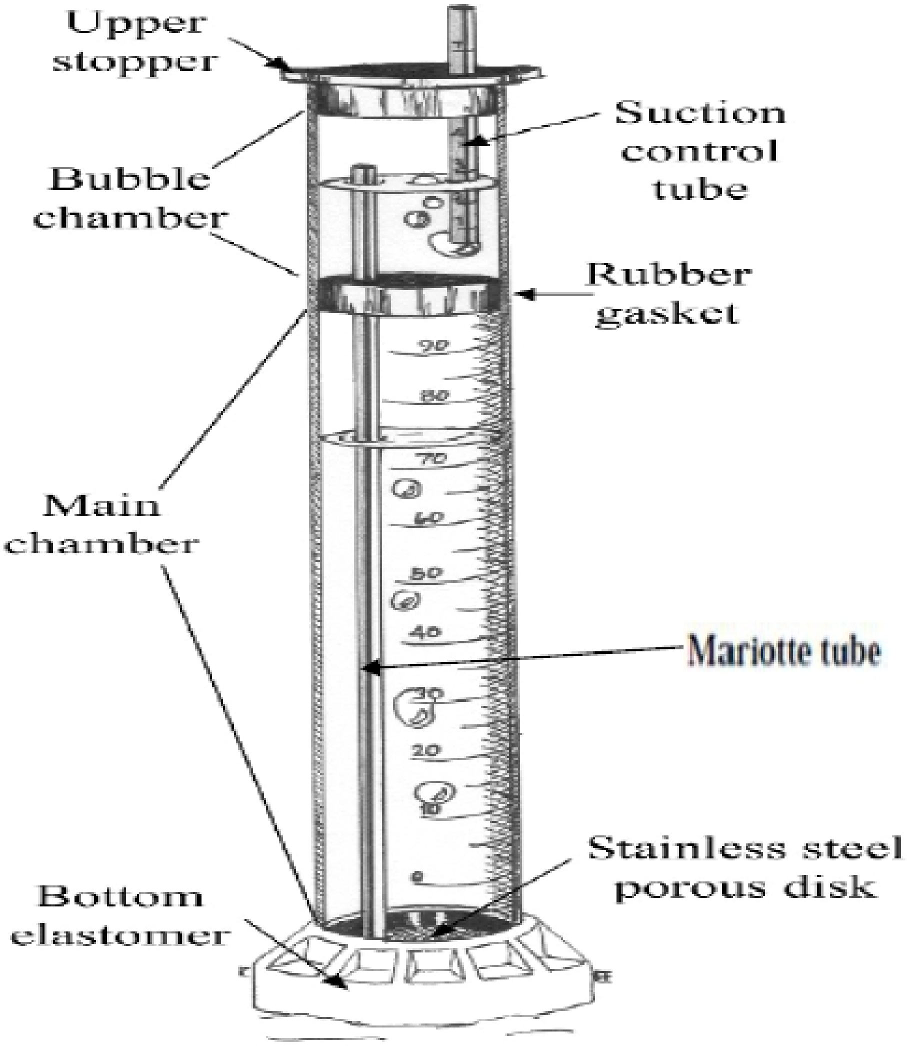

Fig. 7. Schematic of Mini Disk Infiltrometer Diagram
(Adapted from: Decagon Devices User's Manual, Version 9 [100])

The steady state sorptivity of soil is calculated using the method of Zhang [130] by measuring cumulative infiltration vs. time and fitting the results with the infiltration function as shown in equation (6).

$$I = C_1 t + C_2 \sqrt{t} \tag{6}$$

Where C_1 (m s^{-1}) and C_2 (m $s^{-1/2}$) are parameters. C_1 is related to hydraulic conductivity, and C_2 is the soil sorptivity.
The hydraulic conductivity of the soil (k) is computed using the relationship in equation (7):

$$K = \frac{C_1}{A} \tag{7}$$

Where C_1 is the slope of the curve of the cumulative infiltration vs. the square root of time, and A is a value relating the van Genuchten parameters for a given soil type to the suction rate and radius of the Infiltrometer disk.

The sorptivity of ethanol (S_e) which is the slope of the cumulative infiltration vs. square root of time relationship is calculated using equation (8):

$$I = S_e \sqrt{t} \tag{8}$$

Where the sorptivity of ethanol (S_e) is in (cm $s^{-1/2}$).

Likewise, the sorptivity of water (S_w) dealing with water infiltration (not ethanol) is the slope of the cumulative infiltration vs. square root of time relationship as shown in equation (9):

$$I = S_w \sqrt{t} \tag{9}$$

Where the sorptivity of water (S_w) is also given in (cm $s^{-1/2}$) and I is the early cumulative infiltration (cm) and t is time (s) in both cases.

The repellency index R *is* defined by Tillman et al. [93] as the ratio of the soil-ethanol sorptivity (S_e; cm $s^{-1/2}$) to the soil-water sorptivity (S_w; cm $s^{-1/2}$) in equation (10).

$$R = 1.95 \frac{S_e}{S_w} \tag{10}$$

The constant (1.95) accounts for the difference in surface tension and the viscosity of ethanol and water. This method is important in that varying range of scales are available but using standard Infiltrometers may require the transportation of large volumes of liquid to the field [98].

3. CAUSES OF HYDROPHOBICITY

Soil hydrophobicity is caused by organic compounds derived from living or decomposing plants or microorganisms. The compounds causing repellency in soil are polar compounds with hydrophobic (water repellent) and hydrophilic (water attractant) ends. During dehydration the shape of the compound changes, so that the hydrophobic surface is exposed to the air/water in soil pores. This then creates a hydrophobic layer preventing the spread of water over the soil particles [25]. The causes and characteristics of soil water repellency (WR) in general can be classified into five predominat categories: decomposition of organic matter, heating of the soils by wildfires, fungal and microbial activity, growth of particular vegetation species, and soil characteristics [25,131]. In addition, Hunter [98] reported that atmospheric conditions such as air temperature [86,94,132], relative humidity [69,86,133] and water content [70] affect soil water repellency.

3.1 Organic Matter

The leading and most documented contributor to soil hydrophobicity is organic matter Fig. 8 [23,25,63,134,135,136]. Soil organic matter is made up of living plants, animals and micro organisms (roots, fungi, bacteria, macro fauna and micro fauna), plant litter, and all the degraded material from decomposing plant and animal material [137,138]. During the decomposition of organic matter such as humic, fulvic acids and fatty waxes present in the soil as coatings on mineral surfaces or as particles, complex organic acids are produced causing soil hydrophobicity [8]. These complex organic acids are waxlike substances that form a coating over particles of soil. The waxy substances penetrate into the soil as a gas and solidifies after it cools, forming a waxy coating around soil particles. These waxy skins effectively repel the water from the soil and limit water availability to the crop. These hydrophobic substances have no polarity and therefore do not attract water. The waxy substance penetrates into the soil as a gas and solidifies after it cools, forming a waxy coating around soil particles. These waxy skins effectively repel the water from the soil and limit water availability to the crop.

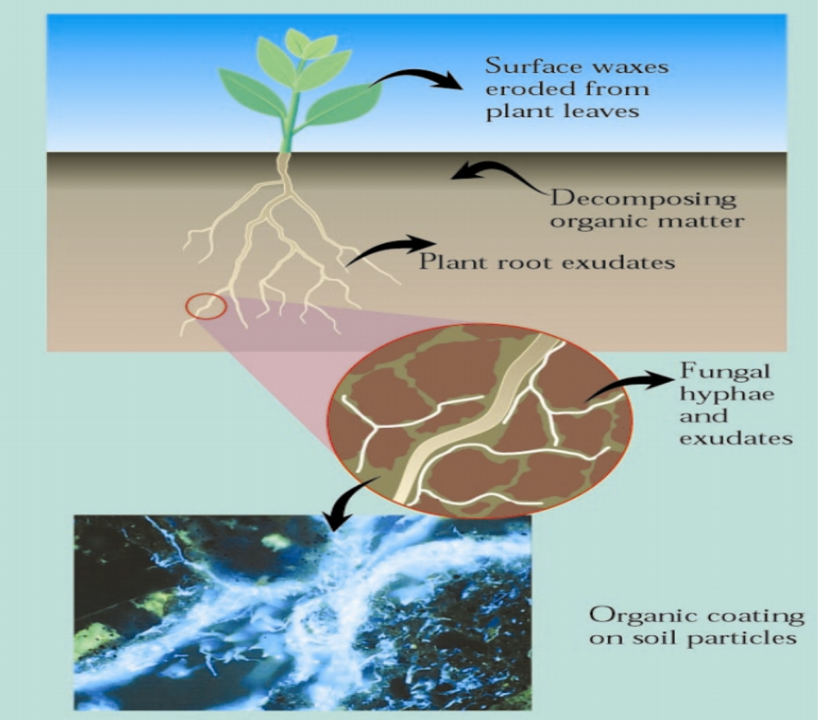

Fig. 8. The origin of hydrophobicity from microbiota and decomposing organic matter in soil (Adapted from Hallet, [2])

3.2 Wildfires

Wildfires and prescribed fires affect the vegetation, soils, wildlife, and water resources of watersheds. Changes in soils after fires produce varying responses in the water, floral, and faunal components of ecosystems because of their complex interdependencies. The effects of fire on soils are a function of the amount of heat released from combusting biomass, the fire intensity and the duration of combustion [139]. Water repellency produced by low-to-moderate severity fires is usually of shorter duration than that produced by high severity fires [7]. When fire consumes vegetation and underlying litter layers, hydrophobic or water-repellant soil conditions can form. During combustion hydrophobic organic compounds in litter and topsoil are volatized [140] and released upwards to the atmosphere and downwards into the soil profile along a temperature gradient Fig. 9. These molecules penetrate into the cool underlying soil layers where they condense around soil particles and either render them hydrophobic or further decrease their affinity for water [25, 141]. The hydrophobic zone appears as a discreet layer in the soil, at or parallel to the surface, where hydrophobic organic compounds coat soil aggregates or minerals. This phenomenon occurs at soil temperatures of 176 to 288 degrees Celsius [5].

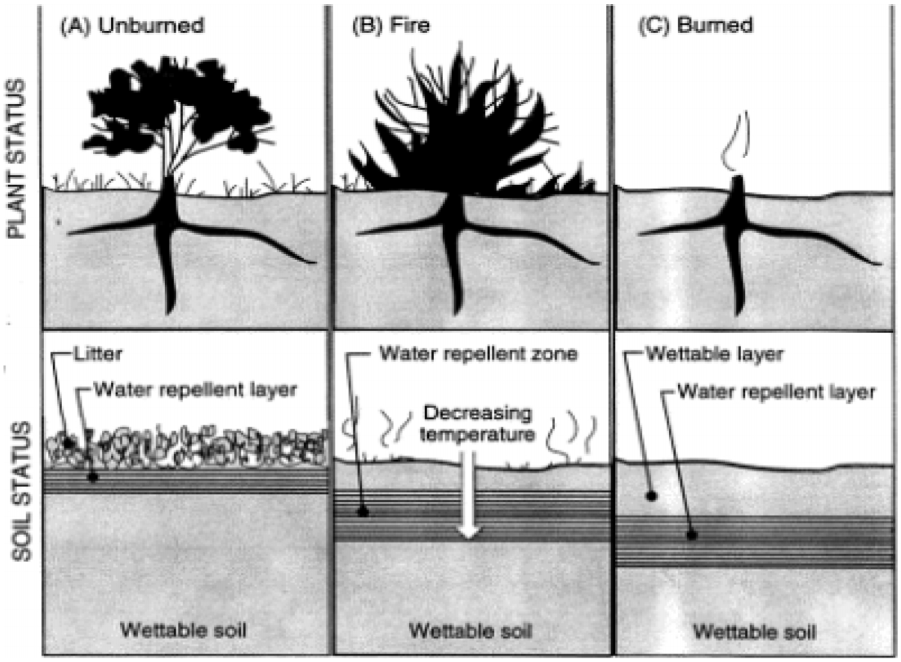

Fig. 9. Fire-induced formation of a hydrophobic soil layer (adapted from DeBano [7])

3.3 Fungal and Microbial Activities

Fungi are generally thought to be the prime cause of hydrophobicity (water repellency) in soil although with mixed evidence [2]. Hallett et al. [142] reported that the first scientific study showing the link between hydrophobicity and fungi was over 40 years ago [143] and that more recent work has identified the role of individual fungal species. The occurrence of natural hydrophobic soil conditions in unburned plant communities is due to coating of soil particles with hydrophobic compounds leached from organic matter accumulations, by-products of microbial activity, and or fungal growth under thick layers of litter and duff material [7,25,144]. Soil fungi and microorganism that have been associated with soil hydrophobicity are *Penicillium nigrican* and *Aspergillus sydowi* [144] and *Actinomycetes* [145]. The basic cause of a hydrophobic soil problem involves soil basidiomycetes fungi which during the process of mycelial decomposition result in their residues forming organic coatings around the sand particles. These basidiomycetes associated with hydrophobic soil conditions tend to be more active on sand root zones that are deficient in a balanced population of soil biological organisms [146].

3.4 Vegetation Species

The formation and strength of a hydrophobic layer is also affected by the type of vegetation and land use type [5,9,73,147]. Water repellent soils have been associated with a wide range of plant species, including trees, shrubs, crops and grasses [85]. For instance, the presence of tall fescue, zoysia grass, Bermuda grass and creeping bent grass has shown the development of water-repellent soils [85]. Soil hydrophobicity has been found under shrubs [27,148] and grassland [149].

Water repellency was also reported in wildland soils (i.e. uncultivated soils supporting natural stands of trees, shrubs, and grass), both in fire and non-fire environments. Several wildland environments, including: dry sclerophyll eucalyptus in Australia [149], eucalyptus and pine forests in Portugal [150], eucalyptus forests in South Africa [151], and under windbreaks in Taiwan [152] were reported to be hydrophobic [7]. Van't Woudt 43] and Adams et al. [153] both reported an apparent relationship between vegetative type and hydrophobicity in underlying soils. Different plant species also give rise to varying hydrophobicity in soils [143]. The importance of vegetative type and microbial products in causing hydrophobicity has also been reported by Bornemisza [154]. However Savage et al. [155] while carrying out further studies, with microbial polysaccharide and several humic acids – like, did not find their influence to contribute much to hydrophobicity in soils. A comprehensive summary of studies showing the relationship between vegetation types and soil hydrophobicity can be seen in Wallis and Horne [13].

3.5 Soil Charateristics and Atmospheric Conditions

Soil texture has been found to affect the strength of hydrophobicity [84]. It is important to note that the occurrence of soil water repellency or hydrophobicity is not limited to any particular soil type as it has been found in many soils around the world in all textures [22,26, 156]. Lewis et al. [157] and Huffman et al. [158] reported that soil texture is one of the determinants of hydrophobicity in Colorado soils. Though coarse - textured, sandy soils are most likely to become hydrophobic because of their relatively small surface area per unit of volume [85], it has also been found and documented in loamy, peaty clay and clayey peat soils [62,159,160], as well as in heavy clay soils with grass cover [161]. Soil with higher percentages of sand result in the formation of a stronger hydrophobic layer, this is because one volume of sand has lower surface area than one volume of clay so it would take more hydrophobic compounds to coat the clay particles than it would to coat the sand particles. The result is that soils with sand show greater effects of hydrophobicity than those with finer particles [84]. Also during combustion, soils that have large pores, such as sandy soils, are also more susceptible to the formation of hydrophobic layers because they transmit heat more readily than heavy textured soils, such as clay. The coarse textured soils also have larger pores that allow deeper penetration of the gas [162] which condense on cooler soil particles at or below the soil surface forming water repellent/hydrophobic conditions [51].

Hydrophobicity is also affected by atmospheric conditions such as air temperature [87,94,132] and relative humidity [69,89,133]. The relative humidity influences the rate of evapotranspiration which in turn affect the soil moisture content [163]. The soil moisture is an important component that can prevent or lead to the formation of a hydrophobic layer. According to Benavides-Solorio and MacDonald [82], an inverse relationship exists between hydrophobicity and soil moisture content. A transition zone or a critical soil moisture zone, defined by two water content thresholds; a critical water content below which every sample is repellent and a second one above which every sample is wettable was established by Dekker and Ritsema [70]. When soil moisture is above this critical value (which varies for every soil), the water repellency effect is temporarily eliminated but when it falls below this critical value, the soil returns to a hydrophobic condition [85]. This critical moisture point varies among soils and is largely influenced by soil texture but it is unclear what governs it [85]. Soil water repellency generally increases during dry weather, while it is reduced or completely eliminated after prolonged and/or heavy precipitation [25]. Maintaining high soil moisture levels through frequent irrigation is an effective method to prevent soil water repellency [56].

4. IMPACTS AND EFFECTS OF HYDROPHOBICITY

In most parts of the world, soil hydrophobicity has been detected, but its tendency to develop is high especially in humid regions where there are high rates of organic matter accumulation [164]. Several researchers have reported numerous effects (mild and severe) of soil hydrophobicity ranging from: Carbon sequestration, preferential flow paths, localized dry spots (LDS), seedling emergence and plant survival, water infiltration, Runoff, Erosion, aggregate stability, flow instability, drainage and leaching of soil nutrients, deep percolation-poor irrigation efficiency and crop performance, uneven distribution of applied chemicals and Pore water distribution uniformity. Some of them are discussed below:

4.1 Carbon Sequestration/ Plant productivity

Soil Carbon (C) sequestration can be defined as the net removal of CO_2 from the atmosphere by plants' photosynthetic action into stable, long-lived pools of C by incorporating it into soil organic matter [165,166]. This means that Soils can act as net sources or net sinks of the atmospheric carbon dioxide. The aim is to improve soil quality by storing C that will also lead to enhanced air quality, water quality and increased productivity as well as to help mitigate the greenhouse effect and global warming [167,168]. However, soil hydrophobicity could change soil's ability to sequester carbon. There is an inverse relationship between soil moisture and hydrophobicity as reported by King, [83], Dekker and Ritsema, [54] and Wessolek et al. [169]. Hydrophobicity is usually most severe in dry soils with higher temperature and as soil moisture content increases, it declines [150,170]. Critical moisture content exists below which soils that are wettable become water repellent and vice versa [169]. Hydrophobicity increases with increase in temperature [171]; this is possibly due to changes in the arrangement of organic matter in soil during the drying process, or through waxes from organic matter coating soil particle surfaces [172]. In drought conditions, the storage of carbon in the soil can be affected due the hydrophobic state of the soil. As a matter of fact, drought is a major factor controlling soil respiration/carbon mineralization (release of CO_2 from the soil surface) [173,174]. Other factors include quality of SOM, temperature, moisture, and aeration. Also, drought, a physiological stress, tends to reduce microbial diversity, favoring those microbes best adapted to coping with the stress [175]. In addition, soil drying limits microbial activity [176]. In general, lower levels of soil moisture associated with water repellent soils suggest microbial activity will be reduced because of the soil moisture deficit and rates of carbon released from decomposition of soil organic matter will fall [172]. The amount of organic matter within the soil is related to the degree at which the soil exhibits hydrophobic behavior (water repellency) [13].

On the other hand, when the soil moisture content is low, the amount of water available to plants will definitely be reduced as the water table will be low, this will slow down the plant growth rate and and CO_2 draw down from the atmosphere, thereby reducing their productivity. In addition, increase in soil hydrophobicity leads to changes in the soil water flow which could encourage more drought tolerant species to grow. These types of plants generally contain more oils and waxes, and together with a shift towards a more drought-tolerant fungal soil community (from one dominated by microbes), could further increases repellency. On the long run, reduced plant productivity that affects soil's potential to act as a carbon sink can outweigh the shorter term benefits of reduced microbial activity that enhance carbon sequestration [172].

4.2 Localized Dry Spots (LDS)

localized dry spots (LDS) are term used to describe the occurrence of irregular patches of drought - stressed turfgrass [177,178]. Localized dry spots is an area of turfgrass and soil that resist water as applied normally and can be the results of many factors such as heavy thatch, physical soil limitations (such as soil compaction, variability and restriction to rooting and water penetration) or fungal organisms activity in the soil, but one of the main causes of LDS is the presence of hydrophobic or water repellent soil [179,180]. When hydrophobicity affects certain soils, it causes the soils to retard or prevent rain or irrigation water from infiltrating into the soil. This inability of the soil to absorb or infiltrate water occurs on due to the partial or complete coating of the surface of the soil particles by an organic material. The source of this coating is the natural decomposition of soil organic matter [178] where the sand becomes coated with hydrophobic molecules. Localized dry spots is at first noticed as a small 2 to 4 inch diameter patches of dead or dying turfgrass after which it continues to enlarge in a circular pattern Fig. 10 [181]. Initially, at the onset of localized dry spots, the turf (bluish colour) wilts. It later degenerates to circular or irregular shaped patterns of brownish to tan - coloured turf which if left unattended to can lead to death of the turfgrass Fig. 10 [182]. Soil beneath these spots is commonly found to be highly hydrophobic (water repellent) to a depth of 1 to 2 inches. As a result of this hydrophobic state of the soil, water will not infiltrate or be absorbed into soil but will runoff the turf leaving the underlying soil dry and powdery [182].

4.3 Water Infiltration/Runoff/ Erosion/Seedling Emergence and Plant Survival and Growth

Normally, dry soil usually absorbs moisture due to the strong interaction between soil particles and water (Adhesive Forces). This type of soil is referred to as being hydrophilic or non – repellent. On the other hand, certain soils do not permit moisture infiltration into the soil due to weak/non interaction between the soils' particles and water; these are called hydrophobic or water repellent soils [3,183]. Hydrophobicity in soils are caused by polar compounds with hydrophobic (water repellent) and hydrophilic (water attractant) ends [184].

As the soil temperature increases, dehydration (drying process) occurs during which the arrangement of organic matter in the soil changes (i.e shape of the polar compound changes), so that the hydrophobic surface is exposed to the air/water in soil pores. This then creates a hydrophobic layer preventing the spread of water over the soil particles [172,183]. This hydrophobic/water repellent layer which developed on the surface of the soil retards or prevents infiltration of rain or irrigation water and thereby promote overland flow/surface runoff [25,82] and increase the risk of water erosion on sloping site [80] and bare soil [25,147,185,186,187,188,189]. Also as soil water is not renewed reduced infiltration will hinder plant growth [190]. Furthermore, Madsen et al. [191] reported that hydrophobicity/water repellency reduced seedling emergence and seedling survival by decreasing soil moisture availability.

Fig. 10. A Turfgrass showing symptoms of Localized Dry Spot (LDS) infection (Adapted from Vincelli and Eshenaur, [181])

4.4 Preferential Flow Paths/ Flow Instability/ Groundwater Contamination

Soil hydrophobicity is a surface phenomenon being found within the upper part of the soil profile [192]. When soil particle surfaces become hydrophobic (non-polar), adhesion is reduced because there is no attraction between water molecules and the non-polar surface. This can reduce soil infiltration capacity, cause rainwater or irrigation water to run off the soil surface and eventually find alternative places or means of infiltrating the soil. Several researchers have reported irregular wetting patterns and significant variability in soil water content in hydrophobic field soils [143,193,194,195,196,197,198]. These non-polar surfaces as a result of soil hydrophobicity can cause instability at the wetting front and promote uneven hydration patterns such as preferential flow of water [170,199,200,201] as infiltration of water into the soil will be non – uniform Fig. 11. Preferential flow refers to the uneven and often rapid movement of water and solutes through porous media, typically soil. Preferential flow leads to bypassing of large parts of the soil matrix [202] and therefore to a much faster displacement of chemical substances towards the groundwater i.e. this by – passing flow can accelerate the transport of chemicals thereby increasing the amount of harmful substances moving into the groundwater [187,201,202,203,204]. This can result in poor distribution of water, fertilizer, pesticides, and also cause a reduction of nutrients and water available for plant growth [205,206].

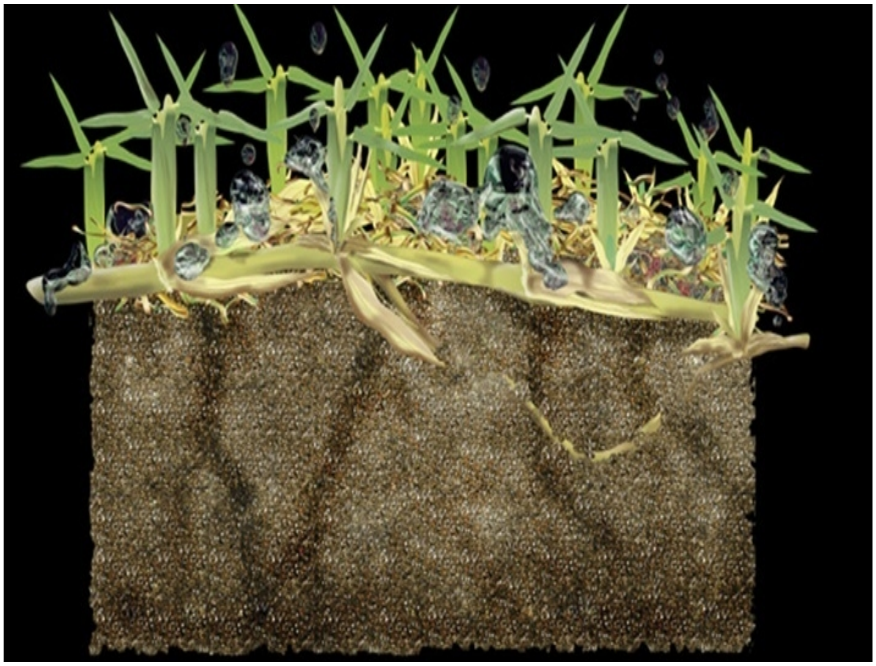

Fig. 11. Cross section of soil profile showing poor infiltration, poor penetration and a non-uniform wetting front – resulting in preferential flow of water (Adapted from Wellhead Numerator Technology Inc [207])

4.5 Soil Aggregate Stability/ Water Harvesting

Although soil hydrophobicity has negative effects on soil hydrological components**,** a small degree of it plays major role in soil structure and soil aggregates stabilization respectively [208,209]. Studies by Ae et al. [210], Bartolli et al. [211], Haynes and Swift [212] and Haynes [213] have attributed increased aggregate stability obtained from organic matter to hydrophobic properties and stronger intermolecular associations of organic matter. The organic matter plays an essential role in aggregation by stimulating microorganisms and acting as a primary binding agent itself [9]. Soil hydrophobicity increases the stability of aggregates, thereby maintaining soil structure [3]. It also seals the soil surface with hydrophobic materials allowing water to be harvested [5].

5. TREATMENT AND AMELIORATION OF HYDROPHOBICITY

Different techniques have been developed to treat and reduce the effects of soil hydrophobicity (water repellency). Knowledge of causal agents that cause hydrophobicity in soils is required for the amelioration or treatment of soil hydrophobicity [214].

Ameliorating soil hydrophobicity includes mulch retention and watering practices. Retention of mulch reduces evaporation of the soil moisture content by up to 50% and assists with retaining moisture [215] while prolonged watering (slow and deep watering) of the soil weakens hydrophobicity by re arranging the soil organic matter so that the hydrophilic surface is re-exposed to the air/water in soil pores [25]. Soil tillage/cultivation is also a physical solution as it may cause the abrasion of hydrophobic soil particles thereby removing hydrophobic coatings from soil surfaces [216]. Adding clay to cover the hydrophobic layers (Masking) increases the specific surface area of the soil, lowers susceptibility to water repellence and improve water infiltration slowly [80,183]. The masking process also acts as an adsorption sites by reducing surface water contamination by [217]. Several researchers [62,218,219,220] have all reported the effectiveness of clay in ameliorating and removing soil hydrophobicity. However study conducted by Ward and Oades [221] showed that unless clay mixed hydrophobic soil is *exposed* to a wetting and drying cycle clay addition to hydrophobic soil is not effective.

Soil hydrophobicity can be reduced by boosting the effectiveness of wax degrading bacteria through the application of lime [222,223]. Roper [223] revealed a ten-fold increase in the number of wax-degrading bacteria in south Western Australia after an application of lime. Lime can improve water infiltration into soils, by providing additional fine material, enhancing mineralization of organic matter and dssolution of hydrophobic organic compounds and corresponding surface area effect [80,183]. On the other hand earlier field trials have shown it is relatively ineffective, especially when compared with clay amendment [220,224]. Also the bacteria being released by the lime need a moist environment to be effective.

Wetting agents are the most effective method for reducing or eliminating hydrophobicity (water repellency) in soils [177,225,226]. They are surfactants/soil wetters used to improve water infiltration on hydrophobic soils [227]. Generally all soil wetting agents can be organized into three primary groups of surfactant chemistry: Anionic Surfactants, Nonionic Surfactants, and block polymer Nonionic Surfactants. The Nonionic surfactants are the most widely used type of surfactant chemistry in agricultural production. The application of Surfactants can be in liquid form [56] or in granular form [228]. When soil particles surface become hydrophobic, adhesion is reduced and surface tension is increased making it difficult for water to infiltrate into the soil. The application of a wetting agent breaks down the surface tension resulting in enhanced penetration, increased water infiltration and the uniform flow of water into and through the soil profile Fig. 12 [229]. When the surfactants are applied to the soil profile, they overcome hydrophobicity by adding molecules to water that have both a polar, hydrophilic (water attracting) end and a non-polar, hydrophobic (water repellent) end; the hydrophobic non-polar end of the surfactants attaches to the hydrophobic coatings on the soil particle. This serves as an attachment site for water molecules allowing the soil to hydrate [35]. Although wetting agents are effective in improving water infiltration and retention, they are expensive, provide only temporary control of soil hydrophobicity [13] and may they may also increase the amount of evaporation from bare soil [2]. However, direct evidence of less evaporation from hydrophobic soils was provided by Bachmann et al. [230]. Furthermore, Hallet [2] noted that a more hydrophobic layer of soil at the surface could form a capillary barrier that reduces evaporation given that water repellency decreases with depth [21]. McGhie [231] also reported that hydrophobic soil treated with wetting agents remains water wettable after drying because the wetting agents molecules are absorbed by the soil particles.

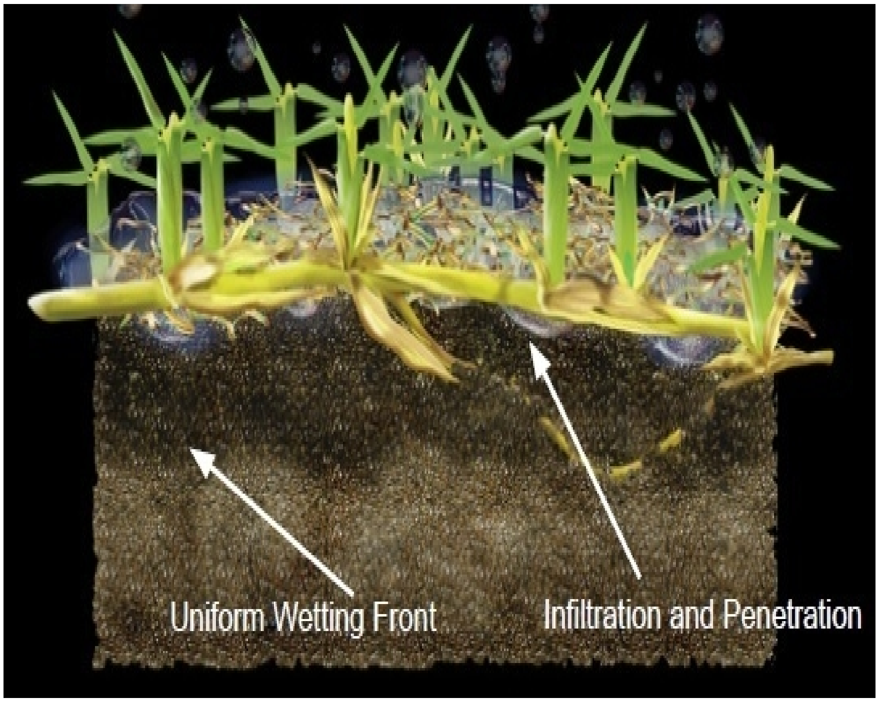

Fig. 12. Demonstration of uniform wetting front after treatment with wetting agent/ surfactant (adapted from wellhead numerator technology inc. [207])

6. CONCLUSION

Hydrophobicity is one of the most important physical properties of soils found all over the world, and it may have significant effects on the eco-hydrological processes of land ecosystems. Some of these effects (mild and severe) of soil hydrophobicity ranges from Carbon sequestration, preferential flow paths, localized dry spots (LDS), seedling emergence and plant survival, water infiltration, Runoff, Erosion, aggregate stability, flow instability, drainage and leaching of soil nutrients, deep percolation-poor irrigation efficiency and crop performance, uneven distribution of applied chemicals and Pore water distribution uniformity. Soil hydrophobicity can be measured both in field and by laboratory experiments. The field technique is known to be generally more reliable than laboratory techniques as recent studies have shown that drying samples by air and oven are not indicative of field conditions. Numerous techniques have been developed to measure and classify hydrophobicity of soil some of which are the water drop penetration time (WDPT) test, which; the molarity of ethanol droplet (MED) test (also known as the ‘Percentage Ethanol’ or ‘Critical Surface Tension’ test) which is an extension of the WDPT test and uses different concentrations of ethanol to alter the surface tension of the liquid; direct measurement of contact angle by the capillary rise method and determination of the Index of soil water repellency, R, from the sorptivities of 95% ethanol and water using the minidisk infiltrometer. Others include the wihelmy plate method, sessile drop method, Du Noüy ring method and modified capillary rise method. Soil hydrophobicity is caused through the production of complex organic acids during the decomposition of organic matter. The formation and strength of a hydrophobic layer is also affected by Vegetation, Trees with amount of resins, waxes or aromatic oils (eucalyptus and pines) are the major contributor of organic matter (whose decomposition is the major cause of soil hydrophobicity) in soils. Fungi are generally thought to be the prime cause of hydrophobicity. It is important to note that the occurrence of soil water repellency or hydrophobicity is not limited to any particular soil type as it has been found in many soils around the world in all textures. Hydrophobicity is also affected by non biological factors such as air temperature, relative humidity, fire and soil temperature. The soil moisture is also an important component that can prevent or lead to the formation of a hydrophobic layer. Soil hydrophobiicity generally increases during dry weather, while it is reduced or completely eliminated after prolonged and/or heavy precipitation. Maintaining high soil moisture levels through frequent irrigation is an effective method to prevent soil water repellency. Consideration of these numerous factors contributing to soil hydrophobicity will be beneficial towards finding lasting solutions to preventing and ameliorating hydrophobicity of soils.

ACKNOWLEDGEMENTS

The authors acknowledge the works of several researchers that have worked extensively on this subject matter and earlier reviewers as well.

We also want to thank three anonymous reviewers for their comments which helped in greatly improving an earlier version of the manuscript.

We equally salute the editorial team of the Journal of Science Research and Reports (JSRR).

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. DeBano, Leonard F, Letey J, eds. Water-repellent soils. Proceedings of symposium on water repellent soils [may 6-10, 1968, Riverside, Calif.], Univ. Calif., Riverside, Calif; 1969.
2. Hallet PD, An introduction to soil water repellency. Proceedings of the 8th International Symposium on Adjuvants for Agrochemicals, International Society for Agrochemical Adjuvants (ISAA), Columbus, Ohio, USA, ISBN 978-0-473-12388-8; 2007.
3. Brandt GH. Water movement in hydrophobic soils. In proceedings of symposium on water repellent soils (May 6-10, 1968, riverside, calif.), Univ Calif, Riverside, Calif. 1969;91-115.
4. Schreiner O, Shorey EC. Chemical nature of soil organic matter. USDA Bureau of Soils Bulletin. 1910;74:2–48.
5. De Bano LF. Water repellent soils: a state of the art. Pacific Southwest Forest and Range Experiment Station, California; 1981.
6. Doerr SH, Woods SW, Martin DA, Casimiro M. Natural background soil water repellency in conifer forests of the north-western USA: Its prediction and relationship to wildlife occurrence. Journal of hydrology. 2009;371(1-4):12-21.
7. DeBano LF. Water repellency in soils: a historical overview. Journal of Hydrology. 2000;231(232):4–32.

8. Franco CMM, Michelsen PP, Oades JM. Amelioration of water repellency: application of slowrelease fertilisers to stimulate microbial breakdown of waxes. Journal of Hydrology. 2000;231:342–351.
9. Scott DF. Soil wettability in forested catchments in South Africa; as measured by different methods and as affected by vegetation cover and soil characteristics. Journal of Hydrology. 2000;231–232:87–104.
10. Jaramillo DF, Dekker LW, Ritsema CJ, Hendrickx JMH. Occurrence of soil water repellency in arid and humid climates. Journal of Hydrology. 2000;231(232):105–111.
11. Doerr S, Ferreira JDA, Walsh RPD, Shakesby RA, Leighton-Boyce G, Coelho COA. Soil water repellency as a potential parameter in rainfall-runoff modelling: experimental evidence at point to catchment scales from Portugal. Hydrol Processes (in Press); 2003.
12. Dekker LW, Ritsema CJ, Wendroth O, Jarvis N, Oostindie K, Pohl W, Larsson M, Gaudet JP. Moisture distributions and wetting rates of soils at experimental fields in the Netherlands, France, Sweden and Germany. J Hydrol. 1999;215:4-22.
13. Wallis MG, Home DJ. Soil water repellency. In: advances in soil sciences. Edited by B.A. Stewart. Springer-Verlag, New York. 1992;96-1:42.
14. Olorunfemi IE, Fasinmirin JT. Hydraulic conductivity and infiltration of soils of tropical rainforest climate of Nigeria. Proceedings of the Environmental Management Conference (EMC), Federal University of Agriculture, Abeokuta, Nigeria. 2011;(1):397–413.
15. Gupta RK, Rudra RP, Dickinson WT, Elrick DE. Modelling spatial patterns of three infiltration parameter. Can Agric Eng. 1994;36:9–13.
16. Russo D, Bresler E. Soil hydraulic properties as stochastic processes: I: An analysis of field spatial variability. Soil Sci Soc Am J. 1981;45:682–687.
17. Gajem YM, Warrick AW, Myers DE, Spatial dependence of physical properties of a typic torriflorent soil. Soil Sci Soc Am J. 1981;45:709–715.
18. Jury WA. Spatial variability of soil physical parameters in solute migration: a critical literature review. EPRI EA-4228, Research Project 2485-6, Riverside, CA; 1985.
19. Saddiq MH, Wierenga PJ, Hendrickx MH, Hussain MY. Spatial variability of soil water tension in an irrigated soil. Soil Sci. 1985;140:126–132.
20. Mohanty BP, Ankeny MD, Horton R, Kanwar RS. Spatial variability of hydraulic conductivity measured by disc. Water Resource Res. 1994;30:2489–2498.
21. Woche SK, Goebel MO, Kirkham MB, Horton R, Van Der Ploeg RR, Bachmann J. Contact angle of soils as affected by depth, texture and land management. Eur J Soil Sci. 2005;56:239–251.
22. Lellamanei, Karube DALJ, Yoshida A. Clay effects on the contact angle and water droplet penetration time of model soils. Soil Sci Plant Nutr. 2010;56:371-375.
23. Karunarathna AK, Moldrup P, Kawamoto K, De Jonge LW, Komatsu T. Two-region model of soil water repellency as a function of matric potential and water content. Vadose Zone J. 2010;9:719-713.
24. Blackwell P. Improving sustainable production from water repellent sands. J Agric Western Austr. 1993;34:160- 167.
25. Doerr SH, Shakesby RS, Walsh RPD. Soil water repellency: its characteristics, causes and hydro-geomorphological consequences. Earth Science Reviews. 2000;51:33–65.
26. Dekker LW, Oostindie K, Ritsema CJ. Exponential increase of publications related to soil water repellency. Aust J Soil Res. 2005;43:403-441.
27. Doerr SH, Shakesby RA, Dekker LW, Ritsema CJ. Occurrence, prediction and hydrological effects of water repellency amongst major soil and land-use types in a humid temperate climate. European Journal of Soil Science. 2006;57:741–754.

28. Ritsema CJ, Dekker LW. Water repellency and its role in forming preferred flow paths in soils. Austr J Soil Res. 1996;34:475-487.
29. Malkinson Dan Wittenberg Lea. Post fire induced soil water repellency—modeling short and long-term processes. Geomorphology. 2011;125:186–192.
30. Hillel D. Introduction to soil physics. Academic Press, Inc. San Dieoga, California; 1982.
31. Mallants D, Jacques D, Vanclooster M, Diels J, Feyen J. A stochastic approach to simulate water flow in a macroporous soil. Geoderma. 1996;70:299-324.
32. Hardie Marcus A, Cotching William E, Doyle Richard B, Lisson Shaun, Influence of climate, water content and leaching on seasonal variations in potential water repellence. HYDROLOGICAL PROCESSES. Hydrol Process. 2012;26:2041–2048.
33. Blackwell PS. Management of water repellency in Australia and risks associated with preferential flow, pesticide concentration and leaching. J Hydrol. 2000;384–395.
34. Ritsema CJ, Dekker LW. Preferential flow in water repellent sandy soils: principles and modeling implications. Journal of Hydrology. 2000;231–232:308–319.
35. Mobbs T. Effects of four soil surfactants on five soil-water properties in agricultural sand and silt loam soils. Thesis submitted in partial fulfillment of the requirements for the degree of master of science in biological and agricultural engineering. Washington State University; 2010.
36. Bayliss JS. Observations on *Marasmius oreades* and *Clitocybe gigantea* as parasitic fungi causing fairy rings. Journal of Economic Biology. 1911;6:111–132.
37. Albert R, Kohn M. Investigations into the resistance of sandy soils to wetting. Proceedings of the International Society of Soil Science. 1926;2:139–145.
38. Kenyon SA. The ironclad or artificial catchment. Journal Department Agriculture of Victoria. 1929;27:86–91.
39. Jamison VC. Resistance of wetting in the surface of sandy soils under citrus trees in central Florida and its effect upon penetration and the efficiency of irrigation. Soil Science Society of America Proceedings. 1947;11:103–109.
40. Robinson DO, Page JB. Soil aggregate stability. Soil Science Society of America Proceedings. 1950;15:25–29.
41. Hedrick RM, Mowry DT. Effect of synthetic polyelectrolytes on aggregation, aeration, and water relationships of soil. Soil Science. 1952;73:427–441.
42. Domingo WR. Some notes on irreversibly dried difficulty wettable soils. Landbouwkund Tijdschr. 1950;62:252–260.
43. Van't Woudt BD. Particle coatings affect the wettability of soils. Journal of Geophysical Research. 1959;64:263–267.
44. Letey J, Pelishek RE, Osborn J. Wetting agents can increase water infiltration or retard it, depending on soil conditions and water contact angle. California Agriculture. 1961;15(10):8– 9.
45. Watson CL, McNeal BL, Letey J. The effect of surfactants on the hydraulic conductivity of salt-affected soils. Soil Science. 1969;108:58–63.
46. Letey J, Welch N, Pelishek RE, Osborn J. Effect of wetting agents on irrigation of water repellent soils. California Agriculture. 1962;16(12):12–13.
47. Osborn JF, Letey J, Valoras N. Surfactant longevity and wetting characteristics. California Agriculture. 1969;23(3):6–8.
48. Osborn JF, Pelishek RE, Krammes JS, Letey J. Wetting agents can reduce soil erosion. Crops and Soils. 1964;19(9):23–24.
49. Morgan WC, Letey J, Richards SJ, Valoras N. Using physical soil amendments, irrigation, and wetting agents in turfgrass management. California Agriculture. 1967;21(1):8–11.

50. Savage SM. Mechanism of fire-induced water repellency in soil. Soil Science Society of America Proceedings. 1974;38:652–657.
51. DeBano LF, Savage SM, Hamilton DA. The transfer of heat and hydrophobic substances during burning. Soil Science Society of America Journal. 1976;40:779–782.
52. Megahan WF, Molitor DC. Erosional effects of wildfire and logging in Idaho. In: Watershed Management Symposium. American Society of Civil Engineers, Irrigation and Drainage Division, Logan, UT. 1975;11–13:423–444.
53. Nulsen RA. Changes in soil properties. In "Reintegrating fragmented landscapes - towards sustainable production and nature conservation." (Hobbs RJ, Saunders DA, eds.). Springer Verlag, New York. 1993;107-145.
54. Dekker LW, Ritsema CJ. Preferential Flow Path in a water repellent clay soil with grass cover. Water Resour Res. 1996;32(5):1239-1249.
55. Wallis MG, Horne DJ, McAuliffe KW. A survey of dry patch and its management in New Zealand golf greens. 2. Soil core results and irrigation interaction. New Zealand Turf Management Journal. 1989;3(4):15–17.
56. Cisar JL, Williams KE, Vivas HE, Haydu JJ. The occurrence and alleviation by surfactants of soil-water repellency on m-based turf grass systems. J Hydrol. 2000;23(1)232:352-358
57. Chakrabarti DC. Investigation on erodibility and water stable aggregates of certain soils of eastern Nepal. Indian Society of Soil Science Journal. 1971;19:441–446.
58. Bishay BG, Bakhati HK. Water repellency of soils under citrus trees in Egypt and means of improvement. Agricultural Resource Review (Cairo). 1976;54:63–74.
59. Rietveld J. Soil non-wettability and its relevance as a contributing factor to surface runoff on sandy soils in Mali. An ingenieurs research. Landbouw Hogeschool, Wageningen. 1978;179.
60. Reeder CJ, Jurgensen MF. Fire-induced water repellency in forest soils of upper Michigan. Canadian Journal of Forest Research. 1979;9:363–373.
61. Roberts FJ, Carbon BA. Water repellence in sandy soils of southwestern Australia: I. Some studies related to field occurrence. Field Station Record Division Plant Industry CSIRO (Australia). 1971;10:13–20.
62. McGhie DA, Posner AM. Water repellence of a heavy textured Western Australian surface soil. Australian Journal of Soil Research. 1980;18:309–323.
63. Ma'shum M, Tate ME, Jones GP, Oades JM. Extraction and characterization of water-repellent materials from Australian soils. Journal of Soil Science. 1988;39:99–110.
64. Shiels G. Dry patch—a new problem on Britain's fine turf, Turf Management. 1982;18–19.
65. Nakaya N. Water repellency in soils. Japanese Agricultural Research Quarterly. 1982;16(1):24–28.
66. Prusinkiewicz A, Kosakowski A. The wettability of soil organic matter as theforming factor of the water properties of forest soils. Roczniki Gleboznawcze T. XXXVII, NR 1, S. Warszawa. 1986;3-23.
67. Barrette G, Slaymaker 0. Indentification, characterization and hydroiogical implications of water repellency in mountain soils. Southern British Columbia, Catena. 1989;161477-489.
68. Roy JL, McGill WB, Rawluk MD. Petrolam residue as water-repellent substances in weathered non-wettable oil-contaminated soils. Can J Soil Sci. 1999;79:367-380.
69. Bisdom EBA, Dekker LW, Schoute JFT, Water repellency of sieve fractions from sandy soils and relationship with organic material and soil structure. Geoderma. 1993;56:105–118.

70. Dekker LW, Ritsema CJ. How water moves in a water repellent sandy soil. I. Potential and actual water repellency. Water Resour Res. 1994;30:2507–2517.
71. Giovannini G, Lucchesi S. Effect of fire on hydrophobic and cementing substances of soil aggregates. Soil Sci. 1983;136:231-236.
72. Giovannini G, Luchesi S, Cervelli S. Water substances and aggregate stability in hydrophobic soils. Soil Science. 1983;135:110–113.
73. Doerr SH, Shakesby RA, Walsh RPD. Spatial variability of soil hydrophobicity in fire-prone eucalyptus and pine forests, Portugal. Soil Sci. 1998;163:313–324.
74. Leighton-Boyce G, Doerr S, Shakesby RA. Quantifying the impact of soil water repellency on overland flow generation and erosion: a new approach using rainfall simulation and wetting agent on in situ soil. Hydrological Processes. 2007;21(17):2337-2345.
75. Wallis MG, Horne DJ, McAuliffe KW. A survey of dry patch and its management in New Zealand golf greens. 2. Soil core results and irrigation interaction. New Zealand Turf Management Journal. 1989;3(4):15–17.
76. Onweremadu E U. Hydrophobicity of Soils formed over different lithologies. Malaysian Journal of Soil Science. 2008;12:19–30. ISSN: 1394–7900.
77. Moral Garcia FJ, Dekker LW, Oostindie K, Ritsema CJ. Soil water repellency in the Natural Park of Donana, Southern Spain. In: Ritsema CJ, Dekker LW, (Eds.), soil water repellency-occurrence, consequences and amelioration. Elsevier, Amsterdam. 2003;121-127.
78. Scott DF, Soil wettability in forested catchments in South Africa; as measured by different methods and as affected by vegetation cover and soil characteristics. Journal of Hydrology. 2000;231–232:87–104.
79. Buczko U, Bens O. Assessing soil hydrophobicity and its arability through the soil profile using two different methods. Soil Sci Soc Am J. 2006;70:718-727.
80. Moore Geoff, Blackwell Paul. Chapter 3: Physical factors affecting water infiltration and redistribution. In: Moore G, (Ed.) soil guide - a handbook for understanding and managing agricultural soils. Department of Agriculture, Western Australia; 2004.
81. Regalado CM, Ritter A. Geostatistical tools for characterizing the spatial variability of soil water repellency parameters in a laurel forested watershed. Soil Sci Soc Am J. 2006;70:1071-1081.
82. Benavides-Solorio JD, MacDonald LH. Post-fire runoff and erosion from simulated rainfall on small plots, Colorado Front Range. Hydrological Processes. 2001;15(15):2931-2952.
83. King PM. 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. 1981;19:275-285.
84. Albright Meredith. Post-wildfire erosion: soil hydrophobicity in colorado soils. GEOG 5401 – fall 2007 – University of Colorado, Boulder; 2007.
85. Karnok K, Tucker K. Water-repellent soils, Part 2: More questions and answers? Golf Course Management; 2002.
86. Dekker LW, Doerr SH, Oostindie K, Ziogas AK, Ritsema CJ. Water repellency and critical soil water content in a dune sand. Soil Sci Soc Am J. 2001;65:1667-1674.
87. Doerr SH, Thomas AD. The role of soil moisture in controlling water repellency: new evidence from forest soils in Portugal. J Hydrol. 2000;231–232:134–147.
88. Hurrab J, Schaumann GE. Properties of soil organic matter and aqueous extracts of actually water repellent and wettable soil samples. Geoderma. 2006;132:222–239.
89. Hallin Ingrid, Bryant Rob, Doerr Stefan, Douglas Peter. The effect of heterogeneity on the measurement of soil water repellency. BSSS postgraduate conference. Swansea University, Prifysgol Abertawe; 2011.

90. Clothier BE, Vogeler I, Magesan GN. The breakdown of water repellency and solute transport through a hydrophobic soil. Journal of Hydrology. 2000;231-232:255-264.
91. Hoffman AS. Lectures on contact angles. Presentation; 2005.
92. Surface Electro Optics (SEO). What is Contact Angle? Contact Angle Catalog. 946, kosekdong, Suwon City, Kyunggido, Korea. 2011;441–813. Available: www.s-eo.com
93. Tillman RW, Scotter DR, Wallis MG, Clothier BE. Water-repellency and its measurement by using intrinsic sorptivity. Aust J Soil Res. 1989;27:63l7–644.
94. Dekker LW, Ritsema CJ, Oostindie K, Boersma OH. Effect of drying temperature on the severity of soil water repellency. Soil Sci. 1998;163:780-796.
95. Buczko U, Bens O, Fischer H, Hűttl RF. Water repellency in sandy luvisols under different forest transformation stages in northeast Germany. Geoderma. 2002;109:1-18.
96. Newton PCD, Carran RA, Lawrence EJ. Reduced water repellency of a grassland soil under elevated atmospheric CO2. Glob Change Biol. 2003;10:1-4.
97. Dekker LW, Ritsema CJ, Oostindie K, Moore D. Methods for determining soil water repellency of field-moist samples. Water Resour Res. 2009;45:33. doi: 10.1029/2008WR007070.
98. Hunter Amanda. Investigation of water repellency and critical water content in undisturbed and reclaimed soils from the Athabasca oil sands region of Alberta, Canada. Department of Soil Science, University of Saskatchewan, Saskatoon. Unpublished Thesis; 2011.
99. Letey J, Carrillo MLK, Pang XP. Approaches to characterize the degree of water repellency. Journal of Hydrology. 2000;231–232. Elsevier Science BV. 2000;61–65.
100. Decagon Minidisk Infiltrometer User's Manual (Version 9). Decagon Devices, Inc., Pullman, WA, USA; 2011.
101. Bachmann J, Woche SK, Goebel MO. Extended methodology for determining wetting properties of porous media. Water Resour Res. 2003;39:1353-1366.
102. Das DK, Das B. Water Repellency in Soils. Division of soil science and agricultural chemistry, IARI, New Delhi, 110021. 1976;42:6.
103. Watson CL, Letey J. Indices for characterizing soil-water repellency based upon contact angle–surface tension relationships. Soil Sci Soc Am Proc. 1970;34:841–844.
104. Wander IW. An interpretation of the cause of water repellent sandy soils found in citrus grove of central Florida. Science. 1947;110(2856):299–300.
105. Bond RD, Harris JR. The influence of the microflora on physical properties of soils: I. Effects associated with filamentous algae and fungi. Aust J Soil Res. 1964;2:111-122.
106. Krammes JS, DeBano LF. Soil wettability: a neglected factor in watershed management. Water Resources Research. 1965;1:283–286.
107. Letey J, 1969. Measurement of contact angle, water drop penetration time and critical surface tension proc symp. Water repellent soils Uni Calif. 1968;43–47.
108. Wessel AT. 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. 1988;13:555–561.
109. Dekker LW, Jungerius PD. Water repellency in the dunes with special reference to The Netherlands. Catena. 1990;18:173-183.
110. Doerr SH. On standardizing the 'water droplet penetration time' and the 'molarity of an ethanol droplet' techniques to classify soil water repellency: a case study using medium textured soils. Earth Surf Proc Land. 1998;23:663-668.
111. Moody, David R, Schlossberg Maxim J. Soil water repellency index prediction using the molarity of ethanol droplet test. Vadose Zone J. 2010;9:1046–1051. doi: 10.2136/vzj2009.0119.

112. Doerr, Stefan H, Shakesby, Richard A, MacDonald Lee H. Soil water repellency: a key factor in post-fire erosion? In Review CHAPTER I. 2007;7.
113. Letey J, Osborn J, Pelishek RE. The influence of the water-solid contact angle on water movement in soil. Bull Int Assoc Hydrol Sci. 1962;3:75-81.
114. Michel JC, Riviere LM, Bellon-Fontaine MN. Measurement of the wettability of organic materials in relation to water content by the capillary rise method. European Journal of Soil Science. 2001;52:459-467.
115. Goebel MO, Bachmann J, Woche SK, Fischer WR, Horton R. Water potential and aggregate size effects on contact angle and surface energy. Soil Science Society of America Journal. 2004;68:383-393.
116. Diehl Dörte. The role of the organic matter for hydrophobicity in urban soils. Dissertation. Zur Erlangung des akademischen Grades eines Doktors der Naturwissenschaften Fachbereich 7: Natur- und Umweltwissenschaften. Universität Koblenz-Landau; 2009.
117. Drelich J, Fang Ch, White CL. Measurement of interfacial tension in fluid-fluid systems. Encyclopedia of Surface and Colloid Science. Marcel Dekker, Inc. 2002;3152-3166.
118. Shang J, Flury M, Harsh JB, Zollars RL. Comparison of different methods to measure contact angles of soil colloids. J Colloid Interface Sci. 2008;328:299–307.
119. Wilhelmy L. Concerning the dependence of the Capillaritäts - Constante the alcohol of substance and shape of the wetted solid body. Annalen Der Physik und Chemie. 1863;119:177.
120. Mennella Aniello, Morrow Norman R. Point – by - point method of determining contact angles from dynamic wilhemy plate data for oil/brine/solid systems. Journal of Colloids and Interface Science. 1995;172:(48–55).
121. Available: www.wikipedia.org
122. Lam CNC, et al. Measuring contact angle, In: Handbook of applied surface and colloids chemistry. Holmberg K, Shah DO, Schwuger MJ, editors. John Wiley and Sons: UK; 2002.
123. Sonntag H. Koloidy, PWN: Warszawa; 1982.
124. Rusanov AI. Prokhorov VA. Interfacial Tensiometry; Elsevier: Amsterdam; 1996.
125. Butt Hans-Jürgen, Graf Karlheinz, Kappl Michael. Physics and chemistry of interfaces (2., rev. and enl. ed. ed.). Weinheim: Wiley-VCH-Verl. 2006;16. ISBN 9783527406296.
126. Thomas Young. An essay on the cohesion of fluids. Philos Trans R Soc Lond. 1805;95:65-87.
127. Yuan Y, Lee TR. Chapter 1: Contact angle and wetting properties. In: Bracco B Holst, (eds.), Surface Science Techniques, Springer Series in Surface Sciences. 2013;51. doi 10.1007/978-3-642-34243-1_1, © Springer-Verlag Berlin Heidelberg.
128. Membranes.edu.au.
129. Vogelmann ES, Reichert JM, Reinert DJ, Mentges MI, Vieira DA, Peixoto De Barros CA, Fasinmirin JT. Water repellency in soils of humid subtropical climate of Rio Grande Do Sul, Brazil. Soil Till Res. 2010;110:126–133.
130. Zhang R. Determination of soil sorptivity and hydraulic conductivity from the disk infiltrometer. Soil Sci Soc Am J. 1997;61:1024-1030.
131. Malkinson D, Wittenberg L. Post fire induced soil water repellency - Modeling short and long-term processes. Geomorphology. 2011;125:186–192.
132. Diehl D, Schaumann GE. The nature of wetting on urban soil samples: wetting kinetics and evaporation assessed from sessile drop shape. Hydrol Process. 2007;21:2255-2265.
133. Doerr SH, Dekker LW, Ritsema CJ, Shakesby RA, Bryant R. Water repellency of soils: The influence of ambient relative humidity. Soil Sci Soc Am J. 2002;66:401-405.

134. Bond RD. Water repellent sands. Trans 9th Int. Congr Soil Sci. 1968;1:339-347.
135. Tschapek M. Criteria for determining the hydrophilicity– hydrophobicity of soils. Z. Pflanzenerna¨hr. Bodenkd. 1984;147:137–149.
136. Ellies A, Ramírez C, Mac Donald R. Organic matter and wetting capacity distribution in aggregates of Chilean soils. Catena. 2005;59:69-78.
137. Cooperband L. Building soil organic matter with organic amendments. Center for Integrated Agricultural Systems (CIAS), College of Agricultural and Life Sciences, University of Wisconsin-Madison; 2002.
138. FAO. The importance of soil organic matter. FAO soils bulletin No. 80. Rome; 2005.
139. Neary D G. Fire Effects on Soils. Rocky Mountain Research Station, Flagstaff, Arizona, Southwest Hydrology; 2004.
140. DeBano LF, Krammes JS. Water repellent soil sand their relation to wildfire temperatures. Int Assoc Sci Hydrol Bull. 1966;2:14-19.
141. Savage SM. Mechanism of fire-induced water repellency in soil. Soil Science Society of America Proceedings. 1974;38:652–657.
142. Hallett PD, White NA, Ritz K. Impact of basidiomycete fungi on the wettability of soil contaminated with a hydrophobic polycyclic aromatic hydrocarbon. Biologia, 2006;61(19):334–338.
143. Bond RD. The influence of the microflora on the physical properties of soils. 11. Field studies on water repellent sands. Aust J Soil Res. 1964;2:123-131.
144. Savage SM, Osbom J, Letey I, Heaton C. Substances Contributing to Fire Induced Water Repellency in Soils- Soil Sci. SOC Arner Proc. 1972;36:674-678.
145. Jex GW, Bleakley BH, Hubbell DH, Munro LL. High humidity-induced increase in water repellency in some sandy soils. Soil Science Society of America Journal. 1985;49:1177–1182.
146. TURFAZ^{tm}. Hydrophobic Problem. 1996;5:2.
147. Imeson AC, Verstraten JM, Van Mulligen EJ, Sevink J. The effects of fire and water repellency on infiltration and runoff under Mediterranean type forest. Catena. 1992;19:345–361.
148. Mallik AU, Rahman AA. Soil water repellency in regularly burned Calluna heathlands: comparison of three measuring techniques. Journal of Environmental Management. 1985;20:207–218.
149. Crockford S, Topalidis S, Richardson DP. Water RepeNency in a Dry sclerophyll Forest - Measurements and Processes. Hydrological Processes. 1991;5:405-420.
150. Doerr SH, Shakesby RA, Walsh RPD. Soil hydrophobicity variations with depth and particle size fraction in burned and unburnt Eucalyptus globulus and Pinus pinaster forest terrain in Aqueda Basin, Portugal. Catena. 1996;27:25–47.
151. Scott DF. The influence of eucalypts on soil wettability. In: Schonau, A.P.G. (Ed.), Proceedings of the IUFRO Symposium on Intensive Forestry: The Role of Eucalypts. Durban. South African Institute of Forestry, Pretoria. 1991;1044–1056.
152. Lin CY, Hsieh ST, Chen MY. Reclamation of water repellent layers in Casuarina windbreaks. Journal of Chinese Soil and Water Conservation. 1996;27(2):101–117.
153. Adams S, Strain BR, Adams MS 1969. Water – repellent soils and annual plant cover in a desert scrub community of Southeastern California. Proc Symp Water repellent Soils Univ Calif. 1968;289–295.
154. Bornemisza E, Wettability of soils in relation to their physic – chemical properties. Diss Abstr. 1964;25:3771.
155. Savage SM, Martin JP, Letey J. Contribution of some soil fungi to natural and heat-induced water repellency in sand. Soil Sci Soc Am J. 1969;33:405-409.

156. Wallis MG, Scotter DR, Horne DJ. An evaluation of the intrinsic sorptivity water repellency index on a range of New Zealand soils. Australian Journal of Soil Research. 1991;29:353–362.
157. Lewis SA, Wu JQ, Robichaud PR. Assessing burn severity and comparing soil water repellency, Hayman Fire, Colorado. Hydrological Processes 2006;20:1-16.
158. Huffman EL, MacDonald LH, Stednick JD. Strength and persistence of fire-induced soil hydrophobicity under ponderosa and lodgepole pine, Colorado Front Range. Hydrological Processes. 2001;15:2877-2892.
159. Dekker LW, Ritsema CJ. Uneven moisture patterns in water repellent soils. Geoderma. 1996;70:87–99.
160. Dekker LW, Ritsema CJ. Preferential flow paths in a water repellent clay soil with grass cover. Water Resources Research. 1996;32:1239–1249.
161. Dekker LW, Ritsema CJ. Variation in water content and wetting patterns in Dutch water repellent peaty clay and clayey peat soils. Catena. 1996;28(1-2):89-105.
162. National park service. hydrophobicity rangeland soil quality. Natural Resources Program Center Geologic resource Division; 2013.
163. Fasinmirin JT, Olorunfemi IE. Pedotransfer Functions for Soil Sorptivity Prediction in the Forest Vegetative Zone of Nigeria. Proceedings of the 11th International Conference and 32nd Annual General Meeting of the Nigerian Institution of Agricultural Engineers (NIAE), Ilorin, Nigeria. 2011;32:751–758, ISBN: 978–036–578–8.
164. Scott AS. An assessment of soil water repellency after wildfire in Southern british Columbia: Comparison of Methodologies and predictive indicators. The University of British Columbia. Vancouver Thesis; 2011.
165. Lal R. Soil carbon sequestration to mitigate climate change. Geoderma. 2004;123:1–22.
166. Gaiser Thomas, Stahr Karl, Billen Norbert, Mohammad Abdel-Razek Mohammad. Modeling carbon sequestration under zero tillage at the regional scale. I. The effect of soil erosion. Ecological Modeling. 2008;218:110–120.
167. Lal R. Residue management, conservation tillage and soil restoration for mitigating greenhouse effect by CO2-enrichment. Lewis Publishers. 1998;128.
168. Reicosky, Donald C. Carbon Sequestration and Environmental Benefits from No-Till Systems. USDA ARS, North Central Soil Cons. Res. Lab, 803 Iowa Ave., Morris, Minnesota 56267 USA. 2002;43–58.
169. Wessolek G, Schwarzel K, Greiffenhagen A, Stoffregen H. Percolation characteristics of a water-repellent sandy forest soil. European Journal of Soil Science. 200859:14–23.
170. Ritsema CJ, Dekker LW. How water moves in a water repellent sandy soil. 2. Dynamics of fingered flow. Water Resources Research. 1994;30:2519–2531.
171. Franco CMM, Tate ME, Oades JM. Studies on nonwetting sands. I. The role of intrinsic particulate organic matter in the development of water-repellency in non-wetting sands. Australian Journal of Soil Research. 1995;33:253–263.
172. Goebel MO, Bachmann J, Reichstein M, et al. Soil water repellency and its implications for organic matter decomposition – is there a link to extreme climatic events? Global Change Biology. 2011;17:2640-2656.
173. Schlentner RL, Van Cleve K. Relationships between CO2 evolution from soil, substrate temperature, and substrate moisture in four mature forest types in interior Alaska. Canadian Journal of Forest Research. 1985;15:97-106.
174. Gulledge J, Schimel JP. Moisture control over soil CH4 consumption and microbial respiration: a unifying measure across sites. Soil Biology & Biochemistry. 1998;30:1127-1132.

175. Atlas RM. Use of microbial diversity measurements to assess environmental stress. In: Klug MJ, Reddy CA, (Eds.), Current Perspectives in Microbial Ecology. American Society for Microbiology, Washington, DC. 1984;540-545.
176. Clein JS, Schimel JP. Microbial activity of tundra and taiga soils at sub-zero temperature. Soil Biology & Biochemistry. 1995;27:1231-1234.
177. Wilkinson JF, Miller RH. Investigation and treatment of localized dry spots on sand golf greens. Agronomy Journal. 1978;70:299-304.
178. Karnok. Dry Spots Caused Hydrophobic Soil. Retrieved from AGCSA; 2003. Available: http://www.agcsa.com.au/static/atm_articles/html/4_6b.html178-191
179. Beard, James B. Turfgrass; science and culture. Prentice-Hall, Inc. Englewood Cliffs, N J; 1973.
180. Tucker KA, Karnok KJ, Radcliffe DE, Landry Jr G, Roncadori RW, Tan KH. Localized dry spots as caused by hydrophobic sand on bentgrass greens. Agronomy Journal. 1990;82:549-555.
181. Vincelli Paul, Eshenaur Brian. Localized Dry Spot. Plant Pathology Fact Sheet. UK Cooperative Extension Service, College of Agriculture, University of Kentucky; 2010.
182. Danneberger Karl, White Susan. Treating Localized Dry Spots. Golf Course Management . 1988;6-10.
183. Quyum Abdul. Water Migration through hydrophobic soils. Department of civil engineering, Univ. of calgary, calgary, alberta national library of Canada. Acquisitions and Bibliographic Services, Ottawa, Canada; 2000.
184. Poulter R. Soil water repellency, DPI, Redlands Research Station, Cleveland Q'ld. 2004;41-46.
185. Walsh RPD, Boakes D, Coelho COA, Goncalves AJB, Shakesby RA, Thomas AD. Impact of fire-induced hydrophobicity and post-fire forest litter on overland flow in northern and central Portugal. The second international conference on forest fire research. Coimbra, Portugal, Domingos Xavier Viegas. 1994;21–24:1149–1159.
186. Ritsema CJ, Dekker LW, Heijs AWJ. Three-dimensional fingered flow patterns in a water repellent sandy field soil. Soil Sci. 1997;162:79-90.
187. Ritsema CJ, Dekker LW. Preferential flow in water repellent sandy soils: principles and modeling implications. Journal of Hydrology. 2000;231–232:308–319.
188. Shakesby RA, Doerr SH, Walsh RPD. The erosional impact of soil hydrophobicity: current problems and future research directions. J Hydrol. 2000;231-232.
189. Pires LS, Silva MLN, Curi N, Leite FP, Brito LD. Water erosion in post-planting eucalyptus forests at center-east region of Minas Gerais State, Brazil. Pesquisa Agropecuaria Brasileira, 2006;41:687–695.
190. Wang Z, Wu L, Wu QJ. Water-entry value as an alternative indicator of soil water-repellency and wettability. Journal of Hydrology. 2000;231–232:76–83.
191. Matthew D. Madsen, Steven L. Petersen, Kaitlynn J. Fernelius, Bruce A. Roundy, Alan G. Taylor. Bryan G. Hopkins. Influence of soil water repellency on seedling emergence and plant survival in a burned semi-arid woodland. Arid Land Research and Management. 2012;26:(3)236-249.
192. Al Hassane Diallo. Methods to Determine Preferential Flow in Water Repellent Urban Soils. From The Faculty VI of the Technical University of Berlin in Order to Obtain the Academic Degree; 2011.
193. DeBano LF. Observations on water-repellent soils in western United States. In: DeBano LF, Letey J, (Eds.). Proceedings of a Symposium on Water Repellent Soils. University of California, Riverside. 1969;6–10. 1968;17–29.
194. DeBano LF. Water movement in water-repellent soils. In: DeBano LF, Letey JJ, (Eds.). Proceedings of a Symposium on Water Repellent soils. University of California, Riverside, 1969;6–10. 1968;49–89.

195. Dekker LW, Jungerius PD. Water repellency in the dunes with special reference to The Netherlands. Catena. 1990;18:173-183.
196. Emerson WW, Bond RD. The rate of water entry into dry sand and calculation of the advancing contact angle. Australian Journal of Soil Research. 1963;1:9–16.
197. Letey J, Osborn JF, Valoras N. Soil water repellency and the use of nonionic surfactants. California Water Resources Center Technical Comp. Report 154. University of California, Davis. 1975;85.
198. Meeuwig RO. Infiltration and water repellency in granitic soils. USDA Forest Service Research paper INT-111. 1971;20.
199. Hill DE, Parlange JY. Wetting front instability in layered soils. Soil Science Society of America Proceedings. 1972;36:697–702.
200. Diment GA, Watson KK, Blennerhassett PJ. Stability analysis of water movement in unsaturated porous materials, 1. Theoretical considerations. Water Resour Res. 1982;18:1248–1254.
201. Glass RJ, Steenhuis TS, Parlange JY. Wetting front instability as a rapid and far-reaching hydrologic process in the vadose zone. Journal of Contamination Hydrology. 1988;3:207–226.
202. Hendrickx, Jan MH, Flury Markus. Uniform and preferential flow mechanisms in the vadose zone. 5. In: conceptual models of flow and transport in the fractured vadose zone. Copyright © National Academy of Sciences; 2001.
203. Ritsema CJ, Dekker LW, Hendrickx JMH, Hamminga W. Preferential flow mechanism in a water repellent sandy soil. Water Resources Research. 1993;29:2183–2193.
204. Taeumer K, Stoffregen H, Wessolek G. Determination of repellency distribution using soil organic matter and water content. Geoderma. 2005;125:107-115.
205. Jamison VC. The penetration of irrigation and rain water into sandy soils of central Florida. Soil Sci Soc Amer Proc. 1945;(10):25–29.
206. Bauters TWJ, DiCarlo DA, Steenhuis TS, Parlange JY. Preferential flow in water repellent sands. Soil Sci Soc Am J. 1998;62:1185–1190.
207. Wellhead (Copolymer Blend Soil Surfactant), Technical Information Bulletin. Numerator Technologies, P.O. Box 868 Sarasota, Florida. 34230. 941.807.5333. Available: www.numeratortech.com
208. Tisdall JM, Oades JM. Organic matter and water-stable aggregates in soils. J Soil Sci. 1982;33:141-163.
209. Hallett PD, Young IM. Changes to water repellency of soil aggregates caused by substrate-induced microbial activity. Eur J Soil Sci. 1999;50:35-40.
210. Ae N, Osazawa S, Kubota J. Effect of phenolioc constituents on soil aggregation. Jpn J Soil Sci. Plant Nutr. 1987;58:233–236.
211. Bartolli F, Philppy R, Burtin G. Aggregation in soils with small amount of swelling clays. I. Aggregate stability. J Soil Sci. 1988;39:593–616.
212. Haynes RJ, Swift RS. Stability of soil aggregates in relation to organic constituents and soil water content. J Soil Sci. 1990;41:73–83.
213. Haynes RJ. Effect of sample pretreatment on aggregate stability measured by wet sieving and turbimentry on soils of different cropping history. L Soil Sci. 1993;44:261–270.
214. Franco CMM, Tates ME, Oades JM. The Development of Water repellency in Sands: Studies on the Physio-chemical and Biological Mechanisms. In: Carter, D., K.M.W. Howes (eds.). Proc. 2nd Natural Water Repellency Workshop, Perth, Western Australia. 1994;18-30.
215. SOILCO, Water repellent soils. Technical sheet. Soilco Pty Ltd. P.O. Box 199 Unanderra NSW 2526. Available: www.soilco.com.au

216. Buczko U, Bens O, Huttl RF. Water infiltration and hydrophobicity in forest soils of a pine beech transformation chronosequence. J Hydrol. 2006;331:338–395. Doi: 10.1016/j.jhydrol.2006.05.023.
217. Deller GA, Blackwell PS, Carter DJ. Physical and Nutrition Aspects of Ading Clay to Water Repellent Soils. In: Carter D, Howes KMW, (eds.). Proc. *2nd* Natural Water Repellency Workshop, Perth, Western Australia. 1994;168-1 73.
218. Robert FJ. The effect of sand types and fine particle amendments on the emergence and growth of subterranean clover with particular reference to water relations. Austr J Soil Res. 1966;17:657-672.
219. Harper RJ, Gilkes RJ. Soil attributes related to water repellency and the utility of soil survey for predicting its occurrence. Austr J Soil Res. 1994;32:1109-1124.
220. Carter DJ, Hetherington RE, Morrow G, Nicholso D. Trends in water repellency measurement from soil samples at different soil moisture and land use. Proc. 2nd National Water Repellency Workshop. 1994;49-57.
221. Ward PR, Oades JM. Effects of clay mineralogy and exchangeable cations on water-repeliency in clay amended soils. Austr J Soil Res. 1993;31:351-364.
222. Roper MM. Potential for remediation of water repellent soils by inoculation with wax-degrading bacteria in South-Western Australia. Biologia. 2006;61:358-362.
223. Roper M. Reducing water repellency in sandy soils. CSIRO Plant Industry; 2011. Available: www.csiro.au
224. Blackwell PS, Morrow GF, Nicholson DF, Webster AW, Yang BJ. Processes induced by furrow sowing water repellent sand. In: Carter DJ, Howes KMW, (Ed.), Proceedings of the Second Natural Water Repellency Workshop. Perth, Western Australia. 1994;1–4. 1994;95–105.
225. Karnok KJ, Tucker KA. Dry spots return with summer. Gol F Course Management. 1999;67(5):49-52.
226. Karnok KJ, Tucker KA. Wetting agent treated hydrophobic soil and its effect on color, quality and root growth of creeping bentgrass. Int Turfgrass Soc Res J. 2001;9:537-541.
227. Letey J, Osborn J, Pelishek RE. Measurement of liquid- solid contact angles in soil and sand. Soil Sci. 1962;93:149-153.
228. Snyder GH, Augustin BJ, Davidson JM. Moisture sensor-controlled irrigation for reducing N leaching in bermudagrass turf. Agron J. 1984;76:964-969.
229. Miyamoto S. Effects of wetting agents on water infiltration into poorly wettable sand, dry sod and wettable soils. Irrig Sci. 1985;6:271-279.
230. Bachmann J, Horton R, Van Der Ploeg RR. Isothermal and non isothermal evaporation from four sandy soils of different water repellency. Soil Sci Soc J. 2001;65:1599-1607.
231. McGhie DA. Non – wetting soils in Western Australia. New Zealand Turf Management Journal. 1987;2:13–16.

Peer-review history:
The peer review history for this paper can be accessed here:
http://www.sciencedomain.org/review-history.php?iid=458&id=22&aid=3907