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The effect of water repellent soil surface layers on preferential flow and bare soil evaporation

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ABSTRACT

Wetting patterns produced by water repellent soils are able to preferentially channel moisture deep into the soil profile, minimising storage in surface layers where it is most susceptible to evaporative loss. Although this effect has been repeatedly described in the literature, the significance of such effects under field conditions remains unclear. In order to quantify the impact of water repellency, preferential flow and evaporation rates were monitored in a series of portable soil tanks packed with soil sourced from a water repellent field site. Tanks were placed outside to expose them to environmental forcing factors and their weights after rainfall and subsequent periods of drying were recorded daily.

Increased water repellency across the wettable, low and medium water repellency classes led to increased maximum pathway depths and decreased cumulative evaporation. However, the high repellency class exhibited no difference to the medium repellency class. Soils layered to generate decreasing water repellency over 10–30 cm depth in distributions similar to that seen in the field recorded evaporative losses 70–80% lower than that in wettable control soils over 4 days of drying in autumn. Shallower layers of 5–15 cm examined during winter had evaporation reduced by 40–80% over a 4 day period even in a period of much reduced potential evaporation. It is concluded that water repellent surface layers are able to effect significant reductions in net evaporative moisture loss, in patterns which may be particularly beneficial during periods of high moisture stress in summer or during low-rainfall years. Though water repellency substantially breaks down in the field during winter, our results suggest it may continue to aid moisture conservation well into the winter season.

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1. Introduction

Soil water repellency occurs when soil particles become coated with hydrophobic chemicals produced by decaying leaf litter or fungal activity (Doerr et al., 2000; Franco et al., 2000; Roberts and Carbon, 1972). Thorough wetting of affected soils requires prolonged contact with moisture, and water repellent effects typically peak under dry summer conditions, gradually breaking down through the rainy season (Crockford et al., 1991; Doerr and Thomas, 2000; Keizer et al., 2008; Rye and Smettem, 2015; Täumer et al., 2006). The detrimental effects of water repellency are well documented in agricultural soils where partial wetting can lead to spatially variable crop growth and generally reduced yields overall (Burch et al., 1989; Ferreira et al., 2000; Leighton-Boyce et al., 2007; Prosser and Williams, 1998; Sheridan et al., 2007). However, the effects of water repellency in natural ecosystems are less well understood. It has been proposed that water repellent soil layers may allow deep-rooted plants to sequester moisture against evaporative loss (Goebel et al., 2011; Imeson et al., 1992; Lozano et al., 2013; Robinson et al., 2010; Verboom and Pate, 2006), but there is still relatively little published work which attempts to quantify this effect (Hallett, 2008; Kettridge et al., 2014; Stephens, 1994).

In water repellent soils infiltration is typically dominated by preferential flow, with active pathways representing only a small percentage of the soil cross-sectional area (Cammeraat and Imeson, 1999; Hardie et al., 2011; Nyman et al., 2010; Wang et al., 1998). Intervening regions often remain dry, allowing infiltrating moisture to bypass large fractions of the soil volume. Strong water repellency is typically confined to shallow surface layers, which contain the highest concentrations of organic matter, with repellency generally decreasing or disappearing with depth (Cammeraat and Imeson, 1999; Jaramillo et al., 2000; McGhie and Posner, 1981; Woche et al., 2005). The presence of hydrophilic soil at depth may serve as a 'redistribution zone' where flow pathways are able to spread laterally, drawing moisture rapidly down from domains above (Doerr et al., 2000; Ritsema and Dekker, 1995; Ritsema et al., 1998b). Although increased evaporation has occasionally been reported where water repellent layers served to trap moisture in thin, overlying layers of hydrophilic soil (DeBano, 1981), the highly heterogeneous nature of water repellent soils means that most moisture will simply travel down slope until it encounters an infiltration site (Doerr et al., 2003; Sheridan et al., 2007). Net effects of water repellency are thus to channel moisture deep into the soil profile while minimising

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that stored in the uppermost soil layers that are most susceptible to loss during first stage evaporation.

Field studies have demonstrated that water repellency can also serve to channel and concentrate soil moisture around the base of plants in the field (Cammeraat and Imeson, 1999; Jaramillo et al., 2000; Robinson et al., 2010), with some authors inferring evaporative benefits from observed infiltration patterns (Imeson et al., 1992). It has also been suggested that water repellency and related preferential flow mechanisms facilitate groundwater recharge (Kramers et al., 2005; Scott and Lesch, 1997; Stephens, 1994) particularly in arid or semi-arid regions where potential evaporation far exceeds precipitation (Lozano et al., 2013; Stephens, 1994).

Non-wetting characteristics can also reduce evaporative loss both by altering the geometry of the liquid/gas interface in partially saturated regions (Bachmann et al., 2001; Birdi and Vu, 1993), and by reducing rates of replenishment to upper soil layers by capillary rise (Bachmann et al., 2001; DeBano, 1981; Letey et al., 1962). Laboratory studies of evaporation rates from evenly wetted hydrophobic soils have thus reported consistently suppressed evaporative losses relative to both wettable soils (Bachmann et al., 2001; Letey et al., 1962; Shahidzadeh-Bonn et al., 2007; Shokri et al., 2009) and modelled predictions of evaporation based on soil hydraulic properties alone (Bachmann et al., 2001). Similarly, evaporation may be reduced by even a shallow surface layer of water repellent material, with reductions increasing with the maximum depth of the hydrophobic layer (Ahn and Im, 2010; Shokri et al., 2008). There is some evidence to suggest that rates of vapour flow and diffusion may also be suppressed in very strongly water repellent soils (Bachmann et al., 2001; Davis et al., 2014).

Though effects on evaporation have been widely recognised in reviews of water repellency (e.g., Doerr et al., 2000; Moore and Blackwell, 2001; Young and Young, 2002; Goebel et al., 2011), studies into the phenomenon (e.g., Cammeraat and Imeson, 1999; Imeson et al., 1992; Kettridge et al., 2014; Robinson et al., 2010; Verboom and Pate, 2006) have depended largely on inference to support the conclusion that water repellent soil layers aid moisture conservation. Attempts to precisely quantify the magnitude of such effects remain confined to laboratory examination of evenly wetted soil samples (eg, Letey et al., 1962; Bachmann et al., 2001; Ahn and Im, 2010), which neglect the significant effects of preferential flow. In the field, the effect of a water repellent soil layer on evaporation will be further complicated by seasonal variation in both the weather and the water repellent soil layers themselves, which have been found to vary in strength in a regular annual cycle at many sites. Work remains to be done to clarify the impact on annual water budgets of water repellency in native ecosystems (Kettridge et al., 2014; Müller and Deurer, 2011), and to better quantify how activities which enhance or reduce water repellency may influence evaporation rates (Hallett, 2008; Müller and Deurer, 2011; Shokri et al., 2008).

In this study, we seek to quantify water repellent evaporative effects by examining flow pathway formation and subsequent relative evaporation rates in layered soil of various water repellencies, including wettable control soils. To generate data reflective of field conditions, soils have been sourced from a water repellent woodland site, and wetting and evaporation rates monitored under ambient weather conditions. Results provide insight into the magnitude of evaporative reduction produced by water repellent soil layers, and the degree to which this advantage is able to persist through the season.

2. Materials and methods

2.1. Soil collection

Soils were obtained from a native bushland field site on the Spearwood dune system in Perth, Australia, approximately 2.5 km west of the city centre. The soil is classified as yellow-phase Karrakatta sand (Salama et al., 2001), consisting of highly water repellent dark brown topsoil over a wettable yellow sandy B-horizon. Soils of the Spearwood system are characterised by coarse textures and low organic carbon content, with Karrakatta phases having silt and clay fractions comprising only 1–2% of the soil volume, and carbon contents <1.5% in the topsoil layers, falling to <0.5% in the B-horizon (Salama et al., 2001). Water repellency was quantified from samples using the Molarity of Ethanol Drop (MED) test (Osborn et al., 1967). Water repellency was found to decrease with depth (Fig. 1), varying from an MED of around 4.0 M at the surface, and transitioning to full wetting at depths between 20 and 30 cm.

Soil was collected from the field site at a variety of depths during summer and sieved to remove leaf debris and particles larger than 2 mm. Soil was oven dried at 105 °C, and allowed to cool. Well-mixed quantities of dried soil were tested for MED in 0.2 M increments and categorised by into one of four water repellency classes. Oven drying was found to have little effect on MED values, excepting slight increases where soil was initially damp. Soil weights increased slightly when left to cool in the laboratory before being packed into soil tanks, suggesting that a small amount of moisture was absorbed from the air. Initial moisture contents after cooling varied somewhat between soil classes; average moisture contents by weight and water repellency class are provided in Table 1.

Fine river sand sourced from the banks of the Swan River in Nedlands, Perth and thoroughly washed to remove any salt was also collected to provide a perfectly wettable reference material.

2.2. Experimental design

Evaporation rates were measured in a set of ten portable clear perspex soil tanks of dimensions 0.40 m high, 0.40 m long and 50 mm in width, with walls 6 mm thick. Tank bases were impermeable, limiting moisture addition or loss to the upper soil surface only. Tanks were packed from above to bulk densities similar to that seen on site (Table 1), with soil of varying water repellency. Soil was wetted either by adding moisture to the soil surface under laboratory conditions or by natural rainfall events when placed outdoors. Tanks were weighed twice daily at 0900 and 1700 h and evaporative losses in millimetres of moisture calculated from the net weight change divided by soil surface area. Flow pathway locations, evident from sharp changes in soil colouration when wetted, were outlined on the sides of the tank with a marker pen following infiltration events so that subsequent spread or drying would be readily apparent. Soil tanks were also photographed periodically from both sides to record flow pathway locations.

To expose soil to ambient weather conditions and produce internal temperature regimes comparable to field conditions, tanks were placed outside during daylight hours. Tanks were stored in two arrays of 5 tanks each, placed side to side with the base and outer sides of the array covered with a layer of 20 mm insulation foam to minimise heat transfer through the outer edges. Tank positions within the array were

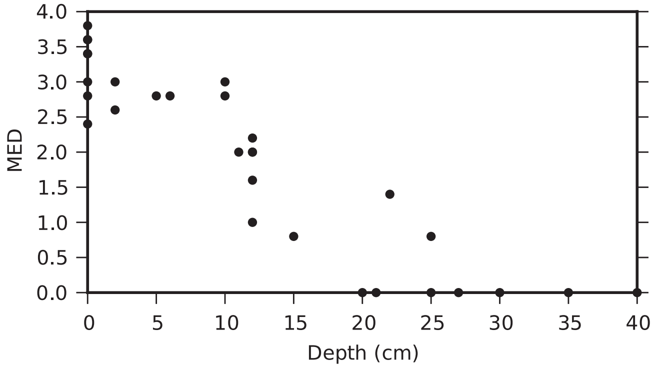

Fig. 1. Soil repellency represented by MED plotted against depth, as measured using 30 disturbed samples.

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