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Patterns of soil water repellency change with wetting and drying: the influence of cracks, roots and drainage conditions

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Abstract

Laboratory experiments were used to investigate the influence of simulated cracks and roots on soil water repellency (SWR) dynamics with and without basal drainage impedance in wetting-drying cycles. Observations and measurements were taken following water application equivalent to 9.2 mm rainfall and then periodically during 80 hours of drying. In total, 180 experiments were carried out using 60 samples of three homogeneous, reconstituted soils with different organic matter contents and textures, but of similar initial severity of soil water repellency (18% Molarity of an Ethanol Droplet (MED)). Water flowing down the cracks and roots left the soil matrix largely dry and water-repellent except for vertical zones adjacent to them and a shallow surface layer. A hydrophilic shallow basal layer was produced in experiments where basal drainage was impeded. During drying, changes in SWR were largely confined to the zones that had been wetted. Soil that had remained dry retained the initial severity of SWR, while wetted soil re-established either the same or a slightly lower severity of SWR. In organic-rich soil the scale of recovery to pre-wetting MED levels was much higher, perhaps associated with temporarily raised levels (up to 36% MED) of SWR recorded during drying of these soils. With all three soils the re-establishment of the original SWR level was less widespread for surface than subsurface soil and with impeded than unimpeded basal drainage.

Key findings are that: (1) with unimpeded basal drainage, the soils remained at pre-wetting repellency levels except for a wettable thin surface layer and zones close to roots and cracks; (2) basal drainage impedance produced hydrophilic basal and surface layers; (3) thorough wetting delayed a return to water-repellent conditions on drying; and (4) temporarily enhanced SWR occurred in organic-rich soils at intermediate moisture levels during drying. Hydrological implications are discussed and the roles of cracks and roots are placed into context with other influences on preferential flow and SWR under field conditions.

Keywords: soil water-repellency, soil hydrophobicity, preferential flow, wetting and drying, cracks and root-holes

Introduction

Soil water-repellency (SWR) is common in a wide range of climates and soil types (e.g. Doerr *et al.*, 2000; Dekker *et al.*, 2005) and ranges in intensity from slight, where infiltration is delayed for a few seconds or minutes, to extreme, where water may fail to infiltrate for hours or days (Doerr *et al.*, 2000). The most important hydrological effects of SWR are overland flow which can enhance erosion and flooding (Shakesby *et al.*, 2000; Pierson *et al.*, 2009); and increased preferential flow, which can result in non-uniform soil moisture distribution causing problems with seed germination, plant growth and groundwater contamination (Doerr et al., 2000; Madsen et al., 2011; Müller *et al.*, 2014). These effects tend to be most pronounced in storms following prolonged dry, warm conditions when the soil is below a threshold moisture content and at its highest SWR severity, and absent in wetter conditions when the soil moisture threshold is exceeded and SWR disappears (Doerr and Thomas, 2000; Vogelmann *et al.*, 2013).

Several studies identified the need for research into temporal changes of SWR and the underlying principles of the transition between the water-repellent (hydrophobic) and wettable (hydrophilic) soil (Doerr and Thomas, 2000; DeBano 2000). Field studies of the transition by Leighton-Boyce *et al.* (2005), Buczko *et al.* (2005, 2006) and Stoof *et al.* (2011) recording spatio-temporal changes in SWR have demonstrated that changes between water-repellent and wettable states can range from a few days to a few weeks depending on various environmental conditions, ecosystems and soil types. In Portugal Stoof *et al.* (2011) have shown that the transition is accompanied by spatial variability of SWR, which is highest in late autumn and spring before soil changes to a more uniform wettable or water-repellent state in winter and summer respectively. Exactly how and when transitions occur and the nature of their hydrological impact remain unclear.

Enhanced overland flow might be anticipated under extreme SWR conditions, especially following heavy rainfall (Schnabel *et al.*, 2013), but if there are preferential flow paths present in the soil (Ritsema and Dekker, 2000; Doerr *et al*., 2000; Shakesby *et al*. 2000), most rainfall might be transferred below any near-surface repellent layer, such that the impact of SWR on overland flow might be barely detectable. Preferential flow has been attributed to wettable soil patches (Dekker and Ritsema, 2000), a high density of stones (Urbanek and Shakesby, 2009), faunal burrows (Walsh *et al*., 1995; Ferreira *et al*., 1997, 1998; Shakesby *et al*., 2007) but most commonly to roots and soil cracks (Dekker and Ritsema, 1996; Kobayashi and Shimizu, 2007). Potentially, these latter two flow paths could hold the key to understanding the patterns of breakdown and recovery of SWR under wetting and drying conditions. To date, however, there has been only limited investigation of the influence of preferential flow in roots or cracks on the SWR patterns in the surrounding soil. Using a dye tracer Kobayashi and Shimizu (2007) applied simulated rainfall to repellent soil and found that wettable conditions spread outwards from preferential flow paths provided by roots. No detailed investigation, however, has been made of partial wetting or drying and how it affects the spatial variability of SWR. In addition, much of the behaviour of water-repellent soil has been interpreted from studies carried out on thin soil overlying impermeable bedrock in the Mediterranean, which raises the question as to how basal impedance to percolating water might affect the wetting and drying behaviour of soil and SWR dynamics.

The present study addresses three research questions: (1) how does water in soil cracks and root holes influence the three-dimensional dynamics of water-repellency of surrounding soil?; (2) what is the influence of basal drainage impedance and its absence on these dynamics?; and (3) what are the short- and medium-term temporal changes in SWR resulting from a simulated rainfall event (minutes) and several days (80 hours) of drying? Given that many features (e.g. soil structural elements, soil faunal activity) in natural soil could affect the changes from wettable to water-repellent conditions and *vice versa*, it was considered important to isolate as much as possible the effects of soil cracks and root holes by conducting the experiments in the laboratory where other features could be eliminated or held constant.

Methodology

Research design

The research design (Figure 1) comprised replicate laboratory experiments to assess the three-dimensional impact on SWR of wetting and at four stages during 80 hours of drying. Each experiment involved a standardized application of water equivalent to 9.2 mm of rainfall (an amount common in SWR-prone environments, but insufficient to saturate the soil). Three different, initially water-repellent soils (see below) were used with and without subsurface drainage impedance, and with and without either artificially created vertical roots or soil cracks. Altogether eighteen soil type-vertical structure-subsurface drainage combinations were tested. Because the experiments were destructive in order to measure SWR at each depth, it was necessary to have five runs of each combination which, with replicates, made 180 individual experiments in total.

<Figure-1>

Choice of soils and preparation

Approximately 20 kg of each of the three soils used in the experiments was collected from 1-3 m^2 areas of the topsoil (0-10 cm) at the following locations: (1) Vale Torto catchment in central Portugal, covered by dense heath scrub dominated by *Erica umbellata* and *Calluna vulgaris* (referred to in the paper as 'Scrub' soil) (see also Stoof *et al*., 2011, 2012; Shakesby *et al*., in press); (2) in the vicinity of a Lawson's Cypress (*Chamaecyparis lawsoniana*) tree on the Swansea University campus, south Wales, UK ('Conif' soil); and (3) a vegetated coastal sand dune area at Nicholaston, Gower Peninsula, south Wales, UK, covered by various grass species ('Dune' soil). The three soils were of similar initial water-repellency *severity* (18% Molarity of an Ethanol Droplet (MED); Doerr, 1998) but differed in terms of water-repellency *persistence* (as measured using the water drop penetration time (WDPT) test), texture, total organic carbon (TOC) content and sampling location. The Conif soil had the highest TOC content and WDPT while the Dune soil had the lowest values of the same two parameters but the coarsest texture (Table 1).

<Table-1>

Soil samples were collected in dry conditions, oven-dried at 30°C for 24 hrs to ensure standard moisture conditions, sieved through a 2-mm mesh and mixed thoroughly. They were then stored under dry laboratory conditions. At the start of the experiment, the gravimetric water contents (Kutilek and Nielson, 1994) of the soil material were 4 % for both Scrub and Conif and 0.2 % for Dune soil. Total organic carbon (TOC) content was determined using a Primacs SC-TOC automated analyzer. Particle-size distributions were determined using a combination of dry sieving and a Coulter LS230 laser particle sizer using a fluid module with Calgon 5% as the dispersion fluid. The SWR of each soil material was determined using the MED and WDPT tests. The MED uses standardized solutions of ethanol in different concentration. The repellency class assigned to a sample (Table 2; Doerr, 1998) is the lowest ethanol strength at which at least 3 out of 5 droplets applied to the soil surface penetrated within 5 seconds. The WDPT test involved placing 5 drops of distilled water on the soil surface and recording the median time to complete penetration (Doerr, 1998).

<Table-2>

Experimental procedure

Samples of prepared soil material (60 of each soil type) were placed into round, slightly tapered, transparent plastic containers with a basal diameter of 11cm. Each sample was gently compacted and smoothed in a standard (replicable) fashion to provide experimental soils 2.5 cm deep with a surface diameter of 11.7 cm and surface area of 107.5 cm^2. Samples were subdivided into one of the following ‘preferential flow’ treatments extending from soil surface to its base: (a) simulated roots, comprising five vertical, regularly-spaced 2-mm diameter, wettable wooden rods, and (b) two simulated soil cracks, 10.7 cm long and 0.2 cm wide, created and maintained using two folded pieces of blotting paper inserted vertically into the soil for the duration of the experiment, and (c) samples where no treatment was applied (control samples). The blotting paper sides were used to ensure replication of dimensions and prevent collapse during experiments. The roots had an areal density of 0.2 % (area per unit area) and a volumetric density of 1.1 %, while the crack densities were 4 % and 11 % respectively. The containers were either sealed at the base to prevent drainage (impeded drainage) or punctured with four 5–mm diameter holes to allow it (unimpeded drainage). To prevent soil loss, these holes were lined with a 142-µm nylon mesh.

The wetting phase involved gentle, uniform application of 100 ml of double-distilled water (equivalent to a rainfall of 9.2 mm) to the soil surface. The infiltration time was recorded and, for unimpeded drainage experiments, the quantity of drained water was measured. After 3 hours, the soil water content was determined gravimetrically (Kutilek and

Nielson, 1994). The three-dimensional SWR patterns of two of each set of ten experiments of each soil/preferential flow/drainage combination were determined at four depths (surface, 0.5 cm, 1 cm, and 2 cm) using the MED test. Between 10 and 15 points were assessed per soil layer, with particular attention given to clarifying patterns close to cracks and roots. After measuring SWR at a particular level, soil was removed to reveal the next depth and measurements repeated.

In the experiments where the impact of drying was assessed, the soil samples were oven-dried at 30°C. Following 9, 24, 48 and 80 hours of oven-drying (a) the progressively fewer remaining soil samples were re-weighed to determine their soil water contents, and (b) two containers of each soil/preferential flow-drainage combination were selected and their three-dimensional SWR patterns determined as described above.

Recording SWR patterns

Using sketches, photographs and MED measurements taken at each depth, diagrams of SWR patterns were created and calculations made using JMicroVision v.1.27 software of the percentage of total area covered by each repellency class at each depth for each experiment. Data shown as means or medians represent the results from all samples including replicates. For the SWR diagrams, however, there was some variation between replicates; cases where replicates exhibited similar patterns and severity of SWR are identified with an R symbol.

Statistical analysis

In order to assess the effect of soil depth, treatment, soil type on the spatial distribution of SWR after wetting and drying, statistical analyses using one-way ANOVA Post Hoc Multiple Comparisons with Tukey or Games-Howell tests were conducted. For the effect of substrate impedance on SWR, independent-samples t-tests were performed using the SPSS v.20. In both cases, the 5% significance level ($p<0.05$) was used.

Results

Wetting phase

Water infiltrated the surface of the Scrub soil rapidly (within 5 min) irrespective of treatment or drainage type, but much more slowly for the Conif (30-60 min) and Dune (10-100 min) soils. Infiltration was much faster (1) with unimpeded than with impeded drainage in Conif and Dune soil experiments, and (2) with simulated cracks and roots than without. Infiltration occurred mainly via the preferential flow paths provided by the cracks and roots where present rather than into the soil matrix, but in control samples it was relatively random (Figure 2). Up to 75 % of applied water drained within 3 hours of wetting where there was basal drainage (Table 3). For Conif and Dune soils, drainage ranged from 20 to 36 % of the applied water in the control experiments, rising to 41-45 % and 59-75 % in the root and crack treatment experiments respectively. In contrast, drainage was minimal in the Scrub soil experiments with a maximum of 12 % recorded for the root treatment. As would be expected, these different drainage outputs led to different post-wetting volumetric soil water contents: 9-24 % for Dune soil, 15-30 % for Conif and 36-39 % for Scrub, with lowest values for experiments with cracks and highest values for control experiments (Figure 4, at 0 hours).

<Table-3>

The application of water created different three-dimensional SWR patterns leaving some soil hydrophilic or with reduced SWR, and other parts dry and with unchanged SWR. The patterns varied according to treatment, subsurface drainage and soil type (Figure 2). Surface soil (A in Figure 2) became completely hydrophilic (shown as unshaded in Figure 2) in 24 of the 36 experiments; in the remaining 12, only isolated patches away from cracks, roots and container edges remained water-repellent (18 % MED) (grey shading in Figure 2). At depth (B, C and D in Figure 2), most experiments had hydrophilic soil around preferential flow paths but maintained the original SWR (18 % MED) in isolated patches away from roots and cracks (19, 24, 25 out of 36 experiments at 0.5, 1, 2 cm depth respectively). Experiments with impeded basal drainage had more extensive wetting at 1 cm (C) and 2 cm (D) depths, with more than 50 % of the total area wetted in 15 out of 18 experiments, whereas in soil with unimpeded drainage, only 9 out of 18 experiments at both depths had this percentage area wetted. Distinct differences in SWR distribution were also observed between treatment types. Wetting was restricted to narrow zones adjacent to cracks and roots where present, with soil patches away from them remaining dry and water-repellent (18 % MED) (Figures 2 and 3). In contrast, in control samples, the hydrophilic and hydrophobic soil areas showed no systematic patterns.

<Figure-2>

<Figure-3>

Drying phase

When drying commenced, the soil water content and distribution became non-uniform, varying according to soil, drainage and treatment type (Figure 4; 0 hrs drying time). Progressive drying caused exponential reductions in soil water content with pre-wetting values being reached after 48 hours for Dune soils and 80 hours for Scrub and Conif soils (Figure 4).

<Figure-4>

Drying was accompanied by changes in SWR as demonstrated by detailed maps (Figure 5) for each depth of each experiment. Soil around simulated cracks or roots and close to container edges remained wet (unshaded) and hydrophilic for longer than elsewhere. In all 36 experiments at each depth after 9 hours of drying, 27 (out of 144 experiment-depths) remained completely wettable, 92 had isolated water-repellent patches and 25 became entirely water-repellent. With further drying (24 hours), most soil samples at each depth became completely water-repellent (101 out of 144), with the remainder rendered either partly (28 cases) or completely (15 cases) wettable. All soils had become entirely water-repellent after 48 hours of drying but the degree of SWR varied considerably.

During drying, of the 108 cases at each depth where soil had become wettable (defined as > 50 % of the soil area being wettable), mainly for surface and basal soil in experiments with impeded drainage, most (88 out of 108 after 80 hours of drying) did not return to the original SWR level but became either one (42 cases), two (40 cases) or three (6 cases) SWR classes lower. In contrast, in experiments where water had wetted <50 % of the soil (mainly experiments with unimpeded drainage at 1 and 2 cm depths), most soil (26 out of 36 cases) retained its original SWR. In these 26 cases, however, SWR severity varied spatially throughout drying with only one-third of experiment-depths exhibiting uniform values.

For Scrub soil, SWR patterns in both the control and root treatments remained variable and patchy; only in some crack experiments was the pattern more systematic with lower repellency near cracks (Figure 5). For Conif and Dune soils, there were differences in repellency patterns not only between the roots, cracks and control treatments but also between impeded and unimpeded drainage runs. Soil in most experiments with impeded drainage became less water-repellent at depths of 1 and 2 cm than before wetting, whereas with unimpeded drainage soil only became less water-repellent close to roots and cracks and retained its original repellency away from them.

<Figure-5>

During drying, many Scrub and Conif (but not Dune) soils at one or more depths became either partly, or in some cases entirely, extremely water-repellent (24 or 36 % MED), thus reaching higher repellency levels higher than that recorded before wetting (18 % MED). Usually, however, repellency declined after 80 hours of drying (Figure 5), with only 5 out of 48 experiment-depths showing extreme repellency. In all, 61 out of 192 and 46 out of 192 cases for all depths of Scrub and Conif soils respectively exhibited some extreme repellency after 9-80 hours of drying, and it was most apparent after 24 hours of drying (22 out of 48 and 15 out of 48 in Scrub and Conif soils respectively). In experiments with cracks and roots, the SWR peak tended to occur in the dry zones immediately adjacent to the wetted areas surrounding the cracks and roots. This SWR enhancement tended to: (1) occur most rapidly in experiments with roots, followed by the cracks and then the control experiments (Figure 5); and (2) be more pronounced with impeded (31 out of 96 and 28 out of 96 experiments in Scrub and Conif respectively) than unimpeded drainage (28 out of 96 and 18 out of 96 experiments in Scrub and Conif respectively).

The overall effect of wetting and drying on SWR observed at the final stage of drying was a net reduction in the severity of SWR at the surface and at 0.5 cm depth (>70 %), while at grater depths the proportion of soil with unchanged severity of SWR was much higher than in shallower soil (Figure 6a). In terms of soil type, the effect of the wetting and drying resulted in a significant reduction in SWR for Dune and Scrub soil, while in Conif experiments the percentage of soil with reduced and unchanged SWR was similar.

In the control and root experiments after wetting and drying, significant proportions of soil had less severe SWR (~70%) while only ~30% retained the original level of severity. In soils with cracks, however, the proportions were nearly equal. For both types of subsurface drainage, the majority of the soil volume had a reduced severity of SWR (57% and 69%) at the final stage of drying, nearly 5% had increased SWR, the remaining soil retaining pre-wetting SWR levels (Figure 6d).

<Figure-6>

Discussion

The discussion is divided to three main sections including the wetting, drying phase patterns, and hydrological implications of here presented findings together with discussion of net hydrological impact of other environmental factors affecting SWR.

Wetting phase patterns

The general patterns of SWR dynamics following wetting (Figure 7) confirm previous research showing that rainwater is mainly distributed via preferential flow paths where they are present (Ritsema and Dekker, 2000; Kobayashi and Shimizu, 2007) (Figure 7; U1-U2 and I1-I2). As significant proportions of the applied water quickly bypass soil surrounding the preferential flow paths, this reduce the potential for the water-repellency of the soil matrix to be broken down and for extensive wetting to take place compared with situations without cracks and roots. A surface soil layer and the zone adjacent to cracks and roots became predominantly hydrophilic but the majority of soil matrix remained dry especially where there was no basal drainage impedance (Figure 7; U3). In soil samples with basal drainage impedance water also accumulated at the base causing extensive wetting and SWR breakdown in that zone (Figure 7; I3). By the end of the wetting phase, the substantial soil volume that did not wet retained its original SWR severity.

In the experiments, results varied with soil type and experimental set-ups. First, drainage (in unimpeded experiments) was significantly higher in Dune and Conif crack and root experiments than in the corresponding control experiments, but drainage was minimal for Scrub soil in both control and crack/root experiments (Table 3). The fact that roots had slightly less influence on drainage than cracks could be attributed in part at least to the limited number and consequently smaller preferential flow area of simulated roots. In the experiments with the simulated cracks and roots extended the short distance to the soil (container) base in all cases. Clearly, the patterns of wetting and SWR change might well have been different if either the soil depth had been much greater if the cracks or roots had not extended to the base.

The reasons for the distinctive behaviour in wetting of Scrub soil are not entirely clear. The most likely, although not certain, explanation lies in a specific combination of texture and soil organic matter explained by Ellerbrock et al. 2005 as a mineral/organic matter ratio which can affect surface wettability and possibly the speed of SWR breakdown.

Drying-phase patterns

During the drying phase the changes in SWR were partly dependent on different moisture patterns created by wetting (Figure 7; U3 and I3). Thus drying and SWR change occurred mainly at the surface and in areas near preferential flow paths and (in impeded drainage experiments) in the basal zone. These changes took place comparatively rapidly once a critical soil moisture threshold had been reached (Doerr and Thomas, 2000; Vogelmann *et al*., 2013) with a change occurring from wettable directly rather than progressively to a SWR level typically lower than the 18% MED pre-wetting value (Figure 7; U4 and I4). The lower post-wetting SWR could have been caused by weakening or breaking of the bonds between the soil particles and hydrophobic substances, as suggested by Diel *et al.* (2009) and Graber *et al.* (2009) and by leaching of hydrophobic organic substances resulting from the percolating water (Doerr and Thomas 2000). As the experiments did not involve living vegetation replenishment of hydrophobic substances was not involved.

In the crack and root experiments, SWR clearly became re-established last in the vertical zones adjacent to them (Figure 7; U4 and I4) which corresponds with evidence from observations (e.g. Ritsema and Dekker, 2000; Bachmann *et al*., 2013) showing that these zones remain wettable longest and, if only partial drying takes place, can quickly become wet and hydrophilic again in subsequent rainstorms. Crack and root zones are likely, therefore, to be the most dynamic SWR locations in a water-repellent soil.

Soils with unimpeded basal drainage remained unaffected by drying in most of the soil matrix as the three-dimensional extent of wetting was limited in the first place (Figure 7; U4 and U5). With impeded drainage, the soil took much longer to dry and especially in Scrub and Conif some samples in basal layers might not become completely dry after 80 hrs resulting in lower levels of SWR re-established or in other cases extreme levels of SWR remaining (Figure 7; I4 and I5).

In addition to these general patterns of SWR changes with wetting and drying some observations in this study were very specific to particular soil or treatment types. The soil samples with higher organic matter contents (Scrub and Conif) exhibited a peak in SWR severity (24 or 36% MED) above the pre-wetting level during drying (Figure 7; U4 and I4), but most of them returned to 18% MED after 80 hrs of drying. Similar behaviour has been observed by de Jonge *et al*. (2007) and Kawamoto *et al*. (2007) in organic-rich soils tested under laboratory conditions. They speculated that molecular conformational changes in organic matter may be responsible (see also Ellerbrock et al., 2005; Kawamoto et al., 2007). Another possibility is that evaporation in soil pores may temporarily raise both humidity and SWR (Doerr *et al*., 2002) before both subsequently decrease. This effect was observed by Urbanek *et al*. (2010) for slightly moist, organic-rich, fine-textured soil subjected to substantial heating in enclosed conditions (during autoclaving). The lack of such a peak in the Dune soil may be a result, therefore, of its comparatively low organic matter content. Support for this interpretation is provided by Schaumann *et al.* (2013), who showed that different soil-water interaction models apply to water-repellent soil rich and poor in organic matter.

Scrub and Dune soils showed more overall weakening of SWR following wetting and drying than Conif soil, much of which remained unaltered (Figure 6b). Although SWR retention can be linked to no or limited wetting, it may also partly result from differences in re-establishing SWR with soil type. The potential for re-establishment of water-repellency in a wetting-drying cycle was thus greatest for Conif soil with the highest organic matter content of the three soils. The reasons for this difference are not certain but might be a result of (1) different quantity and quality of hydrophobic substances in each soil originating from different vegetation, (2) a greater ability for leaching of hydrophobic substances in the sandy, and hence more permeable Dune soil, and (3) uncompleted drying of some soils especially with impeded drainage even after 80 hrs of drying. The partial re-establishment of SWR may be associated with the re-arrangement of the organic molecules as suggested in several studies (e.g. Graber *et al*., 2009; Bayer and Schaumann, 2007; Schaumann *et al*., 2013), or simply with the redistribution of waxes already present in the soil matrix as interstitial globules (Franco *et al*., 1995).

Hydrological implications

Despite the fact that the research study described here was conducted at a small scale and under standardized laboratory conditions, the results show a number of potentially significant implications for natural, field conditions. First, it is evident that preferential flow pathways provided by roots and cracks not only allow water to bypass repellent soil (e.g. Dekker and Ritsema, 2000; Kobayashi and Shimizu, 2007), but also assist in the breakdown of repellency in surrounding soil. It is logical that differences in densities of such pathways may control the speed and completeness of the switching from repellent to wettable conditions. The mechanisms by which the simulated roots and cracks facilitate preferential flow and consequent water-repellency breakdown may include: (1) the creation of continuous soil voids with the presence of either roots or open cracks, and (2) the introduction of non-hydrophobic surfaces by the roots themselves (Mao *et al.,* 2014). Although the first mechanism may not completely simulate field conditions, roots must accomplish much the same effect as that caused by the insertion of the rods through their natural movement and growth and are able to create voids and macropores for air and water flow (Clark *et al*., 2003). The second mechanism has some parallels with the effect of stones on vertical water movement in water-repellent sand (Urbanek and Shakesby, 2009), where enhancement of preferential flow by stones at sufficient concentrations to enable stone-to-stone contact throughout the vertical soil profile was more marked for stones with hydrophilic than hydrophobic surfaces. Unlike the simulated roots in our experiments, however, actual root surfaces, may not be entirely hydrophilic due to the accumulation of hydrophobic microbial exudates in the rhizosphere (Czarnes *et al*., 2000; Brundrett, 2002).

Another important factor in soil water repellency breakdown is the basal drainage impedance which is relatively common especially in shallow soils overlying impermeable bedrock. In that case, rain water will wet a very thin surface layer, percolate down via preferential flow paths where present to the impermeable subsurface layers and then start wetting the overlying soil and creating hydrophilic conditions from beneath (Leighton-Boyce *et al*., 2005; Stoof *et al*., 2011). On steep slopes, the effect of wetting the soil from beneath could be potentially restricted, as water might start moving downslope as through flow along the soil-rock interface. In soils with unimpeded subsurface drainage, on the other hand, preferential flow paths created by deep cracks, tree roots or interconnected stones could reach the subsurface soil horizon or highly permeable soil and only very limited wetting of soil matrix would take place leaving large sub-surface zones water-repellent. Robinson *et al*. (2010) suggested that such deep percolation of soil water along tree roots in a dry season may enable trees to harvest water at depth by limiting water availability to shallow-rooted vegetation.

Non-uniform wetting of water-repellent soil followed by drying reduces (at least temporarily) the severity of SWR and is one of the main causes of spatial variability in hydrophobicity along with patchy replenishment of hydrophobic substances from tree leaves, litter or living roots (Doerr and Thomas, 2000) under natural conditions. Such high spatial variability of SWR demonstrates that wettable and highly water-repellent soil can co-exist in close proximity suggesting that a sufficiently dense network of SWR point measurements is needed to avoid making incorrect predictions about the hydrological behaviour of soils exhibiting water repellency. Soils with basal drainage impedance will tend to produce a soil with layered hydrophobicity dynamics, with a highly dynamic surface, overlying a more persistently hydrophobic upper/middle soil, which in turn overlies a quasi-permanent hydrophilic basal zone.

The net hydrological impact of soil cracks and root-holes in soils exhibiting water-repellency is shown in the wider context of other environmental factors in Figure 8. These factors would be expected to act in various combinations to affect wetting and drying patterns and SWR states. In the current study, soil surfaces were deliberately made bare and level, which allowed water to pond until it either overcame SWR or percolate via roots or cracks. On a slope, (1) overland flow infiltrating the soil matrix would be less likely, (2) water ponding would be less long-lived thereby reducing the chance of a breakdown of repellency, but (3) movement via macropores including cracks and root-holes where present might be expected to be proportionally more important. High overland flow but low infiltration rates on slopes of 38% in central Portugal reported by Stoof *et al*. (2011, 2012) could, therefore, be interpreted as indicating that macropores were relatively sparse in the highly water-repellent soil. Other studies, however, have attributed preferential flow paths to lower than expected overland flow in highly water-repellent soil (Barrett and Slaymaker, 1989; Doerr *et al*., 2000; Ferreira *et al.*, 2000; Shakesby et al., 2000; Walsh *et al*, 1998).

Our experiments necessarily excluded replenishment of hydrophobic substances from vegetation and litter, but it is clear that in many natural environments such as forest and scrub (Doerr *et al.* 2009; Stoof *et al.* 2011), residual organic matter will provide compounds necessary to maintain water repellency (Doerr and Thomas, 2000). In burnt environments, however, vegetation removed by fire will limit the sources of hydrophobic substances and therefore the patchiness of SWR created by partial wetting can be expected to have longer-lasting effects. In these environments, SWR together with removal of the vegetation cover will have a major effect on post-fire erosion and flooding events (Shakesby *et al*. 2000, Stoof *et al.*, 2011).

The density and depth of the roots and cracks creating the preferential flow paths would be expected to have a substantial effect on the scale of SWR breakdown, so that it is logical to assume that with greater densities of preferential flow paths of any type, SWR breakdown would be faster and more complete, although this has yet to be investigated. It follows, too, that breakdown would be enhanced by basal wetting in a shallow soil overlying impermeable bedrock (Doerr *et al*., 2000). Breakdown would also be expected to occur more readily with multiple rainfall events, provided they occurred over a sufficiently short period to prevent substantial drying of any wetted soil between events. The anticipated effect would be the progressive extending of wetted zones farther into the dry soil matrix beyond the narrow zones surrounding preferential flow paths.

<Figure-8>

Soil texture and organic matter content are known to be important influences on SWR (Doerr *et al*., 2000; Ellerbrock *et al*., 2005; Schauman *et al*., 2013). Coarse-textured soils have always been considered to be more prone to development and persistence of SWR (DeBano, 1991; McGhie and Posner, 1980) but, paradoxically, they can be highly permeable once SWR is overcome. Given that the hydrophobic substances that make soil water-repellent are supplied by organic matter, it follows that soils rich in organic matter will be more likely to show and retain SWR characteristics, including the curious tendency for SWR to reach extreme values temporarily at intermediate moisture contents during drying.

Conclusions

Replicate controlled laboratory experiments were carried out involving the wetting and drying of soil samples of three different soil types with and without simulated cracks, roots and basal drainage impedance. Wetting of soil with preferential flow paths created either by roots or cracks resulted in non-uniform wetting of the soil matrix and SWR remained unchanged in non-wetted areas. On the other hand, soil in a shallow surface layer, adjacent to preferential flow paths and at the base (where there was impeded drainage) changed to a hydrophilic state.

Changes in SWR during drying were largely confined to soil that was wetted and hence varied with the degree and pattern of wetting in the wetting experiment. The soil dried quickly at and near the soil surface and left SWR levels predominantly reduced compared with the pre-wetting. At depth, drying took longer, especially in areas near the preferential flow paths created by the roots or cracks and the basal layer in soils with impeded drainage. In the final stage of drying, SWR recovered to pre-wetting levels or was reduced. The degree of SWR recovery depended not only on the degree of wetting but also on the ability of a particular soil to re-establish water-repellency without the input of external hydrophobic substances; for the experimental soils, this was dependent on the organic matter. The two comparatively organic-rich soils also showed increased levels of SWR during intermediate stages of drying, which could have partly contributed to better recovery of SWR levels. The study also shows that the presence or absence of basal drainage impedance can significantly affect the magnitude of changes in SWR during wetting and drying. A lack of basal impedance prevented wetting of large volumes of the soil matrix. In contrast impeded drainage speeded up the wetting and loss of SWR of subsurface soil but paradoxically may have helped to retain the hydrophobic substances within the soil to facilitate the re-establishment of SWR after drying.

There are several important implications of this laboratory study for the SWR and hydrological behaviour of natural soils. First, the pattern and completeness of the breakdown of repellency and subsequent recovery can be expected to be substantially affected by the density of preferential flow pathways and presence or absence of basal drainage. This may explain why point measurements of water repellency in the field have sometimes shown considerable spatial variability under all but the driest soil conditions. It can be expected nevertheless that the greater the density of preferential flow paths, the more spatially uniform will be the measurements of SWR under all soil moisture conditions. Second, SWR can be expected to be broken down more effectively for thin soils with rather than those without, basal impedance. This may help to explain how degraded Mediterranean soils with extreme levels of SWR can become hydrophilic under wet winter conditions even though high water amounts applied to dry soil under simulated rainfall conditions can fail to wet the soil.

For the purposes of this study, it was assumed that water can freely enter soil cracks and move downwards along relatively coarse plant roots. Under natural conditions, water movement might well be impeded by the water-repellent surfaces associated with them, in addition to any other factors affecting wetting and drying. Furthermore, many natural roots are fine and dendritic rather than coarse and linear, which could be expected to have a different effect to that reported here. Lastly, cracks and roots comprise just two possible preferential flow pathways in water-repellent soil. How all the different pathways individually affect water flow and wetting patterns and how they interact with each other and with other soil and topographic factors need further investigation in order to be able to predict more accurately the hydrological responses of water-repellent soils.

Acknowledgement

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Figures description

Figure 1 Research design. Total number of experiments = 180 (18 treatments x 2 replicates x 5 time stages). Shaded squares represent samples necessarily destroyed in order to carry out the analyses. For clarity, only the subdivisions for one category (e.g. soil type, treatment) are shown.

Figure 2 Spatial distribution of water repellency (MED), in three soils - Scrub, Conif, Dune at four depths (A-surface, B-0.5 cm, C-1 cm, D-2 cm), with impeded and unimpeded subsurface drainage at the end of the wetting phase (0 hrs drying in Figure 6). The type of shading indicates the severity of soil water repellency (unshaded=wettable; darker shading indicates more water–repellent soil). Black dots and vertical lines represent simulated roots and cracks respectively. The R symbol in the right-hand top corner indicates that the wetting behaviour was similar for replicates.

Figure 3 An example of changes observed during the wetting phase. Side views of the distribution of wet (dark tone) and dry, water-repellent (light tone) patches 5, 10 and 15 min after applying water to the surface of Dune soil with simulated cracks and impeded subsurface drainage. Note how initially the change to a wettable state is focused particularly on a relatively thin surface soil layer and zones adjacent to the two cracks. In this case, with impedance of basal drainage, soil near the base becomes wettable after 10 minutes. After 15 minutes, only patches well removed from the cracks, base and surface remain dry and water repellent. (Compare this example with the schematic representation of changes given in Figure 7.)

Figure 4 Mean water content (% vol.) of soil samples after each drying interval. Bars show standard errors of the means (n=10). The number of samples is 10, 8, 6, 4 and 2 after each drying interval respectively. Open and closed symbols represent unimpeded (U) and impeded (I) subsurface drainage respectively.

Figure 5 Spatial distribution of water repellency according to MED repellency class, in the three soils (5a - Scrub; 5b - Conif; 5c - Dune) at four depths (A - surface, B – 0.5 cm depth, C – 1 cm depth, D – 2 cm depth), with impeded and unimpeded subsurface drainage following 0, 9, 24, 48 and 80 hours of oven-drying. The type of shading indicates the severity of soil water repellency, as shown in the accompanying key.

Figure 6 Shaded composite bar graphs showing the mean percentages of the soil areas having a soil water repellency class lower than (<), equal to (=) or more than (>) 18% MED by a) depth, b) treatment type, c) soil type, and d) impedance. Bars indicate standard errors of the means. Different letter symbols (a, b, c) indicate significant differences between groups within the same columns.

Figure 7 Schematic representation of the main soil water repellency changes observed during and following the application of water and subsequent drying for experiments with unimpeded (diagrams U1-U5) and impeded (diagrams I1-I5) basal drainage. The main points are that: (a) basal impedance of drainage leads to an additional wettable basal layer of soil compared with experiments without basal impedance, (b) only patches away from the soil made wettable during wetting retain their original level of water repellency, and (c) soil patches that remained dry and water repellent following the wetting phase tended to undergo temporarily increased repellency levels at some point during the drying phase.

Figure 8 Ten key factors influencing the impact of soil water-repellency (SWR) on hydrological processes in soils prone to soil water repellency. The first five factors relate to the finding presented in this paper, the other five referring to previous field and laboratory observations published in the literature.

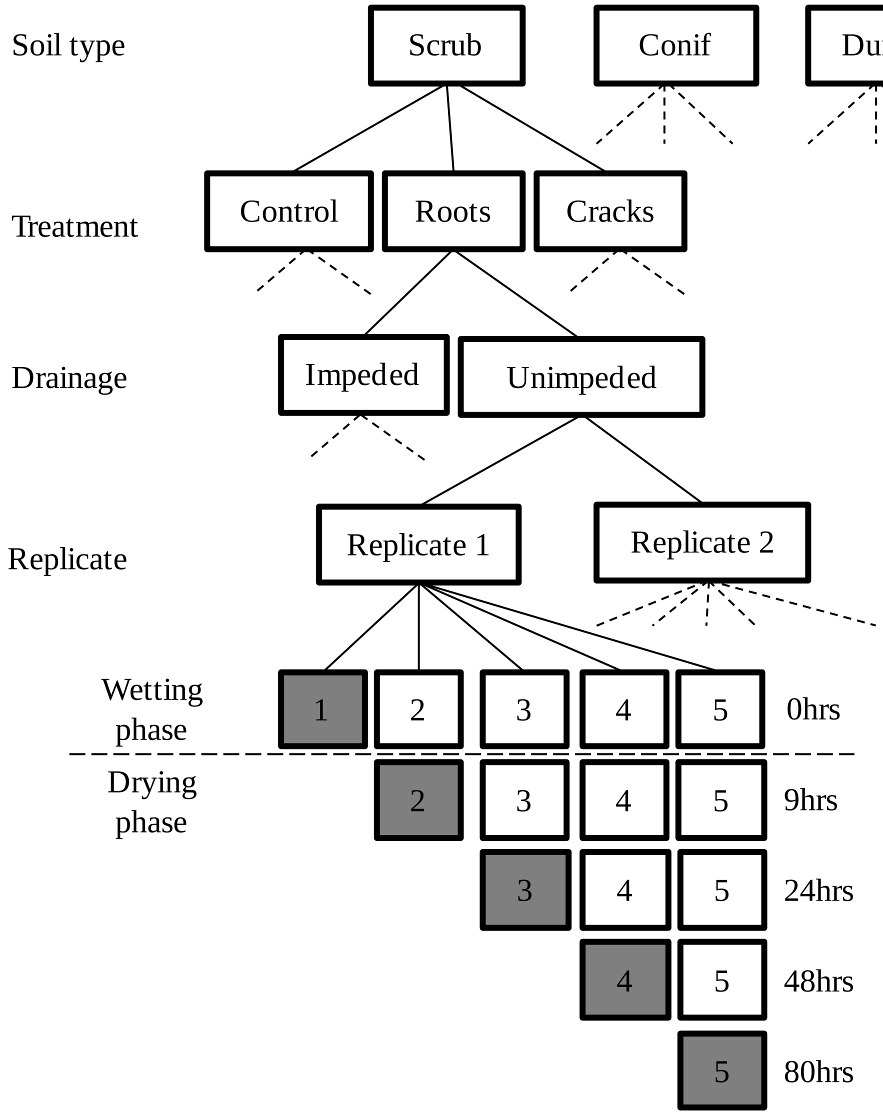


Figure 1

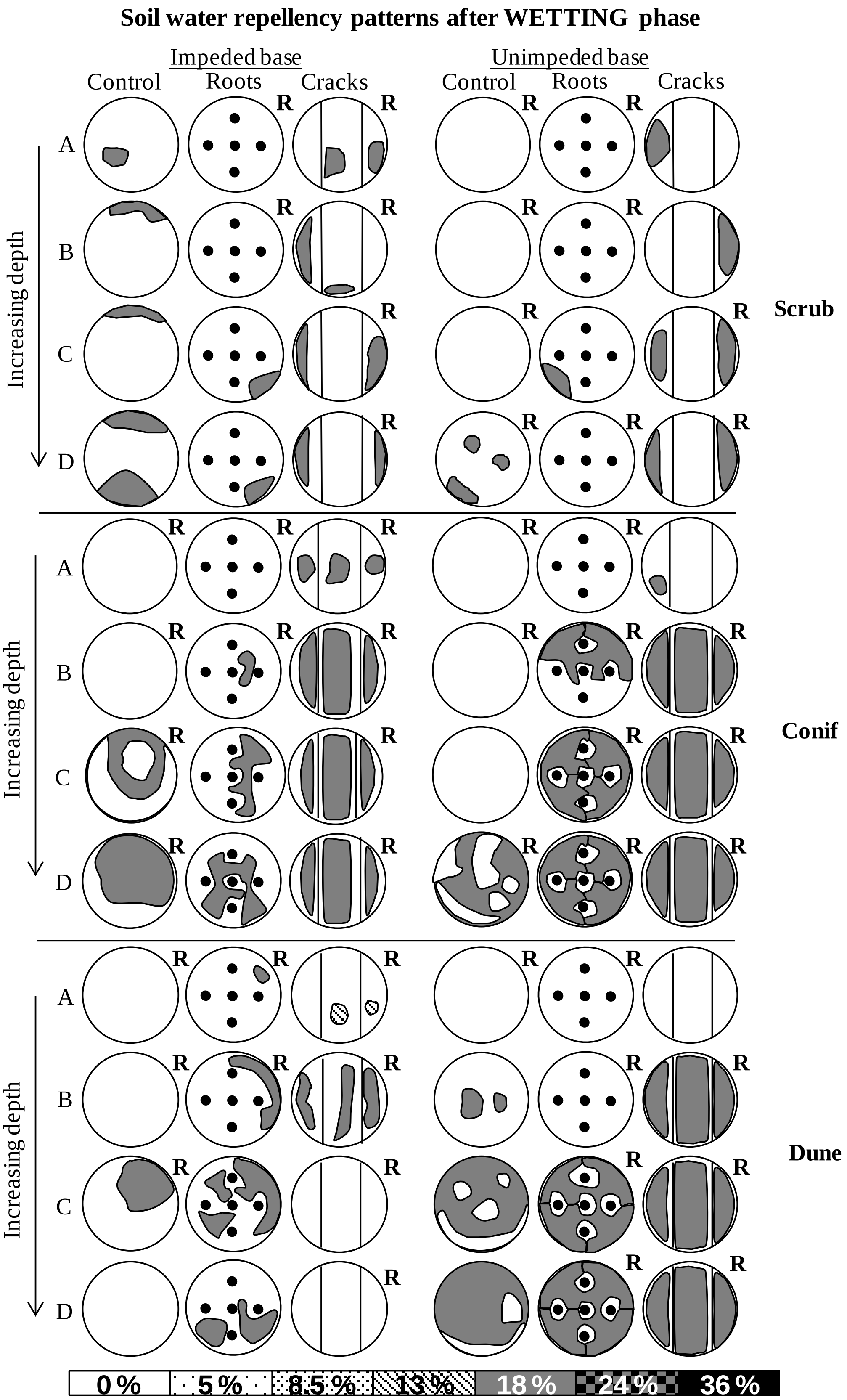

Soil water repellency patterns after WETTING phase
Impeded base
Unimpeded base
Control
Roots
Cracks
Control
Roots
Cracks
Increasing depth
A
B
C
D
R
Scrub
Conif
Dune
0%
5%
8.5%
13%
18%
24%
36%

Figure 2

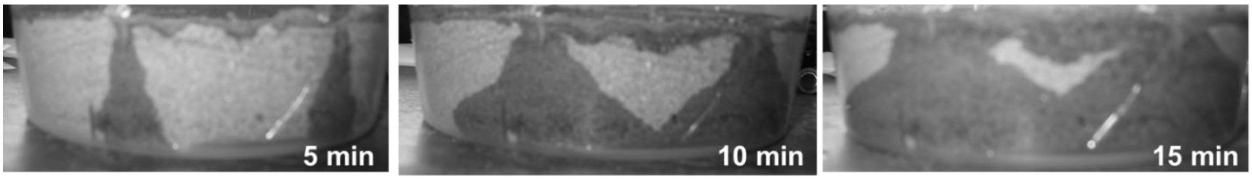


Figure 3

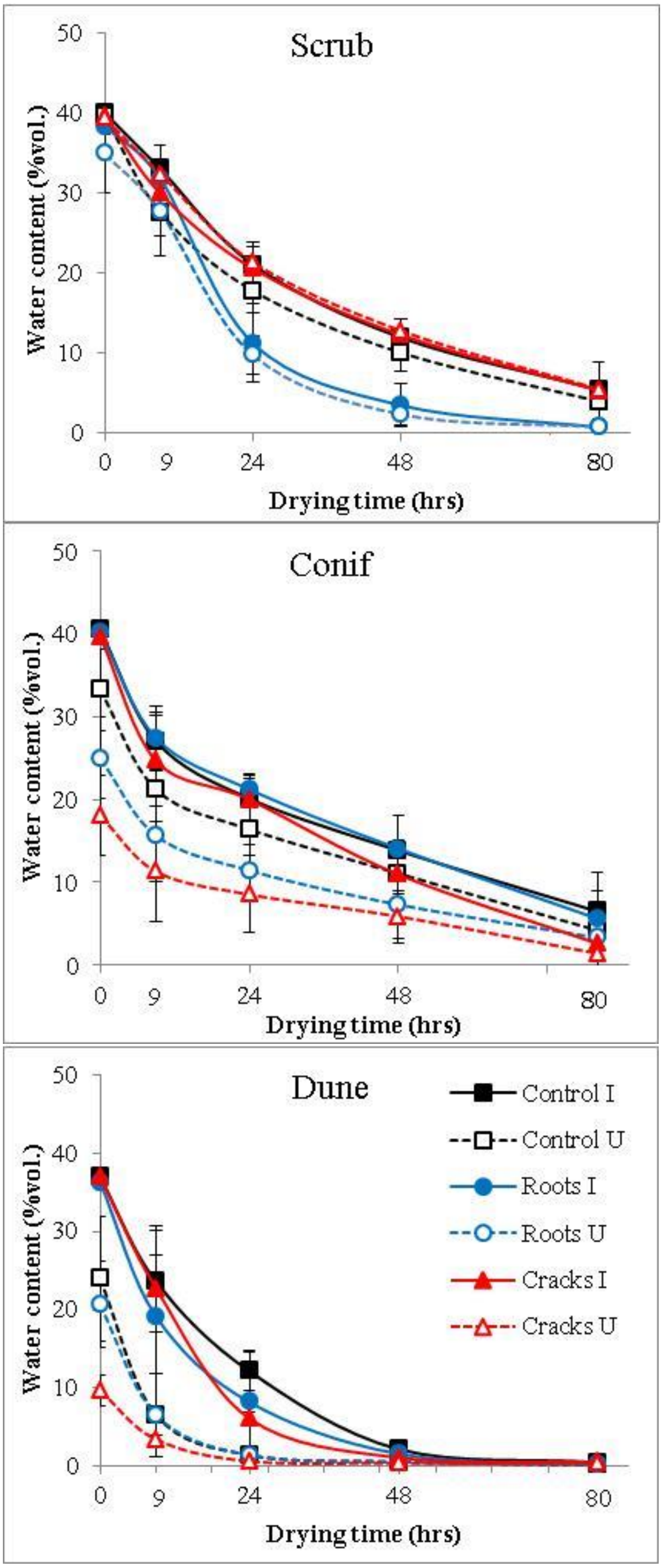
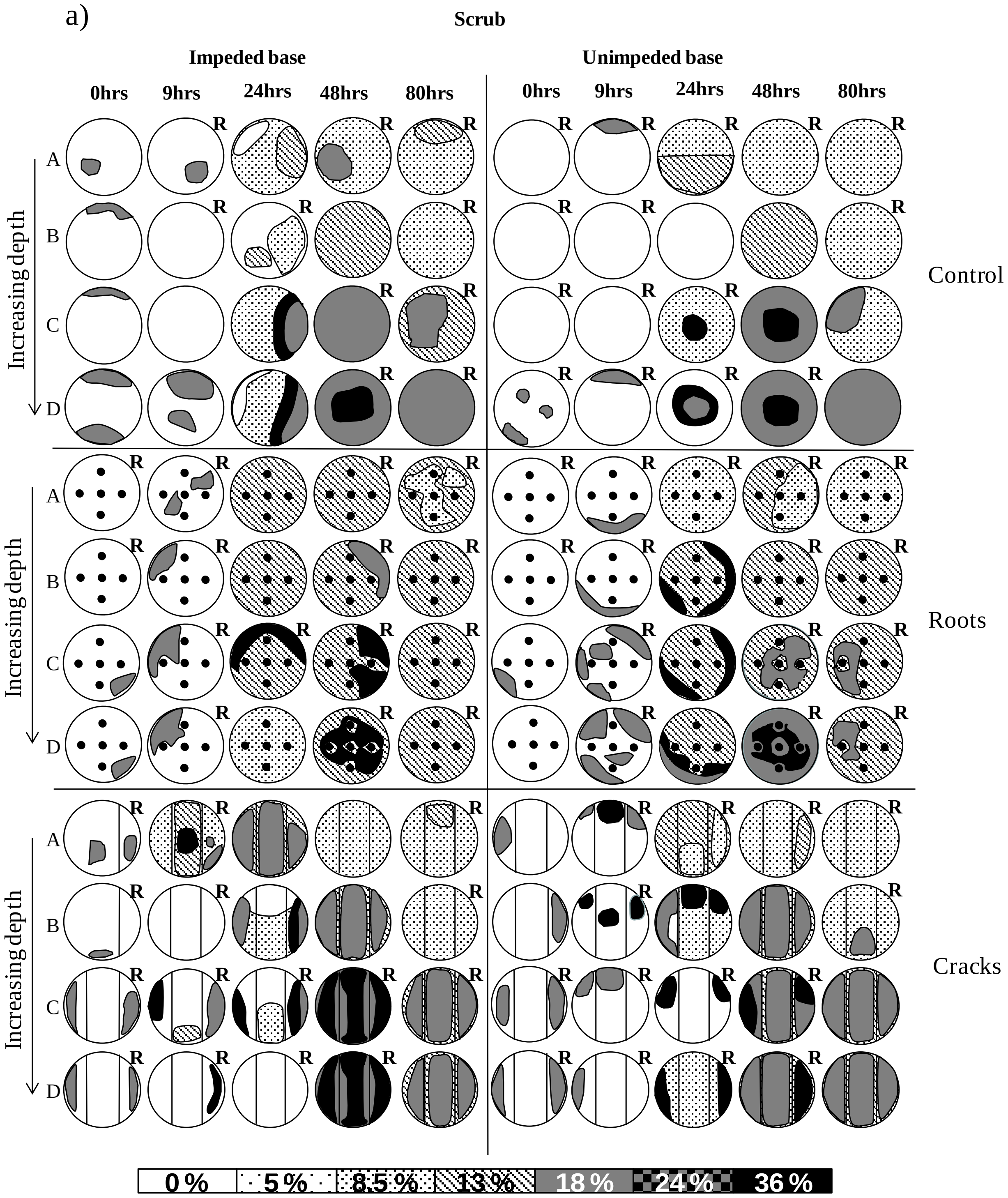
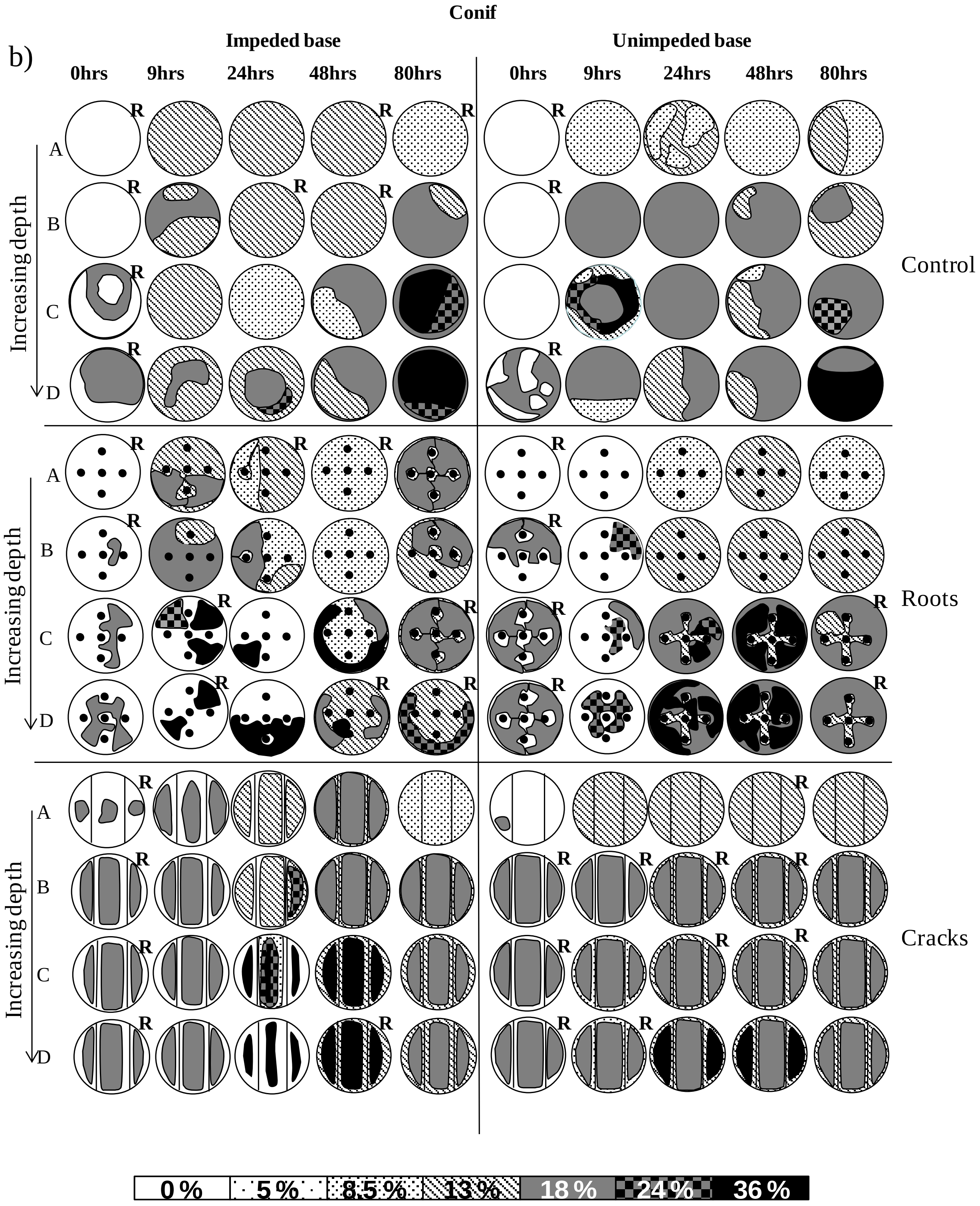

Scrub
Water content (%vol.)
50
40
30
20
10
0
0
9
24
48
80
Drying time (hrs)
Conif
Water content (%vol.)
Drying time (hrs)
Dune
Water content (%vol.)
Drying time (hrs)
Control I
Control U
Roots I
Roots U
Cracks I
Cracks U

Figure 4


a)
Scrub
Impeded base
Unimpeded base
0hrs
9hrs
24hrs
48hrs
80hrs
0hrs
9hrs
24hrs
48hrs
80hrs
R
A
B
C
D
Increasing depth
Control
Roots
Cracks
0 %
5 %
8.5 %
13 %
18 %
24 %
36 %


Conif
b)
Impeded base
Unimpeded base
0hrs
9hrs
24hrs
48hrs
80hrs
0hrs
9hrs
24hrs
48hrs
80hrs
R
A
B
C
D
Increasing depth
Control
Roots
Cracks
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5%
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13%
18%
24%
36%

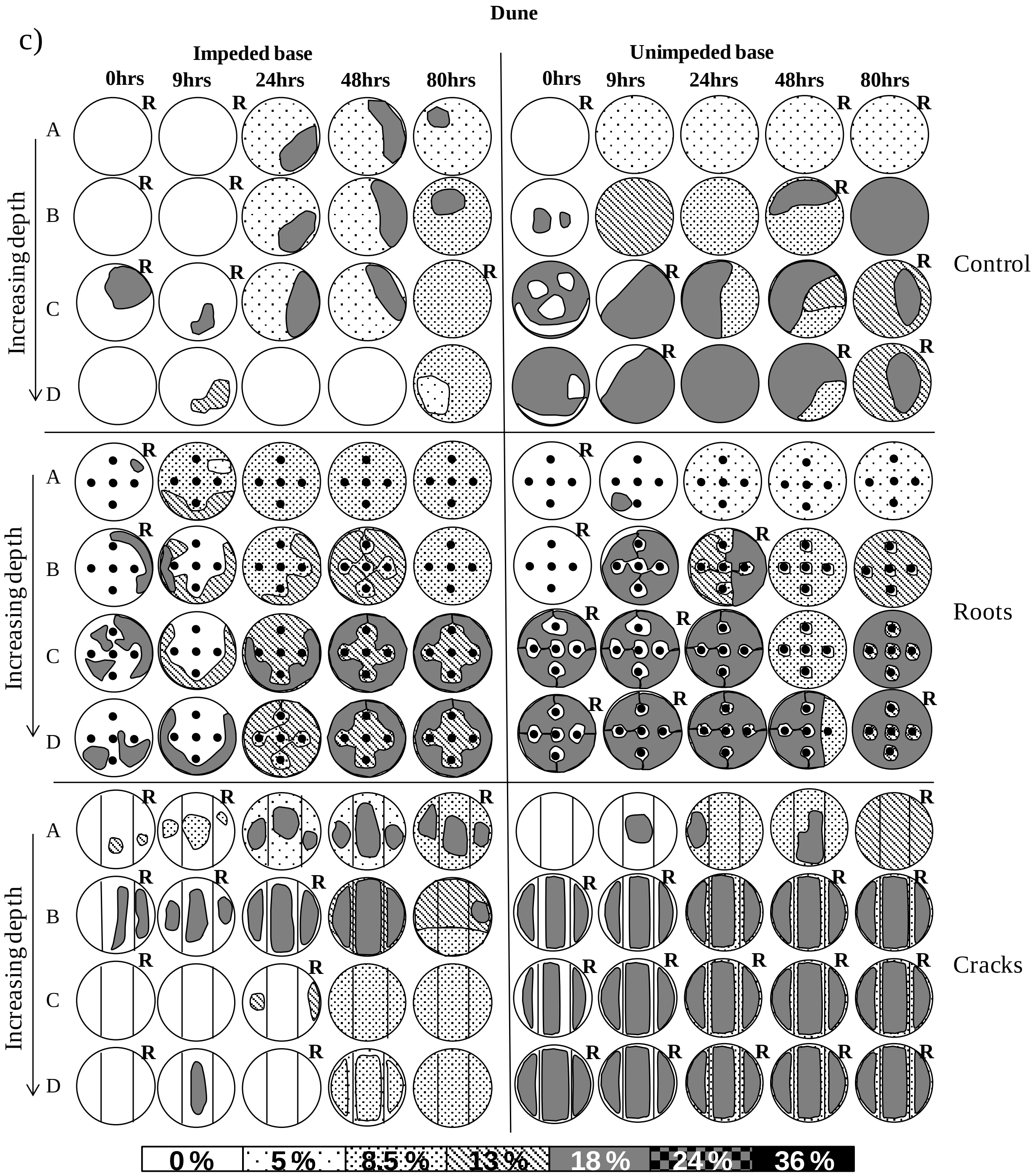

Dune
c)
Impeded base
Unimpeded base
0hrs
9hrs
24hrs
48hrs
80hrs
A
B
C
D
Increasing depth
R
Control
Roots
Cracks
0%
5%
8.5%
13%
18%
24%
36%

Figure 5

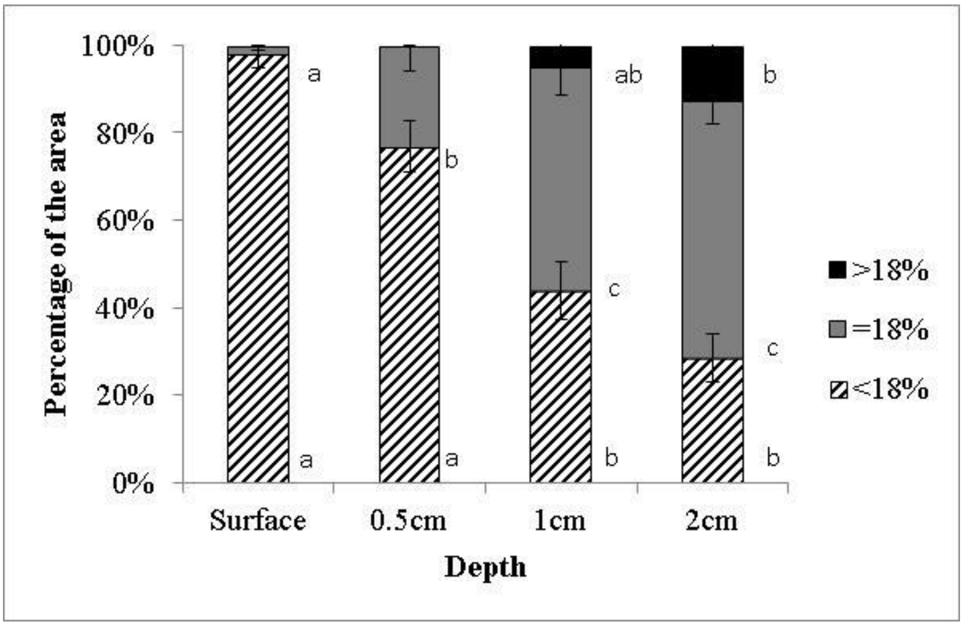
725 

Figure 6a

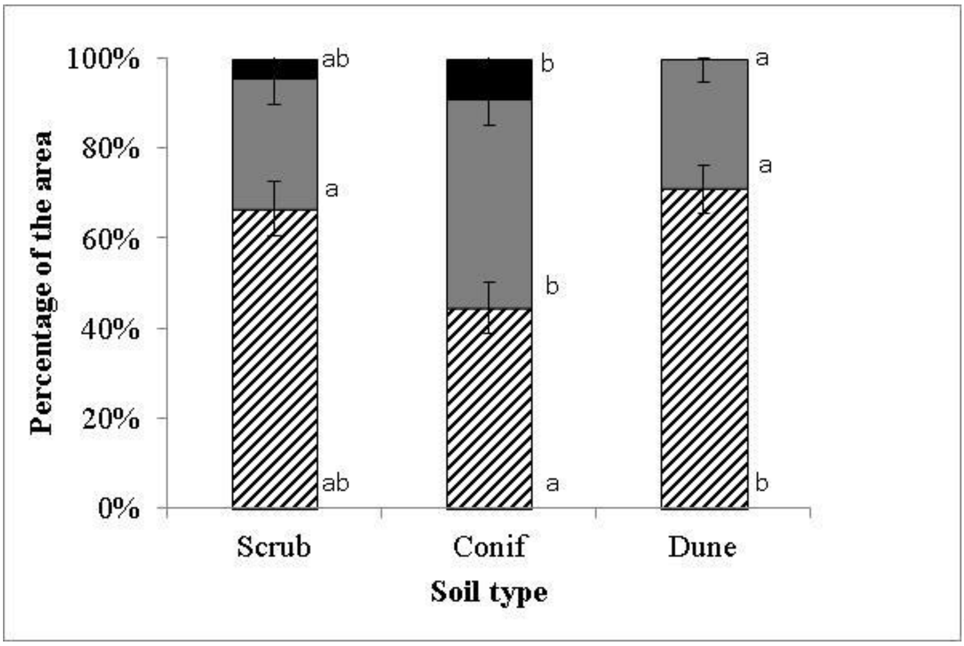
726 

Figure 6b

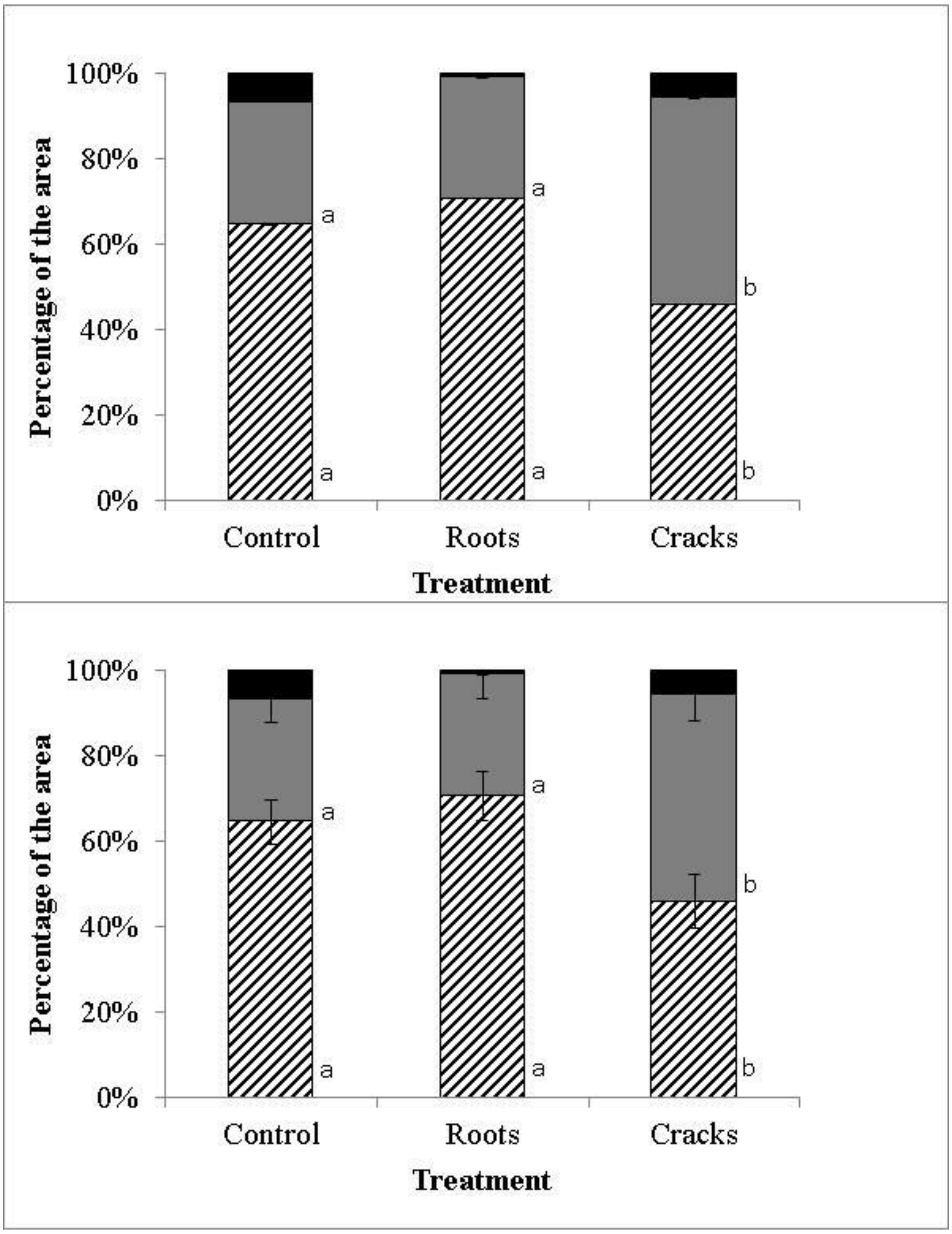
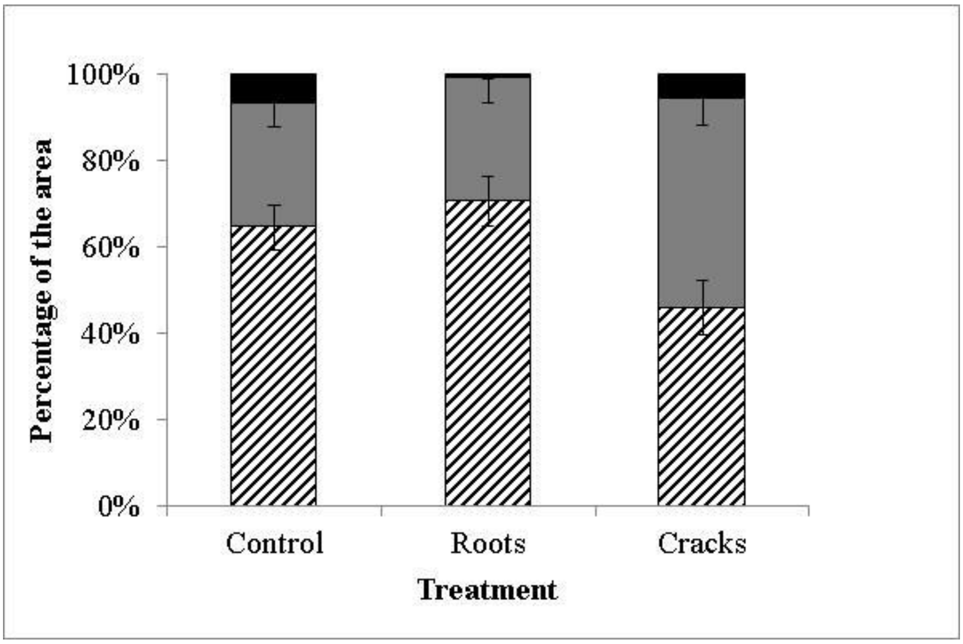

100%
80%
60%
40%
20%
0%
Percentage of the area
a
a
a
a
b
b
Control
Roots
Cracks
Treatment
100%
80%
60%
40%
20%
0%
Percentage of the area
a
a
a
a
b
b
Control
Roots
Cracks
Treatment

Figure 6c



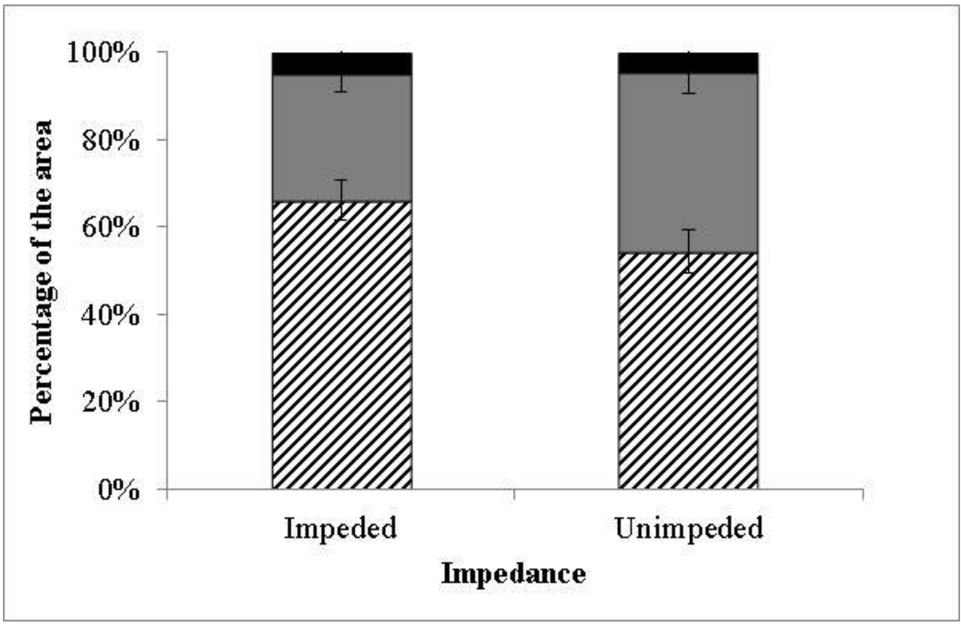


Figure 6d

Figure 6

Table 1 Selected properties of the three soils studied prior to the laboratory experiments.

Sample ID	**Scrub**	**Conif**	**Dune**
Vegetation type	Heath and heather	Lawson's Cypress	Coastal dune grassland
Site location	Vale Torto, Portugal	Swansea, UK	Gower, UK
Site coordinates	40°06'N, 8°07'W	51°36'N, 3°58'W	51°34'N, 4°08'W
Soil type†	Umbric Leptosol	Anthrosol	Hyposalic Arenosol
Texture	Sandy loam	Sandy loam	Sand
Particle size distribution (sand/silt/clay) %	88/11/1	85/13/2	96/3/1
Total Organic Carbon (TOC) (% ± st. dev)	8.3 ±0.4	15.3 ±3.3	0.6 ±0.2
Bulk density (g/cm^3)	0.93	0.73	1.75
Water content (grav. %)	4.2	4.4	0.2
Molarity of Ethanol (MED) (% Eth)	18	18	18
WDPT (s)	800	1500	600

† World Reference Base (FAO, 2006).

Table 2 Ethanol-water concentrations and descriptive labels used to categorize the level of soil water repellency in the MED test (modified after Doerr, 1998).

Descriptive label	**Wettable**	**Water-repellent**					
		Slightly	**Moderately**	**Less Strongly**	**More Strongly**	**Very strongly**	**Extremely**
Ethanol concentration (%)	0	5	8.5	13	18	24	36

Table 3 Means and standard errors of the water drainage volume expressed as percentages of applied water volume in experimental runs with unimpeded drainage at the final stage of wetting. Different superscript letters next to the standard errors identify significant differences between the treatments for each soil type

Treatment	**Scrub**	**Conif**	**Dune**
Control	0.4 ±0.15^{a}	20.3 ±4.82^{a}	35.8 ±6.79^{a}
Roots	12 ±4.00^{b}	41.3 ±4.19^{b}	44.8 ±4.73^{a}
Cracks	1.2 ±0.47^{a}	59.3 ±3.57^{c}	74.6 ±1.66^{b}