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Impact of Soil Water Repellency on Hydrological and Erosion Processes; A Review

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ABSTRACT

Introduction Soil water repellency was first reported in the first half of the 20th century for peat soils. Depending on the severity of water repellency, a water repellent soil will resist water penetration during seconds to hours or even days. This has detrimental effects on surface and subsurface flow processes such as increased runoff, erosion, and preferential flow. The present study was conducted with the aim of investigating the effects of Soil water repellency on hydrological and erosion processes in order to identify gaps in the existing investigations.
Conclusion Major survey gaps remained, including the dissociation of the symptoms of water repellency on soil erosion such as the existence of a soil crust and little knowledge of the temporal patterns of water repellency and their hydrological outcomes. Understanding the mechanisms of water repellency is relevant to the separation of different causal chains as well as the adjust runoff coefficients in different water repellency areas. Soil water repellency can be caused by a variety of compounds and processes and generally occurs after a period of drying weather. Under such conditions, the soil can change from a wettable to a water-repellent state when dried below its critical soil water content. Soil water repellency is found to occur in different soils worldwide, ranging from coarse to fine-textured. Water repellency in soils can result in losses of plant-available water, reduced agricultural crop production, and deterioration of turf quality on sports fields.

Keywords Hydrology; Runoff; Soil; Erosion; Soil Water Repellent Layer

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Introduction

Only a few decades ago, it was assumed that soils simply and quickly should be wetted by rain and irrigation. However, recent literature has highlighted the actuality of a water repellent behaviour in a range from slight to extreme grades in the sand, loam, clay, and peat soils all over the world and under different land use and climatic conditions [1].

The resistance of soil against wetting may last a few seconds, however, under special situations even several months [2, 3]. The water-repellent behaviour is generally limited to a few to tens of centimeters within the soil profile, whose upper part is rich in nutrients and organic matter. The concept of soil water repellency refers to a significant reduction in wetting and infiltration as a result of the creation of hydrophobic coatings on soil particles and the presence of intermittent hydrophobic organic matter [4].

As early as 1910, Schreiner and Shorey described that some soils in California "could not be properly wetted, either by man, by rain, irrigation or movement of water from the subsoil, with the result that the land could not be used profitably for agriculture" [5].

Jamison reported that "large bodies of difficultly wettable soil remained unwetted even during the rainy season under Florida citrus trees, consequently, reducing crop productivity" [6]. The 1960s as a decade with great interest in the issue of soil wettability is defined [7]. Since the 1980s, wetting agents were regularly used in horticulture and turf grass activities [8], and clay additions and advanced irrigation techniques became a common amelioration method in agriculture.

Following fire incidents, soil water repellency acts as a key factor in increasing soil erosion and exacerbating the hydrological processes from hillslope to watershed scales [9].

However, water repellency is not exclusively undesirable. Some researchers have reported positive effects for it such as an increase in aggregate stability [10], organic carbon sequestration [11], and reduced soil moisture loss via evaporation [12]. The intensity of soil water repellency may vary from a high level in soils under burned eucalyptus species [13] to a low level in some agricultural soils, which only is detectable with a micro infiltrometer. As we know, water repellency is found to be rule than the exception [14].

This study primarily provided an overview of the origin of water repellency, measurement approaches, and the effects of various factors on its persistence under different types of vegetation. An introductory discussion was, then, provided on some of the challenges ahead in understanding and quantifying the effects of soil water repellency on hydromorphological properties such as runoff and erosion processes.

The aim of this study was to comprehend the overall concept of soil water repellency and its effects on different hydromorphological soil properties.

The origin of repellency and measuring water repellency: Firstly, it should be noted that water repellency is a relative term [15]. There are certain interactions between the liquid and the solid surface over the course of time and no absolutely hydrophobic soil surface exists in practice.

Large droplets are spread over to form a continuous membrane on a water-repellent surface [16]. If the surface is a porous medium like sand or loam, water is not capable of passing through the gaps and conveyance channels (Figure 1).

As for hydrophobic sand or soil characterized with enough macropores, water can fill in pores, but would not enclose the individual grains, while hydrophilic grains will be surrounded by a layer of water. The affinity or the hydrophobicity of the solid surfaces are originated from the reverse forces of adhesion and cohesion among the particles.

A summary of the measurement techniques and classification frameworks for soil water repellency have been provided by Letey *et al.* [16]. The advantages and disadvantages of the various methods are presented in Table 1.

Figure 1) Water droplets resisting infiltration into soil due to the extreme water repellency

Table 1) The different tests used to measure the soil water repellency

Method	Advantages	Disadvantages
Contact angle	Direct measurement	Time-consuming, difficult to conduct test
Repellency index, R	More reliable mean values at the sites with high spatial heterogeneity of soil properties than the older method	The interaction between ethanol and soil may affect the results
Molarity of an ethanol droplet (%)	Quick and easy; indirect method for calculating contact angle; gives the "potential" repellency value	The physical meaning requires further research
Water drop penetration time (Time)	Easy measurement	Time-consuming, not physical meaning
Fourier transform infrared (cm^{-1})	Examining changes in soil organic matter properties related to the thermal destruction of hydrophobicity	Difficult to conduct test
nuclear magnetic resonance (μm)	Quantify and study organic matter in whole soils	Time-consuming
Infrared thermography (μm)	Accurate and fast technique of monitoring surface temperature; Applicable to assess different processes such as crust formation and microrelief and rill morphology	Extensive instrument

A direct measurement of contact angle was suggested by Letey *et al.* [17], who used a capillary rise and infiltration technique to determine. Contact angles have often been expressed as water droplet contact angle on soil surface, which is more than 90° for soil water repellent (SWR; Figure 2).

Another simple technique used in the measurement of soil water repellency is the molarity of an ethanol droplet test. The molarity of an ethanol droplet test is quickly and simply set and it is applicable to field and disturbed samples. Furthermore, it can be used on highly repellent soils, where water drop penetration time values are more than 1 hour.

Theory of intrinsic diffusivity and sorptivity was first introduced and modified by Philip [18]. Afterwards, Tillman *et al.* [19] developed a new technique for the measurement of soil water repellency based on the intrinsic sorptivity of the medium. This repellency index was evaluated by Wallis and Horne [20], who measured the index on a range of New Zealand soils.

The water drop penetration time test consists of placing a drop of deionized water (~50μl) on the surface of a soil sample and recording the time for the water drop to fully penetrate (Figure 1) [21]. The longer the time, the more persistent is the soil water repellency [16]. Due to its direct hydrological relevance, the water drop penetration time test outperforms (or excels) molarity of an ethanol droplet test by means of the speed and simplicity, its applicability to the field and disturbed samples, and is more appropriate to measure and classify soil hydrophobicity.

However, in contrast to water drop penetration time, the molarity of an ethanol droplet test is more practical for soils with long penetration times [22]. Contact angle has been often used to study soil wettability, which is measurable by sessile drop method [23]. This has prompted the development of further techniques such as the capillary rise and intrinsic sorptivity. Fourier Transform Infrared Spectroscopy (FTIR) and Nuclear Magnetic Resonance (NMR) together with the recently developed method can be used to determine the hydrophobicity of the soil [24].

Sources of affecting on water repellency: A series of factors are responsible for soil water repellency such as vegetation, soil fungi and microorganisms, soil organic matter and humus, fire, soil texture, and clay content.

Clay content is one of the pivotal factors affecting soil water repellency. As for disturbed soil samples, clay content increases water drop penetration time and contact angle in non-repellent soils [25], whereas in slightly to severely repellent soils, it decreases them [26]. However, soil water repellency is mainly controlled by the content of soil organic matter [27].

Moreover, Leue *et al.* [24] argued water absorption at intact surface structures, in which mass exchange between preferential flow paths and soil matrix can be locally affected by a mm-scale organic matter distribution if organic matter is of increased content.

Badía *et al.* [28], Jiménez-Pinilla *et al.* [21], and Rodríguez-Alleres *et al.* [29] suggested that burning litter and heating the sand grains can provoke soil water repellency, depending on the temperature of the fire, the amount and type of litter burned, and the level of soil moisture. Some studies were presented, in which the fire was the main factor of hydrophobicity (Table 2).

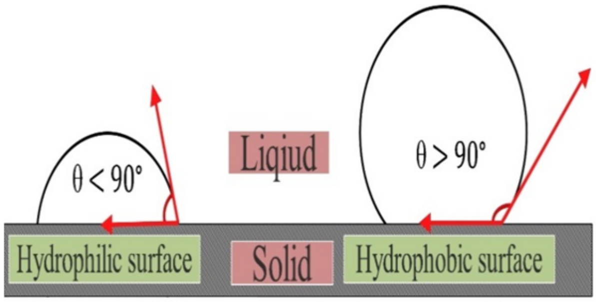

Figure 2) The contact angle between water and soil

Table 2) Soil water repellency rates measured in studies investigating fire-affected terrain

Authors	Unburnt	Burned	Methodology	Vegetation cover	Location
Jiménez-Pinilla *et al.* [21]	66% of control <5 second	44% of the plots>900 second	WDPT	Pine and shrubs	Gorga, SE Spain
Badía-Villas *et al.* [31]	22% ethanol	18.3% ethanol	MED	Pinus halepensis and Quercus coccifera	Ebro Basin, NE-Spain
Rodríguez-Alleres *et al.* [29]	>6 hour	<5 seconds	WDPT	Pinus pinaster	Galicia, NW Spain
Larsen *et al.* [32]	Very little	significantly stronger than unburnt	critical surface tension	Pinus ponderosa and Pseudotsuga menziesii	Colorado Front Range in SW of Denver
Pierson *et al.* [33]	7.4% reduction in infiltration	22.5% reduction in infiltration	water repellency index	Artemisia tridentate, vaseyana	Denio, SW Nevada
MacDonald and Huffman [34]	55 ($Nm^{-1}\times10^3$)	38 ($Nm^{-1}\times10^3$)	critical surface tension	Pinus ponderosa, P. contorta	Bobcat. SW Fort Collins
Akbarzadeh *et al.* [35]	1% ethanol	4% ethanol	MED	Carpinus betulus, Diospyros lotus and Pinus taeda	Kanroud forests, North of Iran

As an acceptable argument to the authors, heat evaporates water-repellent organic matter existing in litter and soil, where a part of the gas is restored, depending on the temperature gradient, densified soil, and litter [30].

Soil texture and structure are among other factors affecting soil water repellency, is considered by many researchers so far. An inverse relationship has been detected between clay content and the strength of soil water repellency. Many studies related to soil water repellency to the occurrence of coarse soil textures such as sandy soils [31-36].

Water repellency is a temporal soil property, which is changed over time [37]. Soil moisture content is an important factor for its variability [38]. Madsen *et al.* [39] pointed out that a fundamental aspect of water repellency is its high variability both in time and space. Water repellency is generally not manifested in wet soils; however, its relationship with soil moisture content is more complex than discussed in the issues so far. The threshold water content, beyond which hydrophobic soils become hydrophilic, depending on the soil type and properties (texture and organic matter), can be very different [40]. Water repellency is reduced or obviated in response to increased soil moisture, and it is expected for the increased runoff volume and sedimentation to return to the pre-water repellency state. On the other hand, increased moisture content due to incessant rainfall events would result in crust formation, which reduces infiltration and increases runoff and sedimentation [32]. Therefore, determining the critical moisture range introduced by Dekker *et al.* [41] as “transition zone” is of great importance in areas with water repellent soils to predict the volume and frequency of runoff occurrence [42]. The threshold water content, beyond which hydrophobic soils become hydrophilic, varied from 0.36 to 0.57cm^3 cm^{-3} [35]. This range specifies the behaviour of water repellent peat soils under different moisture regimes.

For sandy soils with the less organic matter, the soil can already become wettable with a very low volumetric soil water content. Extremely water repellent in sand dunes of the Netherlands with actual water repellency of more than 6 hours with water drop penetration time can become wettable after only wetting to 3 to 5vol.% water content. Heavy clay soils in the Netherlands became water repellent when dried to about 35vol.% water content. Soils with greater critical moisture ranges are more prone to the development of preferential flows and surface runoff production due to remaining water repellency to higher moisture contents.

Variability in these factors has different bearings on soil, the most important of which is hydromorphological changes in soil properties that require closer examination of the mechanism and behaviour.

Hydrological and erosive consequences of water repellency: Some hydrological effects have been mentioned in the previous section. Among other hydrological effects of soil water repellency, one can mention heterogeneous wetting patterns, the development of preferential flow, accelerated leaching, increased risk of surface and groundwater contamination, and less availability of water and nutrients to plants. Given the importance of this phenomenon to studies and environmental management, it is necessary to increase the knowledge of hydrological and erosive mechanisms in water repellent soils.

Overland flow: Water repellency effects on hydrological processes are supposed to be extensively related with reduced infiltration [43] and increased overland flow (from sandy to loamy soils) [9, 44].

In a study conducted to identify the factors affecting the hydrograph and sediment graphs in Mie Prefecture, Japan, Sadeghi *et al.* observed that after an intensive rainfall, discharge increased rapidly, but moisture at a depth of 5cm remained low [45]. They stated that the main factor of this phenomenon is the presence of intense hydrophobic layer. Elsewhere, the infiltration capacity of a water repellent soil (subjected to higher temperatures) is 25 times less than that of a wettable soil [30]. The infiltration capacity of a water repellent sandy soil under aridity was found to be 6 times less than that of a wet soil [46].

In another study, the water repellent soil was reported to have only 1% of its infiltration capacity in the first 5 minutes of measurement compared with that of its wettable state [14].

In a water-repellent surface layer, owing to the accumulation of rainwater and high surface tension, a Hortonian or infiltration excess state occurs. In this layer, voids such as the intral-layer gaps, root channels, activities of microorganisms, and the presence of spots with hydrophilic or hydrophobic states determine the type of flow [47-49] (Figure 3a).

Water repellency in soil and the associated preferential flow are like “barriers” and “leaks” in the soil plumbing system, respectively. Water repellent soils can be particularly effective in preventing or hindering downward water movement, directing it into structural or textural preferential flow paths [49] (Figure 3a and b). Accordingly, soils may not wet completely and water may be channelled via biopores [50], cracks, and pipes [49].

In addition to reducing the permeability, soil water repellency can cause ponding above this layer (Figure 3b). Accumulated water would take either of these routes [15]. 1) Becomes stored in the hydrophilic layer and later be evaporated; 2) Generates runoff after saturation of the hydrophilic layer, given the infiltration surplus; 3) Propagates laterally in the form of a ‘distribution flow’, moves vertically in the form of ‘preferential flow’, via the microchannels and other voids in the water-repellent layer, or moves downward through the hydrophilic micro tubes or through less hydrophobic conveyances; 4) Lateral flow over the water-repellent layer; 5) Enters the matrix of a water-repellent layer under sufficient pressure and causes a phase change from water repellent to wettable states.

In New Zealand, hill country under rangelands, runoff triggered through a rising water table, perched, or nonetheless, is produced when the moisture content in the root zone is up to field capacity and low-permeability subsoil prevents escaping all the surplus water.

Hortonian flow is less regular because of the normally high penetrability of the topsoil, but it can happen in various circumstances, one of which is the advancement of repellency in the dry surface soil. In this manner, two instruments regularly create surface spillover under differentiating hydrological conditions. Where water repellency is the leading cause of the surface runoff generation, it is often not clear whether it is the outcome of either Hortonian or saturated forms or a combination of both. This is especially more pronounced for thin or discontinuous hydrophilic layers (Figure 3b). For example, a study carried out by Jordán *et al.,* [51] in a fir, pine, and oak mixed forest soil in Mexico showed that the formation of water-repellent layer increased the amount of surface runoff from 15.7% to 19.9% compared to hydrophilic soils. Akbarzadeh *et al*. showed that total erosion, infiltration rate, and water repellency had significant differences in burned and unburned sites [35]. But, this is not always a simple interpretation.

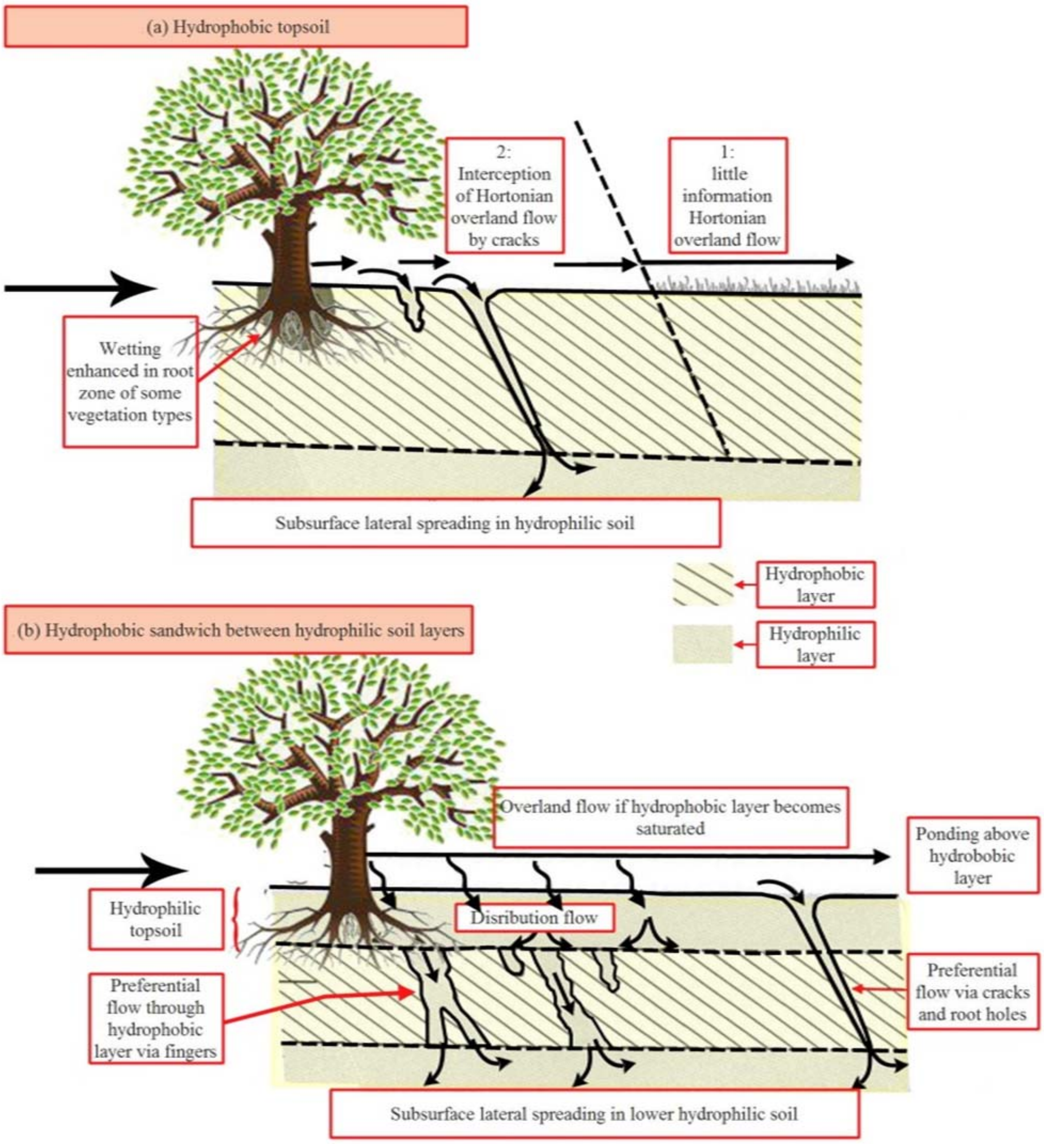

Figure 3) Possible hydrological responses of soil (a) with a water repellent surface layer; (b) with a repellent layer sandwiched between wettable layers. [15]

In another case, Doerr *et al*. stated that hydrological impacts associated with fire effects are more complex than simply the increase of overland flow and runoff with increasing fire intensity.

Data of several studies suggest that soil water repellency is one of the series of factors affecting surface runoff generation in burned areas [52, 32]. A study performed by MacDonald and Huffman [34] in the Front Range Forests in Colorado with a rainfall simulation showed that the destruction of a water-repellent layer did not restore the pre-fire runoff volume and sediment yield. In another case, Walsh *et al*. demonstrated 5% to 25% growth in surface runoff in the burnt Portuguese pine areas compared with unburned pine and eucalyptus forests [53]. The increased surface runoff may not only be caused by soil water repellency, but other factors such as the loss of protective surface cover, reducing soil particle size, permeability, stone lag development, soil sealing, and loss of organic matter might affect it [32, 54-56].

This increase in surface runoff was also investigated, using a rainfall simulator at a plot scale under dry conditions in Portugal in the close vicinity of an area with a history of fire [53]. The results showed that throughout the 1-hour rainfall with 40-46mm, the soil remained dry and hydrophobic beneath a water layer on top of it.

Surface runoff generation was on average 4% on the unburned soil, while most of the added water infiltrated through cracks, root holes, and burrows. Yet, the surface runoff for the burned soil was more substantial and amounted to 8% to 20%. Therefore, depending on the pre-fire conditions, the increase in the average surface runoff generation after the fire episode can be caused by the following factors:

1) Fire creates or reinforces a water-repellent surface; thus, surface runoff generation from a water repellent soil will increase until the water repellency returns to the pre-fire state (Figure 4a and b);

2) If, other fire-related changes are more pronounced than the increased surface runoff due to water repellency, the soil will remain wettable whether before or after the fire period.

Hortonian overland flows are more common in areas with a continuous hydrophobic layer (Figure 3a/1). Numerous studies pointed to the spatial inference of the surface runoff in water repellent soils [16]. For example, only 25% of the soil showed evidence of water repellency after a fire episode in the Southwest region of Oregon State, which had little effect on the surface runoff and infiltration [56].

Meeuwig [57] and Imeson *et al.* [54] studied pine forests of North America and of Northeast Spain, respectively. They found that the Hortonian runoff flow created in water repellent soils around the trees and shrubs tended to infiltrate into the soils (Figure 3a/2). Such a pattern in simulated rainfall was also observed in Southwest of Denver [3].

Some investigations showed that the effectiveness of hydrophobicity after the fire only remained stable for a short period [58]. Rye and Smettem also found that properties such as water repellency rapidly changed during rainfall simulation [59], whereas the permeability of hydrophilic soil declined during rainstorms, increased the infiltration capacity of the hydrophobic soils, often due to the higher moisture contents [59]. Imeson *et al.* stated that although hydrophobic soils can induce high amounts of overland flow, its impact at the watershed and hillslope scales may be offset by the large spatial variations in infiltration level [54]. This means that the effects of water repellency on overland flow vary at different scales [60].

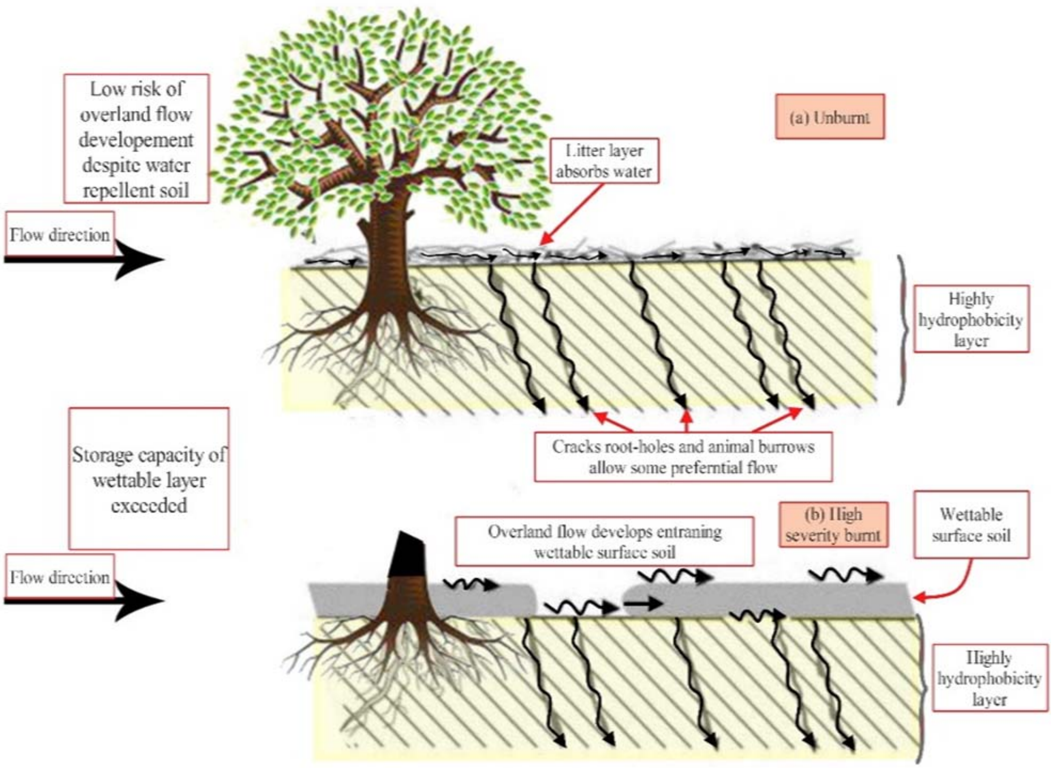

Figure 4) The effects of fire and water repellency on surface runoff; (a) unburnt conditions; (b) High severity burn [47]

Preferential flow: Preferential flow is the term used for the vertical and channelized movement of water through the soil matrix and subsurface layers and fractures [15]. This may have a variety of reasons, including wettable soil patches [61], a high density of stones [62], faunal burrows [50] and the existence of fine soil cracks and roots [63]. However, although this process is not limited to water repellent soils, water repellency may obstruct the movement of water to low depths and directly convey water into the soil preferential flow paths (Figure 3a and b) or create an unstable wetting front (Figure 5). As a result, the soils do not completely develop a wet state by a hydrophilic front, and water may probably be conveyed via root holes and soil cracks into the soil matrix [60]. In this regard, root holes and tunnels excavated by animals create special sub-routes in water-repellent soils [64].

The multiplicity of preferential flow paths within the water-repellent layer exerts influence over soil moisture distribution and dynamics, including evaporation patterns. For example, the presence of preferential flow paths in a strong water repellent surface layer can lead to a dry soil surface and wetter subsurface layers [42].

Figure 5) Uneven wetting, preferential flow and ponding of water on a water repellent sandy soil in a nature reserve [1]

Fingered flow induced by water repellency can result in major alterations in soil moisture content in an initially repellent soil such that areas of very dry soil can abut straight against areas of wet soil [49]. Walsh *et al.* [53] argued that the main cause of low runoff under intense rainfall events in the pine and eucalyptus forests of Portugal might be associated with these routes. They reached the conclusion that if a hydrophobic layer exists under a hydrophilic layer, water tends to accumulate onto the boundary layer, and, then, drains in the form of preferential flow paths through the fractures and seams within the body of the hydrophobic layer. This phenomenon was first described by De Bano [7] for burned soils, followed by the investigation of distribution flow in water-repellent soils by Dekker and Ritsema [2].

Elsewhere, Carrick *et al.* [65] examined the distribution of water in a grass-covered dune sand by means of tracers and they observed that water moved through preferential flow paths from an actual wettable topsoil into an extremely water repellent subsoil. It was accordingly tagged as fingered flow [66]. The fingered flow was formed after a dry period in the sandy water-repellent layer with a critical volumetric soil water content of less than 4.75%. Depending on the amount of moisture, the width of the fractures can range from about 10-50cm, acting as the conveyors of water within the soil profile under continued rainfall. This role will be provided till the seams within the soil profile recur hydrophilic. Ritsema *et al.* [67] showed that the seams reoccur repeatedly at similar locations after successive precipitation, which might facilitate leaching of hydrophobic nutrients through the provided paths (Figure 6a).

In contrast, in the very thin actual hydrophilic top layer in a sandy soil with winter wheat (Figure 6b), fingered flow was possibly substituted into an irregular wetting front into the hydrophobic soil beneath it [59]. The extension of a horizontal wetting front in an actual hydrophilic soil layer can create fingered flow in sandy soils with different degrees of water repellency [66]. The spatial distribution of actual hydrophilic areas is closely linked to joint's diameter as well as to water and soil characteristics [16]. The effectiveness of preferential flow paths is not only dependent on the persistence of water repellency, but it also varies by changing the position of the water-repellent layer in the soil profile, the thickness of the overlying layer, the extent, and the spatial vicinity of water repellency per unit area.

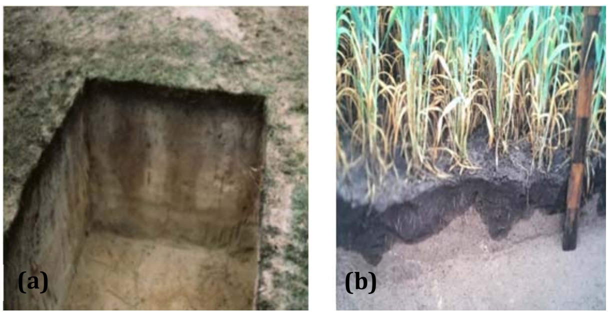

Figure 6) (a) Fingered flow shape in a grass-covered water repellent sand [41]; (b) wavy saturating front in a water repellent sandy soil under winter wheat [61]

Erosion: Most of the water repellent soils show higher erosion rates due to lower infiltration capacities and greater overland flow volumes during rainfall events. Some researchers tend to use inferential relations instead of establishing a direct causal relationship between erosion and soil water repellency.

For example, Megahan and Molitor mentioned pine and fir forests in Idaho, an increase in soil loss in water repellent regions [56]. Likewise, higher post-fire soil loss rate has been linked to an increased water repellency and the expansion of rills and gullies in the burned areas. A thermal effect caused by fire on soil water repellency is highly variable. This might be explained by the fact that fire can remove the protective vegetation and litter cover [30, 44], destroy organic matter [68], destruct soil aggregates [39], and reduce soil particle size [3], all of which providing the ground for higher erosion rates. Therefore, it is difficult to determine the exact amount of soil loss proceeding fire-induced water repellency.

Efforts have been made to separate the water repellent effects from the results of other soil erosion factors. For example, a study conducted by Osborn *et al.* [69] in California estimated soil loss in burned plots. Results showed that the amount of soil lost in the control plots (hydrophobic) could rise to more than 13 times higher than that of the hydrophilic plots (treated; Diagram 1).

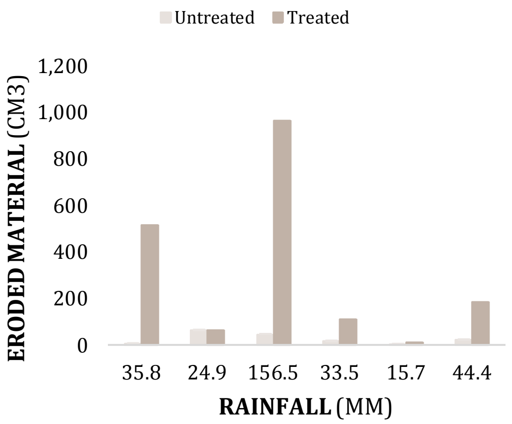

Diagram 1) Soil erosion and rainfall in hydrophilic (treated) and hydrophobic (non-treated) plots in a burned forest in California [69]

As the overland flow winds up gathered into little rivulets, this can start rill erosion [70]. Rills, 100mm in depth, were observed in all control plots at the end of the monitoring period. For the hydrophilic plots, no sign of rills was observed and the plots had retained their pre-treatment characteristics.

Effects of hydrophobicity in soils in wetter climatic zones, such as sand dunes in the Netherlands and Portugal have been considered by Jungerius and Ten Harkel [71]. In these studies, short-term changes in water repellency and overland flow effect on soil loss were studied. In winter, when the sand was moist and hydrophilic, infiltration capacity was extremely high, so that heavy rainfall caused very little erosion. Subsequently, after dry spells in summer, a water-repellent state is re-established and soil will encounter severe erosion even under a relatively slight rainfall [15]. Runoff from a rainfall event in these dunes is due to the rapid drying on the south-facing slopes, the patchy cover with moss and algae, as well as the fact that topographic disconformity is caused by the water repellency. The runoff creates small rills between the bushes and deposits sand and organic matter at the foothill. On dunes with slopes greater than 6 degrees, runoff infiltrates into the sand grains and leads to mudflows at the foothills [71]. As a result, the difference in aspect in these areas is conducive to the variation in water-repellent re-establishment time and leads to an asymmetric sensitivity to erosion. At a bigger scale, joining of overland flow in sunken parts of hillslopes can prompt the development of gullies, and to downstream channel bank and bed erosion [72].

Jordán *et al.* [3] stated that water repellency caused by fire in the forests is the major contributor to the increased erosion after a long period of drought. In one case, the results showed that a 20mm rainfall event in summer produced a soil loss 35 times more than a similar situation in winter. Nevertheless, due to higher rainfall amounts and overland flow, the total sediment delivery was greater in winter.

Likewise, soil water repellency can specifically influence erosion rates by adjusting the erodibility of the soil. Laboratory tests have demonstrated that individual water drops falling on a water-repellent soil deliver less, slower-moving discharge beads than those on wettable soils; yet, the splash ejection drops created on the previous conveyed greater sediment.

Elsewhere, laboratory studies have shown that under simulated rainfall, the ratio of the droplet splash in the hydrophilic to hydrophobic soils was merely 52% to 58% on flat areas to a range of 51% to 72% on sloping surfaces. With progressive drops, the surface of the water-repellent soil stayed dry and non-cohesive, and the soil particles kept on being disputed by rain splash in spite of the maintenance of an overlying film of water.

Conversely, drops falling on the surface of the wettable soil fixed and compressed it, which expanded its protection from detachment by rain splash. Aggregate stability, interestingly, has been appeared to be higher in water-repellent soils, which may counter the above-mentioned impacts to some degree in soils that show aggregation [73]. The difference in droplet splash between flat and sloping surfaces is attributable to the droplet size differences. In water repellent soils, the surface layer is adhesive due to high humidity and gradually becomes more compact during the rainfall simulation, while the hydrophilic layer is vulnerable to droplet splash and soil particles are easily detached from the surface layer.

Evidence has been provided by different researchers [74], concerning the profound effect of rain splash on soil particle detachment. Dual function of the hydrophobic layer in soil loss from different erosion types have arisen many questions in relation to the magnitude of the impact and the threshold levels, which requires more detailed research in this field.

The sensitivity to soil erosion on water repellent soils depends on the continuity of adjacent surfaces [75]. For example, splash and surface erosions dominate after fire-induced water repellency on rill banks and in the rills traversing a water-repellent layer [76]. On the other hand, where preferential and subsurface flows dominate, higher landslide risks are encountered with respect to higher infiltration rates. In addition to the direct effects of water repellency on the erosion process, this phenomenon bears also other secondary effects. For example, Krammes and Osborn [77] investigated sandy loam soils after fire and provided evidence for the water repellency of the debris cones, deposited at the foothills, as a result of sediment creep (dry ravel).

Although most studies suggest that soil erosion in water repellent soils increases the sediment yield, coarser textures and well-developed aggregates just cause resistance to soil erosion [21]. Water repellency in soils with a well-developed aggregate (especially aggregates ranging 0.5-5mm) could improve aggregate stability due to the presence of aliphatic and aromatic compounds [78]. This increased aggregate stability in coarser textures is related to the entrapment of air in the voids of soil aggregates.

At hillslope and watershed scales, the part of soil water repellency in expanding erosion is less sure. Its general effect is probably going to be diminished where regions with macropores or wettable soil patches advance interception of overland flow created locally on water-repellent areas.

Since the late 1980s, the study of soil water repellency was expanded to both field and lab researches. Recent findings indicate that some factors could develop full or patchy water repellency (Figure 7) within the soil profile. Research has shown that the factors affecting soil water repellency can be classified into two categories, including biological and non-biological factors.

The first factor is the organic and hydrophobic molecule released by the decomposition and burning of plant litter. It was recently that the roles of the root zone and plant leaves have been acknowledged as the probable causes of releasing hydrophobic compounds. These particular organic compounds incite hydrophobicity by providing a coating on particles, acting as aggregate constituents or by binding soil particles. The second factor is the role of fire, which has drawn attention over the recent years. The results indicate the significant effects of fire on the rigidity and function of hydrophobic layers. These impacts correspond to the effects of low temperatures on water repellent soils that can only be detected in the early years after the fire. Soil hydrophobicity is a common characteristic of post-fire soils, and it is much stronger and more persistent than in the same soils prior to burning.

The analysis of the soil water repellency affects preferential flow generation or augmentation suggests an asymmetry in the surface and subsurface flow. To date, these effects and the influencing factors, including fire-induced water repellency have not been precisely established. The frequency and effectiveness of flow paths through each water-repellent layer, soil structure, vegetation type, location, intensity, persistence, and the temporal regime of the water-repellent layer in the soil profile are also crucial factors (Figure 7). Very little is known about the hydrophobicity characteristics and the resulting consequences. Much uncertainty still exists about spatial contiguity of water-repellent surfaces, frequency, and effectiveness of preferential flow paths and their overall impact on overland flow generation.

A bibliography published by Dekker *et al.* [1] in 2005 indicated that since 1883, more than 1,200 theoretical and applied research papers had been published on the topic of soil water repellency. At present, this bibliography contains more than 3,150 papers (Dekker, personal communication), showing an exceptionally increased interest by scientists in unravelling the causes, effects, and potential management strategies for the widely occurring phenomenon of soil water repellency.

Certain researchers, including one of the authors of this paper, have in the past practiced and recommended oven-drying samples in the lab to determine the potential degree of soil water repellency, using the method outlined by Dekker and Ritsema [2]. However, recent studies have clearly shown that oven-drying does not necessarily provide information that is relevant to field conditions. On the contrary, oven-drying does not appear to reflect conditions observed in the field under prolonged drought conditions [79]. Diagram 2 illustrates the results of oven-drying two different soil samples, one from Greece and the other from The Netherlands.

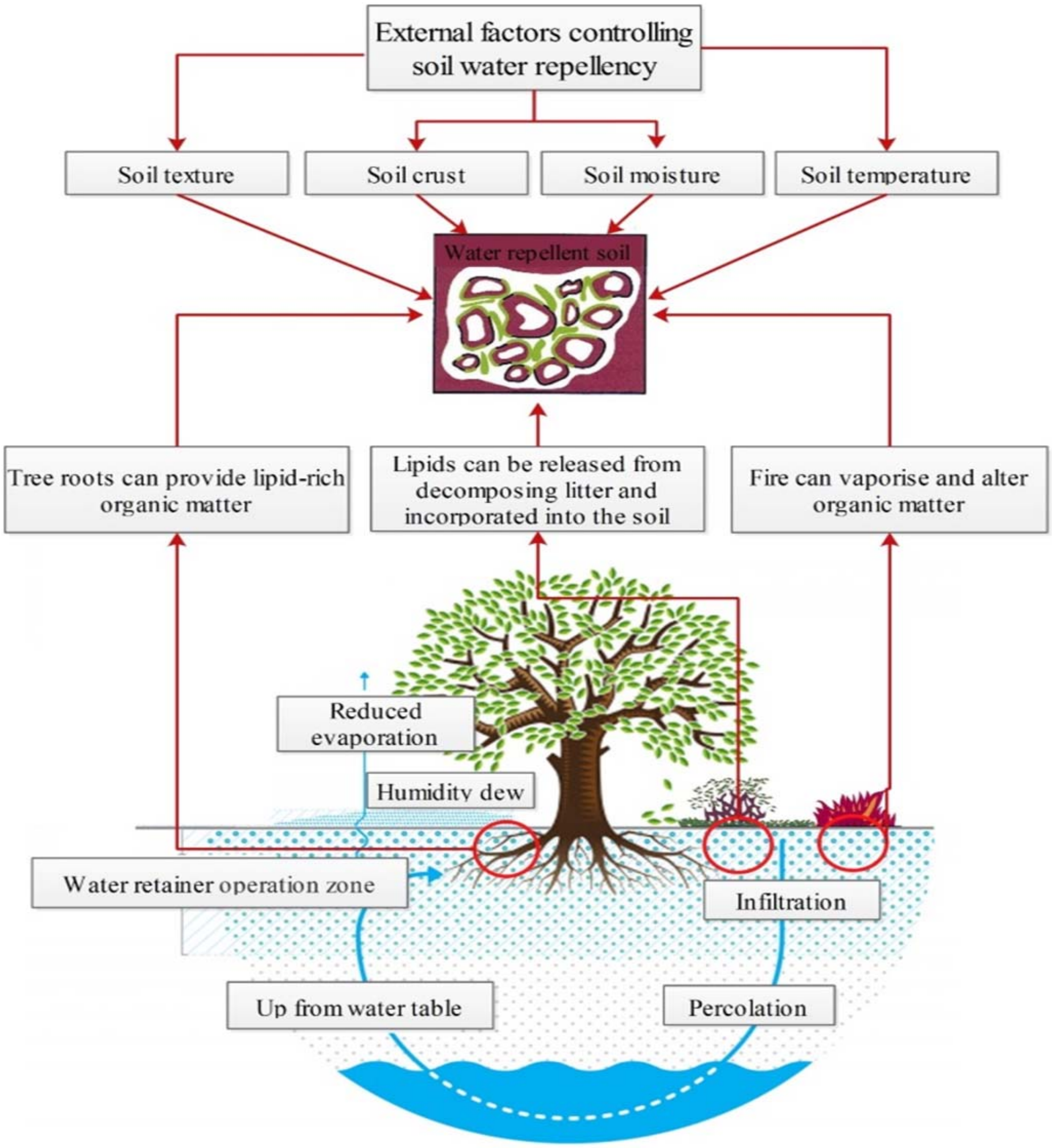

Figure 7) Summary of commonly held views on the development of water repellency in soils and their controlling external factors

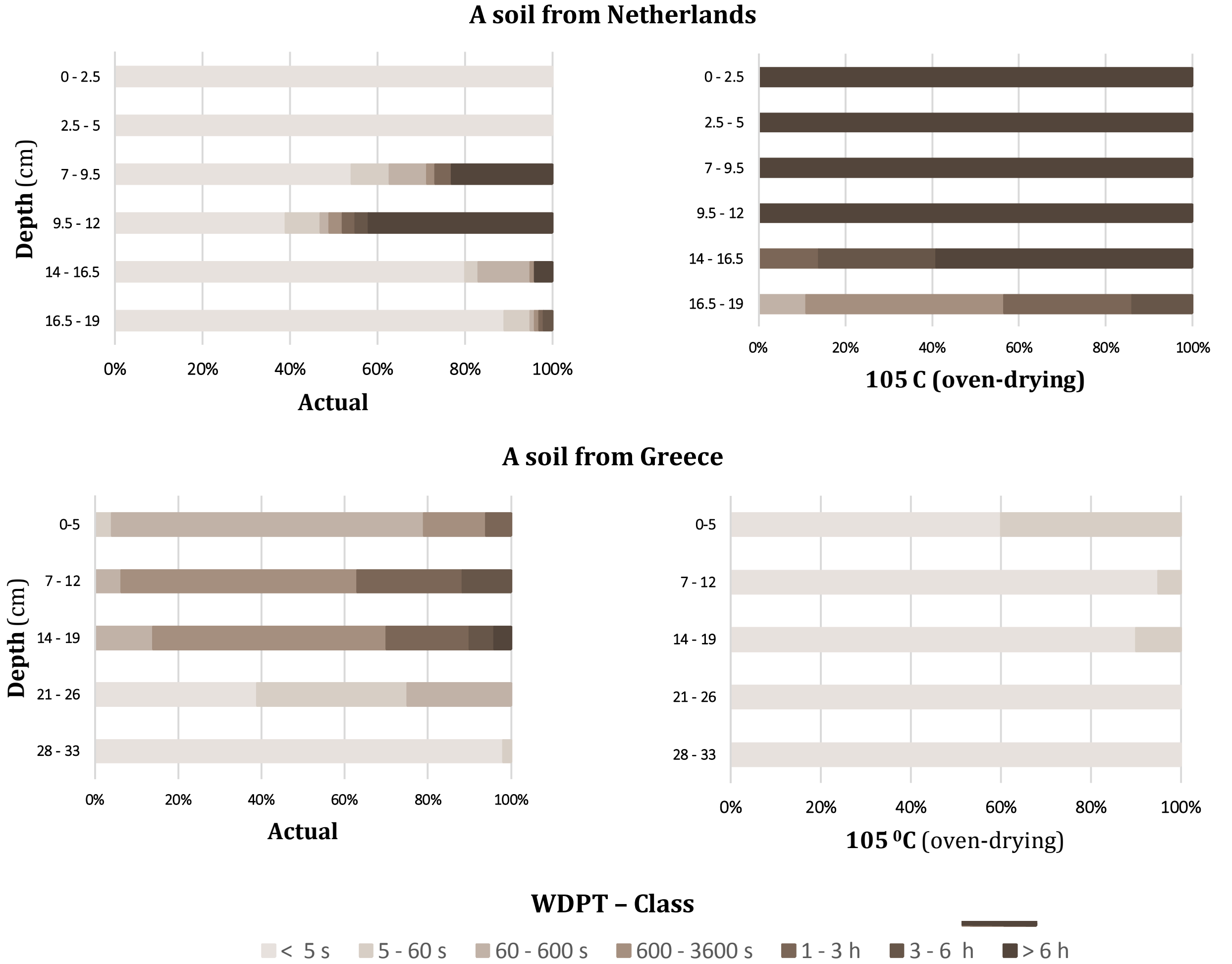

Diagram 2) The relative frequency of water repellent soil by depth for a Dutch and a Greek soil, for both actual field-moist conditions and after oven-drying of the samples at 105⁰C. (n=75 samples per layer for Dutch and n=35 samples per layer for Greek soil)

Figure 8 illustrates the difference in grass performance between two surfactants treated and two untreated plots on a sandy fairway of a golf course in The Netherlands. Generally, it has been assumed that performance of water repellency tests on oven-dried (to 65⁰C or 105⁰C) samples revealed information on the maximum degree of soil water repellency for that soil. However, this is not always the case, as can be seen in the two different soils. The degree of soil water repellency in the soil from Greece actually decreased during drying in the oven, while in the Dutch soil, the opposite occurred. This means that the best way to correctly reveal information about the water repellency condition of a soil is to take measurements directly in the field [80, 81].

Some researchers use the Molarity of Ethanol Droplet (MED) or ethanol percentage test [20, 31, 35] instead of the Water Drop Penetration Time (WDPT) test. One of the primary reasons is that this test can be conducted even more quickly than the WDPT test, especially when soil samples are exhibiting severe to extreme degrees of soil water repellency. Recently, however, comparison of the methods suggest that the MED test may be more sensitive to the organic matter content of a soil than the organic coatings that are often the primary cause for extreme soil water repellency in the field [82]. According to these authors are further studies of the sensitivity of the different test methods needed.

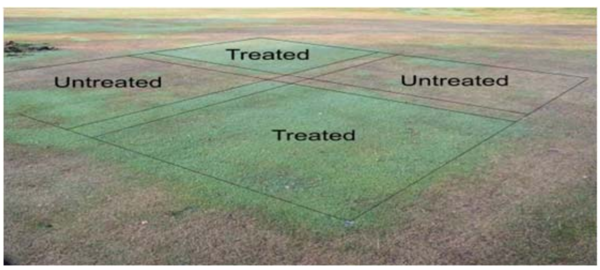

Figure 8) Differences in grass performance between two surfactant treated and two untreated plots on a water repellent sandy fairway [85]

The water repellency phenomenon is most pronounced in coarse-textured soils and is common in sandy soils supporting turf or pasture [8, 83]. It results in ongoing management problems on sand-based turfgrass systems. Over the past 20 years, a major shift has occurred in how turfgrass managers deal with soil water repellency.

Initially, water management's strategies focussed solely on remediating localized dry spots, the visible effects of hydrophobic soils. Research during the last decades resulted in not only a better understanding of the implications of this phenomenon on soil hydraulic properties and plant productivity, but also the development of new strategies, particularly surfactants to improve water capture, reduce preferential flow, increase irrigation and water use efficiency, and reduce leaching of nitrogen [83, 84]. Turfgrass on treated sites appears to have a much better and more uniform quality and shows darker green leaves than found on untreated plots. It is hypothesized that observed positive effects of regular surfactant treatments are caused by the combined effect of improved water availability for the grass, as well as increased nitrogen (N) availability. The decrease in soil water availability decreases microbial mobility and growth, which in turn is responsible for promoting N mineralization [85].

Further studies are required to examine the extent to which soil water repellency affects runoff generation and soil erosion under rainfalls of different intensities and spatial scales.

Limitation of this research included lack of sufficient information on microscopic studies and their relationship with soil erodibility.

Conclusion

Under certain conditions, soil can become water repellent, causing changes in hydrological behaviour and affecting water and solute use, plant growth, and the risk of environmental contamination. Once it is all green again, we forget it until next time. Soil water repellency can be caused by a variety of compounds and processes and generally occurs after a period of drying weather. Under such conditions, the soil can change from a wettable to a water-repellent state when dried below its critical soil water content.

Soil water repellency is found to occur in different soils worldwide, ranging from coarse to fine-textured. Water repellency in soils is currently receiving increased attention from scientists and practitioners, because it can result in losses of plant-available water, reduced agricultural crop production, and deterioration of turf quality on sports fields.

Despite substantial research and the significant implications for productivity and management of soils, actual soil water repellency and critical soil water content are still not regularly assessed in soil analyses or surveys. Above the critical soil water content, a soil behaves as a wettable porous medium and below as a water repellent one. This change in state of the soil affects flow and transport processes drastically, leading to a completely different hydrological behaviour for wettable versus water repellent soils.

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