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Is subcritical water repellency an issue for efficient irrigation in arable soils?

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ABSTRACT

In New Zealand a resurgence of irrigation development is underway. Considerable effort is focused on developing efficient irrigation technology to maximise production per unit of applied water while ensuring minimal environmental impacts. Most New Zealand pastoral soils have the potential to develop soil water repellency (WR). Its occurrence limits water infiltration, leads to ponding of water on the soil and may enhance runoff and macropore flow. Some limited New Zealand research has shown that subcritical WR may also be common, where water infiltration is impeded by WR and water absorption into the storage pores of the soil matrix may be restricted even though the soils appear to wet readily. The objective of this research was to assess the potential of arable soils to develop WR and to analyse potential tillage effects. Soil cores were collected from the 0–5 cm depth across the three dominant soil orders used for arable production in the Canterbury region, four common tillage practices and histories, as well as from two long-term tillage trials. At each site, duplicate soil cores were collected to compare the infiltration of water to ethanol using tension disc infiltrometers. Ethanol infiltration is not affected by repellent substances, so it is used as the reference infiltration liquid to assess the degree to which water infiltration is retarded. Our results showed that subcritical WR developed in arable soils irrespective of soil order. We found significantly higher WR with decreasing tillage intensity for the long-term tillage trial. In contrast, no such significant trend was found in the regional survey, which similarly only considered sites with known long-term tillage history. It is possible that any potential effect of tillage intensity on WR was masked by confounding site or soil factors in the survey. Tillage effects on subcritical WR were shown not to persist upon change of tillage system. Our results indicate that soil management affects the degree of subcritical WR and the resultant inhibition of early-time infiltration dynamics. Hydrological significance of the results was shown by comparing actual and potential short-term infiltration, showing that suboptimal infiltration into subcritical water-repellent soils limited soil wetting and water storage efficiency. Further research is recommended that develops soil and irrigation management practices that minimise the occurrence of subcritical WR and assist in capturing more water, resulting in increased irrigation efficiencies and reduced water footprints.

1. Introduction

Fresh water scarcity is one of the most severe natural resource constraints humanity is facing. Globally agriculture is the largest user of fresh water, accounting for about 70% of total withdrawals. Agricultural water usage is essentially driven by irrigation (WWAP United Nations World Water Assessment Programme, 2014). New Zealand ranks at the top of all OECD countries in irrigated land area change. In the decade from 2002 to 2012, the irrigated land area in New Zealand has increased by 54% (254,000 ha) largely due to the expansion of irrigated dairying, viticulture and arable land in the South Island. Another important factor has been increasing application rates (OECD, 2014; Statistics New Zealand, 2012).

Over recent decades the development of efficient irrigation technology and management practices to maximise agricultural production per unit of applied water while ensuring minimal environmental impacts has been key topic in irrigation research (Hedley et al., 2009). A major challenge for efficient irrigation is the

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ability to wet up soils homogeneously. A lot has been achieved with new precision technologies such as variable rate irrigation. However, predicting the occurrence of heterogeneous soil properties potentially affecting water infiltration, permeability and water-holding capacity is difficult. Clothier and Heiler (1983) highlighted early on that heterogeneous soil properties enhancing bypass and macropore flow through the soil profile can counter the benefits of achieving homogeneous water application achieved through advanced irrigation systems. A transitional property of many soils is that they do not readily wet on contact with water. Although the soils may not be hydrophobic, wetting is slower than would be expected based on their pore size distribution, and water absorption into the storage pores of the soil matrix may be restricted. This soil property is referred to as subcritical water repellency (WR). Generally, it is assumed that a contact angle of 90° distinguishes between subcritically water repellent and hydrophobic soil conditions. A hydrophobic soil has a contact angle >90° while in a subcritical soil the contact angle is >0° and <90° (Lamparter et al., 2009). Recent experimental and theoretical work suggests that infiltration in textured materials may not occur for contact angles >50° (Shirtcliffe et al., 2006). However, as to date no experimental work with soils has been conducted to support these findings, we decided to use the traditional definition of subcritical water repellency in our study, in particular, as we did not measure contact angles directly but only inferred them indirectly. Hallett et al. (2004) concluded from their research on different scales that 'repellency can induce levels of spatial variability in water transport at small scales comparable to what macropores induce at larger scales'. Quantifying subcritical WR is potentially significant for water and nutrient use efficiency under irrigation, particularly on sloping land susceptible to runoff or soils prone to preferential flow with an enhanced risk of contaminant leaching. To the best of our knowledge the relationship between irrigation efficiency and subcritical soil WR has not been analysed yet.

Previous research has found that New Zealand pastoral soils are prone to develop severe WR independent of soil order and climate (Deurer et al., 2011). Subcritical WR is generally less well studied (Hallett et al., 2001) than severe WR (Doerr et al., 2007). One reason for this is that simple WR tests including, for example, the water drop penetration time (WDPT) test and the molarity of ethanol droplet (MED) test (King, 1981) cannot determine subcritical WR, where the contact angle formed between the tangent of the soil-water surface and the tangent of the water-air surface is smaller than 90°. The MED test can only be used to determine apparent contact angles >90° (Carrillo et al., 1999). Bachmann et al. (2003) summarised problems of the WDPT test. Tillman et al.'s (1989) repellency index, the ratio of ethanol and water sorptivity, taking into account the properties of the liquids, is a physical meaningful measure of subcritical WR. Using this method, some limited New Zealand research has shown that subcritical WR may be common in New Zealand soils irrespective of land use (Wallis et al., 1991).

Management of agricultural land affects soil properties that are regulating water infiltration and fluxes in soil. For example, conservation cultivation such as no-till is generally assumed to increase organic carbon levels (West and Post, 2002) although recent work suggested that these beneficial effects could be restricted to topsoil horizons (Baker et al., 2007). Comparatively little work has been conducted on the impact of tillage practices on soil WR. It is common knowledge that cultivated land is less prone to WR than permanently vegetated land (Doerr et al., 2006; Urbanek et al., 2007; Woche et al., 2005). In line with this, the general assumption is the lower the tillage intensity, the higher is the level of WR (Blanco-Canqui, 2011; Hallett et al., 2001). Indeed results showed decreased sorptivities under reduced tillage systems (Hallett et al., 2001; Król et al., 2013) which coincided with increased bulk density and organic matter contents in one study (Lipiec et al., 2006). The impact of subcritical WR on aggregate stability has been studied in some detail (e.g., Goebel et al., 2005; Hallett et al., 2001; Urbanek et al., 2007; Vogelmann et al., 2013). Low levels of WR have been shown to promote aggregate stabilisation (Eynard et al., 2004). But all these measurements have been restricted generally to single aggregates.

In the first part of this study we assessed the potential of arable soils in New Zealand to develop water-repellent surface conditions. We identified the most prevalent soil orders used for arable production to be included in the survey, Luvisol, Fluvisol and Cambisol, and assessed their potential to develop repellent surface conditions during dry periods. The more specific objectives of this study were (i) to investigate the effect of tillage intensity on subcritical WR at the scale of tension infiltrometers (disc area 85 cm^2) and soil organic carbon contents, (ii) to analyse the persistence of such potential effects, and (iii) to test the hypothesis that greater levels of organic carbon are associated with increased levels of soil WR.

2. Materials and methods

2.1. Sites

To assess the predisposition of arable soils to develop WR, we concentrated on the Canterbury region, where the majority of arable production occurs in New Zealand. In a GIS analysis overlaying soil maps with land use maps, we identified the three most extensive soil orders in the New Zealand Soil Classification (Hewitt, 2010) under arable production, with 49% of arable land occurring on Pallic soils, 20% on Brown soils, and 13% on Recent Soils. These soils classify as Luvisol, Cambisol, and Fluvisol in the World Reference Base Classification (Hewitt, 1998; IUSS Working Group WRB, 2006). Furthermore, we considered four long-term tillage intensity treatments, long-viz. intensive tillage, minimum tillage in a crop rotation, minimum tillage with a 1- to 2-year grass period in the crop rotation and direct drilling, which represent the most typical tillage systems practised in Canterbury. Grass is used as a restorative phase in typical crop rotations. We sampled 45 sites representing the three soil orders and four tillage systems with three to four repetitions per factor combination in an unbalanced two-factorial experimental design. While we aimed for four repetitions per treatment, we did not find four arable sites under long-term direct drilling and minimum tillage in a crop rotation under Recent Soil in Canterbury. For these two factor combinations we used an unbalanced design with three repetitions. Information on the location of the sampling sites is provided in Table 1 and Fig. 1. Long-term median annual rainfall in Canterbury plains varies from 900 mm at the western foothills of the Southern Alps to <500 mm in the coastal eastern area of the plains, with annual long-term mean potential evapotranspiration deficit ranging from 50 to 500 mm (NIWA, 2015). The majority of sites used in this study were located in the 500–700 mm annual rainfall zone.

A long-term tillage trial established in 2008 under maize (*Zea mays* L.) on an Allophanic Soil (Andosol; (Hewitt, 1998; IUSS Working Group WRB, 2006)) was chosen as additional site in the Waikato region, North Island (Fig. 1). The plot trial has several replicated tillage treatments (plots, 50 m long with 16 rows of maize) plus a 'control' of uncultivated permanent pasture surrounding the trial area. We considered the following treatments: intensive tillage, minimum tillage and direct drill. The locations of our sampling sites are detailed in Table 2. Median annual rainfall in this area is 1070 mm, and the average temperature is around 14 °C, with 40–50 mean annual days of soil water deficit (Chappell, 2015).