A Brief Overview of the Causes, Impacts and Amelioration of Soil Water Repellency – a Review

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Abstract: This article describes the phenomenon of soil water repellency, starting from the fundamental principals of water transport and storage in soil. Soil water repellency is a reduction in the rate of wetting and retention of water in soil caused by the presence of hydrophobic coatings on soil particles. For crop production and the maintenance of amenity turf, water repellency can stress plants resulting in poorer yield quality or grass 'playability', respectively. The biological causes of water repellency, primarily the influence of fungi, will be discussed, as an understanding of the source of the problem will be beneficial in developing solutions. Exacerbation of repellency through climate change and the use of 'engineered' soils for amenity surfaces will be demonstrated using research findings from around the globe. In developing solutions to soil water repellency, its positive benefits, if maintained at very low levels, need to be considered. Water repellency is a key process in the physical stabilisation of soil and its impact on evaporation also needs to be considered. Before developing a rapid solution to repellency based only on water transport rates, a holistic understanding of the impacts on soil water relations is essential.

Keywords: soil; water repellency; hydrophobicity; agriculture; land management; water shortages

No resource will be more precious to agriculture in the future than water. Past exploitation has depleted global reserves of water considerably and predictions of climate change suggest that the proportion of water supplied to agriculture by precipitation is declining (Foster & Chilton 2003). The potential implications to mankind are cataclysmic, as decreased food production on our already vulnerable soils will place increasing stress on a growing global population (Tilman *et al.* 2002).

A short-term solution to less available precipitation is greater irrigation. Apart from the obvious limitation of the amount of available water from precipitation and freshwater reserves (acquifers, rivers etc.), greater drying of soils is making them less able to retain water (Doerr *et al.* 2006). Drying accentuates the movement of organic solutes to soil surfaces and if a critical water content is reached, a water repellent barrier can form that limits the rate and capacity of water absorption (Wallis & Horne 1992; Ritsema & Dekker 1996). In some arid regions, water repellency has become so bad that agricultural production is impossible without costly amelioration (Roper 2005). In other regions of the world, water repellency occurs to a lesser extent, but its management with wetting agents has been shown to increase crop yields (Crabtree & Henderson 1999) and reduce the impact of diseases (McDonald *et al.* 2006).

There is great scope to develop amelioration strategies to combat water repellency. These include more effective soil management, the addition of clays to increase particle surface area, tillage to break-up and abrade hydrophobic surfaces and the use of chemical wetting agents (Wallis

& Horne 1992). Wetting agents are already used extensively in horticulture and their use in agriculture is increasing (Feng *et al.* 2002; Hopkins & Cook 2005). More expensive wetting agents are also used extensively for improving water infiltration and retention in amenity soils (Mitra *et al.* 2006). As the cost of water increases, the use of wetting agents in larger scale agricultural operations will become more attractive.

The phenomenon of water repellency and its amelioration are discussed in this article. After a short overview of impending shortages to the global water resource, the physical processes governing water transport and retention in soil are described. This provides the basics for a description of the development of water repellency and the techniques used for its measurement. The causes of water repellency are then reviewed, concentrating on biological processes. Finally the overall occurrence of water repellency and the current use of wetting agents are reviewed. This article provides only a brief overview of water repellency as considerable research has been conducted in this area. Readers interested in learning more are recommended to read the comprehensive review articles by Wallis and Horne (1992), DeBano (2000) or the more recent scientific articles in the reference list.

Soil and water

How precious is our water resource for agriculture?

Groundwater reserves have been exploited extensively over the past 50 years to provide water for agriculture and urban consumption (Foster & Chilton 2003). A shortage of usable groundwater has arisen not only because of the depletion of reserves but also salinisation and pollution. As the amount of water that can be exploited is declining, climate change models predict that soils will be much drier in summer months by 2070, particularly in northern temperate latitudes (Gerten *et al.* 2007).

When writing this article, the feature article on the front page of the World Bank website (www.worldbank.org) was titled: 'Making the most of scarcity – the global water challenge'. It is not surprising that politicians and international agencies are now extremely concerned about water. Globally, a staggering 45% of crops are produced on the 16% of agricultural land that is irrigated (Tilman *et al.* 2002). Agriculture consumes over 85% of water in the Middle East. About 20% of the irrigated land in the U.S. is supplied by groundwater pumped in excess of recharge. This problem is far worse in China, India and Bangladesh, which is home to almost half of the world's population (Tilman *et al.* 2002).

How does water move through soil?

Water moves through soil because of gradients in water content or gravity. Usually when water infiltration is measured it is based on the volume of water that passes through a given area of soil in a defined time. So when reporting values of water transport the following units arise:

$$\frac{m^3/m^2}{s} = m/s \qquad (1)$$

The change in soil water content, θ with time, *t* can be described theoretically with the convective-dispersion equation

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial s}\left(D\frac{\partial\theta}{\partial s}\right) + \frac{\partial}{\partial s}\left(k\frac{\partial z}{\partial s}\right) \qquad (2)$$

where:

s – distance

z – pressure head

This equation is based on the effects of gradients in water content, measured as diffusivity, *D* and gravity measured as hydraulic conductivity, *k* on water transport.

Eq. (2) is so complex that no general analytical solution exists to allow its use in practice. Philip (1957) observed the typical trends in infiltration, *I* versus *t*, which is illustrated in Figure 1. At the onset of wetting, the moisture gradient is greatest, hence more rapid infiltration. With time, the infiltration rate slows. The shape of the curve in Figure 1 can be fitted using the relationship,

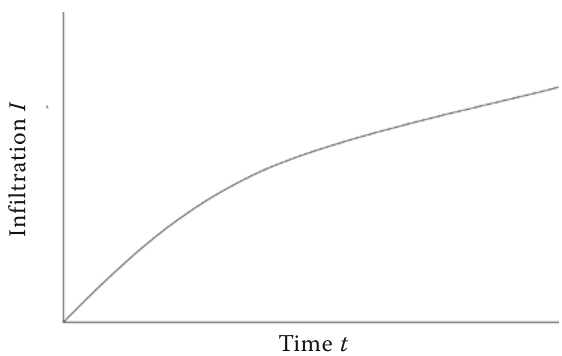

Figure 1. Typical shape of infiltration versus time relationship for soil

$$I = St^{1/2} + At + Bt^{3/2} + Ct^2 + \ldots \quad (3)$$

where:
S, A, B and C – fitting parameters

For the short times typical of infiltration, only the first two parameters are needed, so the equation can be shortened to

$$I = St^{1/2} + At \quad (4)$$

If I is plotted against $t^{1/2}$ then a linear relationship is usually found for the first 1 to 3 minutes of infiltration (i.e. the steep part of the curve at early time). This time range defines the soil sorptivity, which can be measured as S and has units m s$^{-1/2}$. The parameter A is related to the hydraulic conductivity of the soil.

Sorptivity is the capacity of soil to 'suck' up water and is dominated by the antecedent water content of the soil. A dry soil typically has a much greater sorptivity than a wet soil. Both hydraulic conductivity and sorptivity are controlled by the shape, volume and tortuosity of pores in the soil. Generally a soil with larger pores has a greater hydraulic conductivity but smaller sorptivity than a soil with smaller pores.

Capillarity

Water is held in soil by cohesive and adhesive capillary forces. Cohesion occurs because water-water bonds are stronger than water-air bonds. Adhesion is the bonding of water to solid surfaces. An ideal diagram of water in a capillary tube is shown in Figure 2. Capillary rise, z is based on the relationship,

$$z = \frac{2\gamma}{r} \quad (5)$$

where:
γ – surface tension and
r – pore radius; the smaller the pore, the greater the capillary rise

As soil dries out, increasing suction occurs as smaller and smaller pores are emptied. When plants wilt and die at 1500 kPa suction, only a thin layer of water exists on soil particles.

Water Repellency

In an extremely water repellent soil, sorptivity and capillary rise will be 0. Drops of water will form on the soil surface and they will often evaporate before infiltrating. A distinctive contact angle, θ forms between the drop of water and soil surface, which for water repellent soils is > 90° (Figure 3). Typically in soil physics, it was assumed that θ was 0 and did not need to be considered when estimating transport and capillarity. Tilman *et al.* (1989) demonstrated that most soils have a certain level of water resistance, where water will infiltrate but at a slower rate than expected. These soils have contact angles between 0° and 90°.

The concepts of sorptivity and capillarity described above can be modified to account for contact angle. Philip (1957) defined intrinsic sorptivity, S_i, as

$$S = S_i \cos(\theta) \quad (6)$$

For a totally non-repellent soil, $S = S_i$ as cos(0°) is 1. Capillarity can also account for θ by modifying Eq. (5) to

$$z = \frac{2\gamma \cos(\theta)}{r} \quad (7)$$

A contact angle of 30° is not uncommon in soils (Woche *et al.* 2005) and this represents a greater

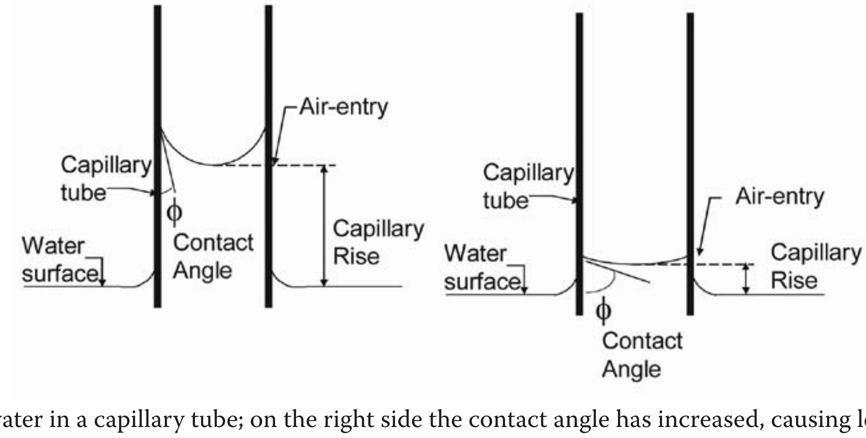

Figure 2. Rise of water in a capillary tube; on the right side the contact angle has increased, causing less capillary rise

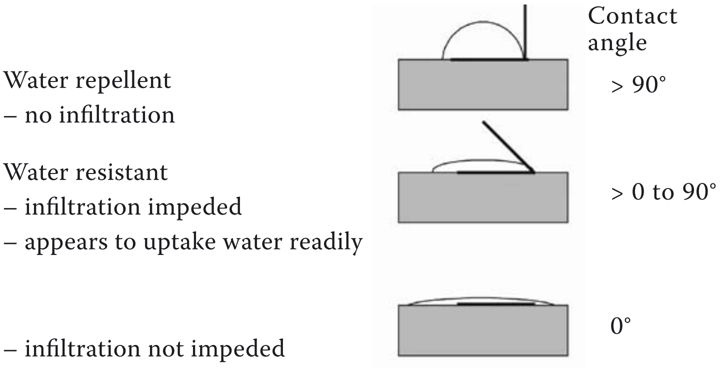

Figure 3. Forms of water repellency in soil based on the contact angle between water and soil

than 6-fold drop in sorptivity and capillarity rise. Of major importance to crop production or the quality of amenity turf is the capacity of soil to retain water. Figure 4 illustrates the potential drop in water content for a given suction caused by repellency. This results because pores in repellent soil drain at smaller suctions than is the case for a non-repellent soil, thus reducing the amount of water stored that can be accessed by plant roots.

Measuring water repellency

Numerous techniques have been developed to determine the water repellency of soil. The most common method is the water drop penetration time (WDPT) test, which is based on the time taken for a drop of water to infiltrate into soil (Dekker *et al.* 1998). This test can be set up easily and conducted in the field; something particularly useful if you want to demonstrate the occurrence of water repellency. The molarity of ethanol droplet (MED) test is an extension of the WDPT test (DeBano 2000) and uses different concentrations of ethanol to alter the surface tension of the liquid. Extending on this concept is the intrinsic sorptivity method developed by Tillman *et al.* (1989), where the sorptivity of water (influenced by repellency) is compared to the sorptivity of ethanol (not influenced by repellency) to obtain an index of water repellency. Probably the most physically meaningful measurement is a direct measurement of contact angle by the capillary rise method (Woche *et al.* 2005). However, intact samples can not be tested with this approach. The advantages and disadvantages of the various approaches are listed in Table 1 below.

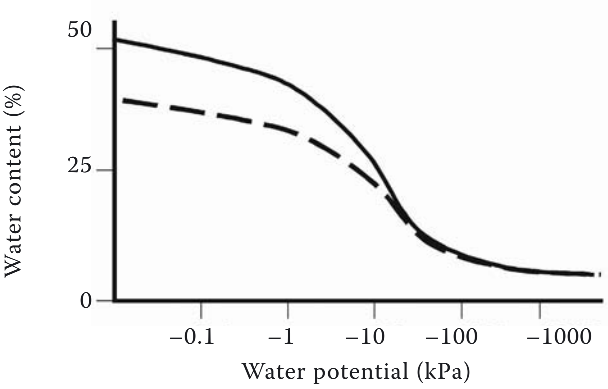

Figure 4. Drop in water retention of a soil caused by water repellency

The origin of repellency

Potentially hydrophobic organic materials are produced by; plant root exudates, certain fungal species, surface waxes from plant leaves, and decomposing soil organic matter (Figure 5; Mainwaring *et al.* 2004; Hallett *et al.* 2006). Exudates are produced by plant roots and some soil microbes to enhance nutrient availability and defend against desiccation stresses (Hallett *et al.* 2003). They are strongly hydrophilic when wet, but below a critical moisture threshold, the hydrophilic surfaces bond strongly with each other and soil particles, leaving an exposed hydrophobic surface (Figure 6; Dekker *et al.* 1998). If a soil prone to water repellency dries to less than a critical water content, its behaviour can shift abruptly from wettable to non-wettable (Dekker *et al.* 2001). Prolonged wetting can reverse this, resulting in water repellent soils regaining wettability (Clothier *et al.* 2000).

The level of repellency depends on the proportion of soil particles with a hydrophobic surface coating (Doerr *et al.* 2006). This is influenced by the surface area of the soil, which varies considerably with soil texture. Sandy soils have the lowest surface area, so a hydrophobic surface will impact

Table 1. The different approaches used to measure the water repellency of soil

Test	Advantages	Disadvantages
Contact angle "capillary rise"	physically meaningful in theory	time-consuming, affected by surface roughness
Intrinsic sorptivity or repellency index, *R*	physically meaningful	difficult to conduct test, interaction between ethanol and soil may influence results
Molarity of an ethanol droplet (MED)	quick and easy (10 s per test) related to contact angle	physical meaning requires greater investigation
Water drop penetration time (WDPT)	easy	no physical meaning, takes considerable time in repellent soil

a larger proportion of particles than for a loamy or clayey soil where the surface area is up to 3 orders of magnitude greater (Woche *et al.* 2005). As many amenity soils, particularly golf greens, are constructed from sandy soils, they are very prone to the development of water repellency (Cisar *et al.* 2000). These soils also provide a better habitat for fungi than bacteria because the small particle surface area and pore size distribution provides poor bacterial habitat (Hallett *et al.* 2001a).

Although the evidence is mixed, fungi are generally thought to be the prime cause of water repellency in soil. The first scientific study showing this link was over 40 years ago by Bond (1964) and more recent work has identified the role of individual fungal species (Hallett *et al.* 2006). On golf course soils, York and Canaway (2000) showed a direct link between the presence of basidiomycetes fungi and the development of fairy rings. Feeney *et al.* (2006a) found a strong relationship between fungal biomass and water repellency in an agricultural soil. However, this could not be simulated in a study that controlled fungal biomass with biocides in the laboratory (Feeney *et al.* 2006b). The area of soil around plant roots, generally referred to as the rhizosphere, has

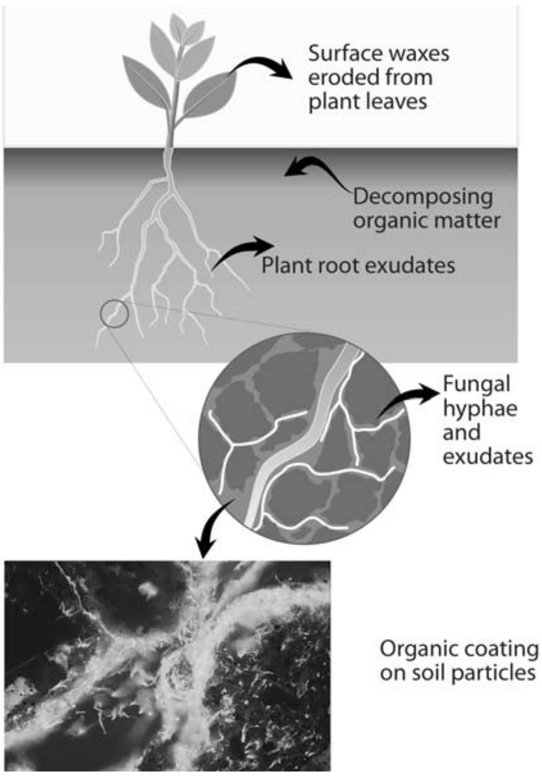

Figure 5. The origin of water repellency from micobiota and decomposing organic matter in soil

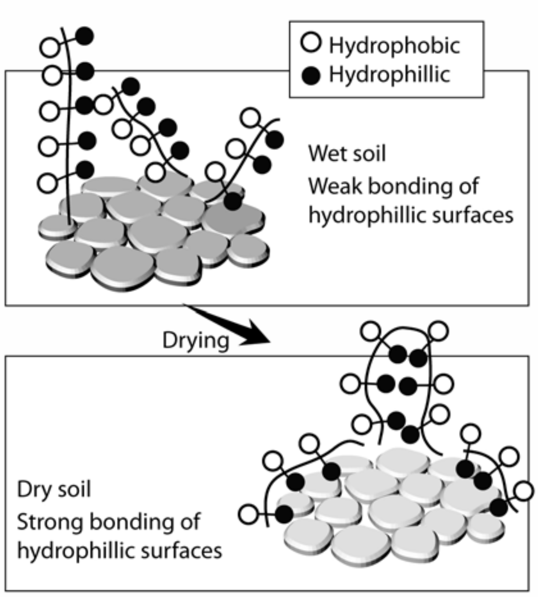

Figure 6. The transient nature of water repellency caused by hydrophilic-hydrophillic and hydrophilic-surface bonding during drying

also been shown to have greater levels of water repellency than bulk soil (Hallett *et al.* 2003). Specific compounds produced by plant roots have been shown to induce water repellency (Czarnes *et al.* 2000), but the effects could also be due to secondary microbial metabolites from root exudate decomposition.

Links between hydrophobic compounds in soil and the development of water repellency have not been convincing. Whilst Mainwaring *et al.* (2004) detected a greater abundance of high molecular mass polar compounds in water repellent soils, adding these compounds to wettable soils did not necessarily induce repellency (Morley *et al.* 2003). There is growing interest in the compound glomalin in soil science as its highly adhesive and hydrophobic properties are hypothesised to be a major driver in pore structure stability (Wright & Upadhyaya 1998). However, work by Feeney *et al.* (2004) showed that it was poorly related to water repellency. Capriel (1997) suggested using Diffuse-Reflectance Infrared Fourier Transform (DRIFT) Spectroscopy to detect hydrophobic compounds in soil. Again, links between DRIFT and actual measurements of water repellency are unconvincing (Doerr *et al.* 2005).

Although considerable advances have been made in the past 10 years in understanding the impact of hydrophobic organic compounds on water repellency, there is still a considerable amount to be learnt. Of particular importance is the interaction between surface coverage and the hydration status of organic compounds (Doerr *et al.* 2000). Current research investigating the chemistry of hydrophobic compounds in soil will also help understanding considerably (Piccolo & Mbagwu 1999; Mainwaring *et al.* 2004). Of particular usefulness is associated research from industrial biochemistry which has detected highly surface active hydrophobins produced by fungi (Hakanpaa *et al.* 2004) that probably play a dominant role in the water repellency of soil (Rillig 2005).

Occurrence of water repellency

Severe soil water repellency is widespread and affects land used for; agriculture, amenity surfaces such as parks and golf courses, and coastal dune sands (Wallis & Horne 1992; Doerr *et al.* 2006). One of the most problematic areas is south-western Australia where over 2 million ha is affected (Franco *et al.* 2000). This soil is used for agriculture, but yields are low unless costly amelioration strategies are employed. Increased use of effluent water is increasing levels of water repellency in some arid regions that are reliant on irrigation (Wallach *et al.* 2005). In amenity surfaces, particularly golf courses where engineered sandy soils have a small surface area, multi-million dollar businesses have developed to provide wetting agents to overcome water repellency (Kostka 2000).

Tillman *et al.* (1989) introduced the concept of 'subcritical' water repellent soil, where water infiltration is impeded by repellency despite the soil appearing to wet readily. This will be referred to a 'water resistance' from herein and it is expected to influence almost all surface soils (Woche *et al.* 2005). Water resistance in agricultural soils has been studied extensively by Hallett *et al.* (2001b) where it has been detected in the unlikely environment of Scotland. Research in drier climates has detected greater levels of water resistance (Wallis & Horne 1992; Doerr *et al.* 2000).

Amelioration of water repellency

Physical, chemical and biological approaches exist to ameliorate soil water repellency. In the vast regions of south-eastern Australia which have large areas of infertile soils incapable of retaining water for much of the year, farmers have tried a range of options. A potential biological solution is to increase populations of wax-degrading bacteria that consume hydrophobic compounds (Roper 2006). Tillage of soil is a physical solution as the abrasion of particles by farm implements can remove hydrophobic coatings from soil surfaces (Buczko *et al.* 2006). It is also possible to increase the surface area of soil by adding clay as an amelioration strategy (Wallis & Horne 1992; Lichner *et al.* 2002), although the costs are prohibitive without a local source of clay.

Wetting agents provide the most immediate solution to combating water repellency and in water resistant soils they have been shown to have positive impacts on crop yield and quality. Early research has found convincing positive impacts of wetting agents on hydraulic properties of agricultural soils (bu-Zreig *et al.* 2003), which is backed by considerable research on sandy amenity soils (Mitra *et al.* 2006). At present there are numerous wetting agents marketed specifically for agricultural production. Some of these compounds are detergents that alter the surface tension of irrigation water, usually with short-term positive impacts. More complex wetting agents used in irrigated potatoes have increased yields by up to 20% and improved tuber quality (Hopkins & Cook 2005) and probably have longer-term positive impacts on overall yield and quality.

Before the widespread adoption of wetting agents is encouraged, the wider environmental implications of eliminating repellency need to be assessed. Hydrophobicity is important to the structural stability of soils (von Lutzow *et al.* 2006), so enhanced water uptake following the application of a wetting agent might result in greater slaking of soil. However, if wetting agents prevent drying of soil, they may reduce the extent of slaking stresses. Preferential flow is enhanced by repellency and increases leaching of agrochemicals to groundwater (Taumer *et al.* 2006). Erosion is also enhanced by the repellency of surface soils (Pires *et al.* 2006). Wetting agents may therefore have positive impacts on chemical leaching and erosion.

Although wetting agents may improve water infiltration and retention, they may also increase the amount of evaporation from bare soil. Bachmann *et al.* (2001) provided direct evidence of less evaporation from water repellent soils. Given that water repellency decreases with depth (Woche *et al.* 2005), a more hydrophobic layer of soil at the surface could form a capillary barrier that reduces evaporation. Research is needed to investigate (1) the potential implications to water budgets if wetting agents are applied and (2) whether a hydrophobic capillary barrier at the soil surface could be a viable method to reduce overall evaporation. It is probable that improved water distribution with wetting agents and reduced preferential flow, would more than off-set any negative impact from evaporation, but it would be worth investigating.

SUMMARY

Given the rising costs and depleting reserves of water, combined with predictions of less rainfall, considerable scope exists to understand the potential implication of soil water repellency. As water becomes more valuable, effluent water rich in organic compounds is used increasingly in arid regions. Climate change may also increase repellency as soils become drier in the summer.

The significance of water repellency to agricultural production is increasingly recognised and changes in water and climate will probably increase the problem considerably. Before wetting agents are employed to address water repellency, however, the potential implications for soil structural stability, water budgets and evaporation need to be assessed.

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