Plant root and microbial derived soil water repellency

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Plant roots and soil microbes have a massive influence on the physical properties of soil. The exudates and cellular biomass that they produce are active in binding together soil particles, thereby creating an aggregated structure that is superior for crop productivity and environmental buffering. These compounds are therefore an essential component of soil sustainability. Some exudates and biomass coat soil particles with films that alter surface properties considerably. One potential consequence is a hydrophobic surface that induces water repellency, thus influencing water transport and retention in soil.

Until recently, water repellency was assumed to affect a small percentage of the world's soil resources, and to be insignificant in the UK. In extreme instances, the soil is rendered infertile because repellency prohibits the uptake and retention of water that is essential for plant growth. The land area affected by this problem tends to have a sandy soil texture or be located in warm climates. In the UK, this problem is found predominantly on engineered sports-turf. Our research programme on biological and physical interactions in soil, however, has identified that repellency at much lower levels is commonplace in most soils. We believe that this property of soil is paramount in causing the preferential flow of water and pollutants, and also an essential component of soil pore structure stability.

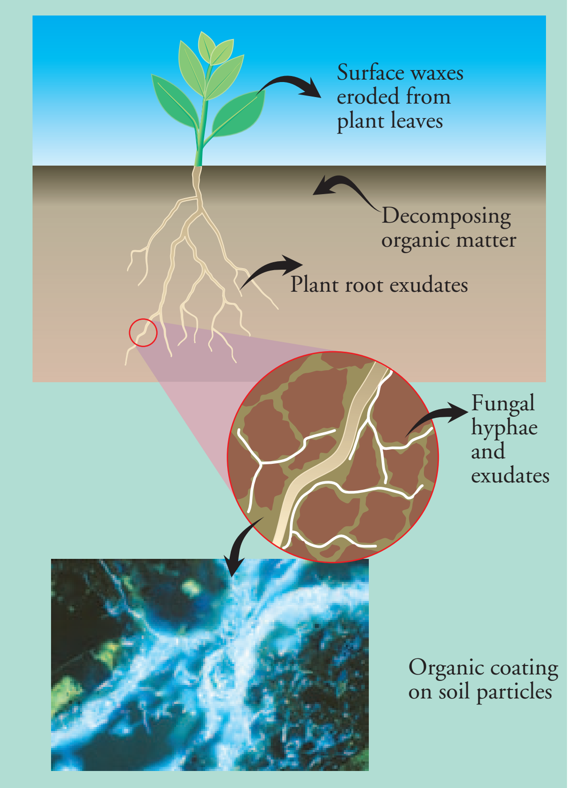

Figure 1 The biological origin of water repellency in soil. The image showing the organic coating on soil particles in a soil thin section with the carbohydrates stained with fluorescent dye.

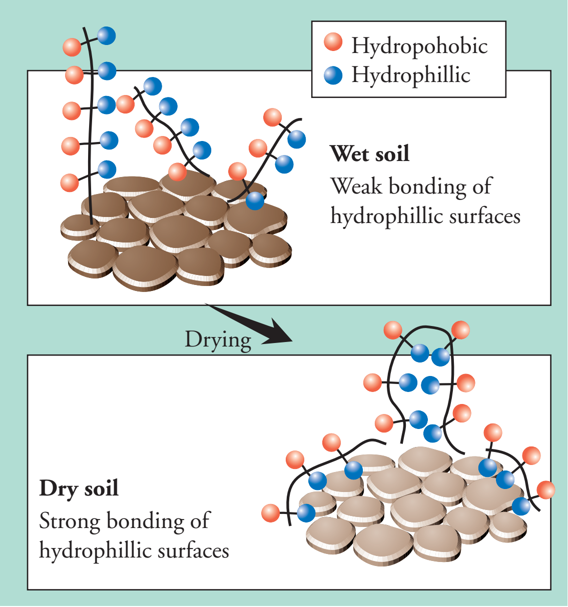

Figure 2 The change of hydrophilic compounds to hydrophobic surface coatings in soil caused by drying. After prolonged wetting, the hydrophilic nature of these chemicals will be recovered.

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 (Fig. 1). Exudates are produced by plant roots and some soil microbes to enhance nutrient availability and defend against desiccation stresses. 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 (Fig. 2). The

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Figure 3 Device that allows the direct measurement of water transport properties of soil and repellency, at hitherto unattainable spatial scales.

level of repellency depends on the proportion of soil particles with a hydrophobic surface coating.

Measuring repellency

Various techniques exist for measuring soil water repellency, but they are only effective when the levels are quite high and some techniques are too crude to provide physically meaningful results. We have developed a highly sensitive testing technique that uses the fundamental properties of soil hydraulic transport to provide a quantified measure of repellency. A miniature infiltrometer probe (Fig. 3) is used to assess wetting rates from which sorptivity (i.e. the physical measurement of liquid absorption by soil) is evaluated on samples as small as a few millimetres in diameter. From these data, a repellency index, *R*, is obtained by comparing the sorptivity of water to ethanol. *R* is directly proportional to the reduction in water transport caused by repellency. If *R* is 5, for instance, repellency causes a five-fold decrease in water transport rates.

Linking soil biology to repellency

Research examining repellency levels in soil is considerable, but very little of this work has investigated its biological origin. Our first experiments, therefore, were devised to verify whether or not repellency could be induced by biological activity. We found that relatively high levels of water repellency could be created by stimulating the biological community in soil with simple sugars (10 mg C g^{-1} soil) and micronutrients. Subsequent, more detailed, work involved investigations of the effects of fertilizer application in the field, cultivation methods and specific organisms.

The addition of fertilizer to soil has obvious benefits for crop productivity, but its stimulation of both plant growth and microbial activity may also affect soil physical properties. As part of a detailed investigation linking biological and physical properties of soil under different levels of nitrogen fertilizer, we found that, after one growing season, 120 kg/ha of added nitrogen increased the repellency index, *R*, from 4.5 to 6.5 in a no-till cultivation experimental site maintained by the Scottish Agricultural College (Beechgrove Field, Penicuik). These levels of repellency are very low, and undetectable using conventional techniques. They will influence soil stability because a major disruption mechanism in soil is slaking caused by air-pressure build up in advance of wetting fronts. If the build up of air-pressure is sufficiently high, the soil explodes and the aggregated structure is lost. The difference in *R* values suggests a 45% drop in air-pressure build up due to repellency alone when a high level of fertilizer is applied. Soil stability is examined in most soil management studies, but this is the first instance where repellency has been isolated as one of the fundamental stabilising mechanisms. A negative implication of this result is that repellency induces preferential flow pathways. This may provide a rapid transport pathway for environmentally sensitive solutes, such as nitrate or pesticides, to groundwater.

Intensive cultivation causes death and destruction to parts of the microbial community in soils. It can also deplete organic carbon levels *via* an enhancement of the degradation of otherwise physically-protected organic matter. On studies at several experimental sites in Europe, ploughed soil had lower *R* levels than adjacent undisturbed soil (Fig. 4). The only exception was pasture soil at the Beechgrove site mentioned previously, where the *R* value was the lowest. Currently, we are investigating the underlying mechanisms that could account for this result. The lower repellency levels that were found generally in the disturbed soil suggests that it will be more susceptible to disruption by slaking, thereby loosing its aggregated structure soon after tillage. This phenomenon is a widespread problem in agricultural soil, causing reduced plant productivity and pollutant buffering.

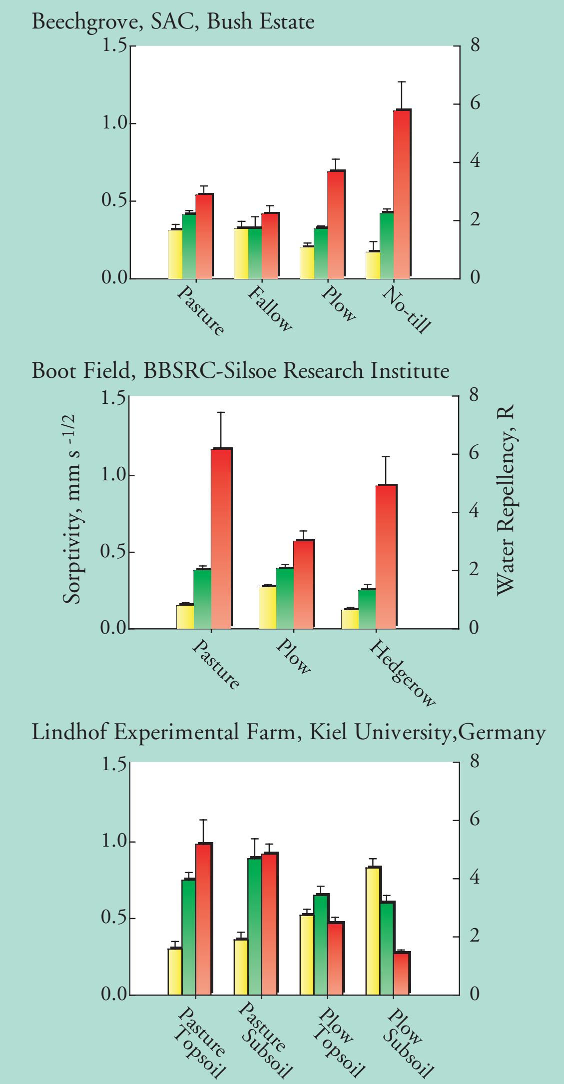

Figure 4 Cultivation effects on water sorptivity (yellow), ethanol sorptivity (green) and water repellency (red) for a range of soils. Water sorptivity is a basic transport property of soil, so these results can be used directly in models to predict and describe water flow properties. Ethanol sorptivity is not affected by hydrophobic substances, so it can be used to assess the structure of transmission pathways in soil. The repellency levels, R, are high enough to buffer wetting stresses that cause soil slaking, but are too low to impede water availability to plants.

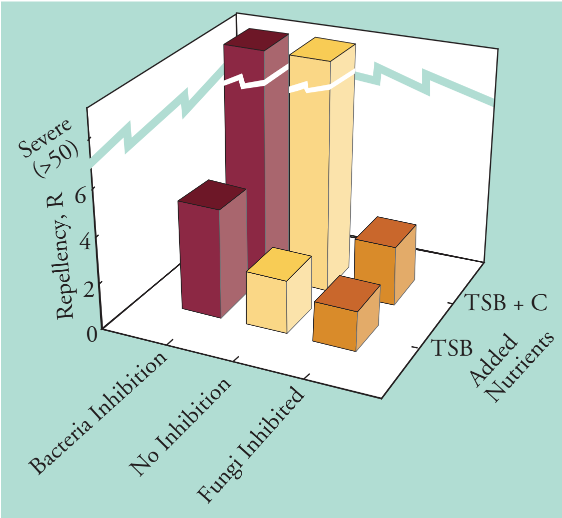

Figure 5 Assessing the microbial groups responsible for repellency. The soil is from a golf course and has been amended with nutrients to stimulate the native microbial community; TSB refers to Tryptone Soya Broth (2 mg carbon g^{-1} soil), and C refers to glucose (18 mg carbon g^{-1} soil). Fungal and bacterial growth are suppressed using the biocides cycloheximide and streptomycin respectively.

The effect of different microbial groups has been studied using biocides to suppress the growth of either fungi or bacteria in soil (Fig. 5). This work confirmed previous speculation that fungi are the dominant microbial group that causes repellency. It also showed that suppressing competition from bacteria caused a higher level of repellency to develop. There are potential applications of this research for the biological control of the organisms that cause repellency by manipulating the microbial community structure. The results presented are for a golf course soil where repellency is a major problem. Treatment costs in the UK alone are about 10 000 000 Euros. We have continued this research to investigate the effect of specific fungal species on repellency.

Linking repellency to preferential flow

Repellency causes water flow through preferential pathways in soil. This limits the soil volume available for pollutant buffering and increases the erosive effect of water across soil surfaces. We measured the spatial distribution of repellency and water flow on the surface of a large slab of grassland soil from south-east Scotland to investigate preferential flow. Our work was unique for two reasons. It was the first where low levels of repellency were measured alongside water transport. Also, the size of our infiltrometer is the smallest in existence, thus permitting sampling on a 50 mm grid, the highest resolution ever recorded for direct water flow measurements in soil.

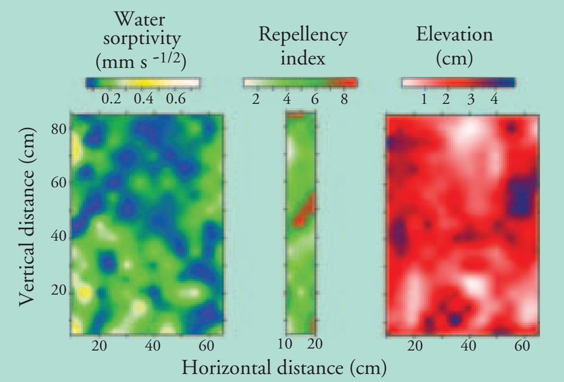

Figure 6 The spatial distribution of water sorptivity, repellency and elevation measured in a 50 mm square grid on an intact block of soil. Patches of low water sorptivity will induce preferential flow pathways that accentuate erosion. These areas are closely linked to areas of higher repellency.

Figure 6 shows the spatial distribution of water sorptivity (i.e. wetting rate), repellency, and elevation. There are some distinctive areas where water sorptivity is impeded severely by repellency. These regions will enhance the overland flow of water, increasing its erosive effect on soil and potentially providing a nucleus for gully formation. Soil erosion is known to be highly problematic where severe levels of water repellency exist. The soil we examined had a very low level of repellency and, like most soils, appeared to take water up readily. Nevertheless, repellency will still influence the development of water channels that enhance erosion. This effect was not known previously. Enhanced overland flow due to repellency, particularly after dry periods, may also increase the risk of flooding.

Future prospects

Our research on repellency is seeking to quantify one of the fundamental mechanisms imparted by plants and microorganisms on the formation of soil structure and water transport. We have shown so far that low levels of repellency occur in most soils, and that these levels are susceptible to physical disruption by tillage and the stimulation of organisms by added nutrients. Some of the research discussed is from larger research projects, where the microbiological properties of the soil are being described in detail.

We have already started to link repellency with other biological mechanisms involved in the formation of soil structure. The common perception is that exudates influence structure primarily by binding soil particles. By studying different exudates of biological origin, we have found certain exudates that impart repellency to be far better at stabilising soil against disruptive stresses.

The research has already isolated a previously ignored physical property of soil that has implications for soil structure dynamics and the development of preferential flow pathways. We want to exploit repellency, so that soil physical structure can be improved by prescribing appropriate plant cultivars and stimulating soil microorganisms that are superior in producing stabilising exudates. This has applications in land regeneration and is an essential component of soil sustainability. In this instance, repellency levels would be too low to affect the plant availability of water (R<5). High levels of repellency, R>50, present a problem to UK sports turf, and in other regions (e.g. Australia) impede agricultural production across very large areas. By understanding the biological origin of this problem, we will help to develop control strategies that do not require the costly application of chemical surfactants.