Agricultural Water Management 143 (2014) 82–92

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Temporal dynamics of soil water repellency and its impact on pasture productivity

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ARTICLE INFO

Article history:
Received 19 January 2014
Accepted 27 June 2014
Available online 18 July 2014

Keywords:
Soil water repellency
Hydrophobicity
Pasture productivity
Temporal variability
Soil water content

ABSTRACT

New Zealand pastoral soils have the potential to develop water-repellent conditions irrespective of regional climate and soil orders. The aim of this study was to improve the understanding of the temporal dynamics of soil water repellency (SWR), the mechanisms leading to this transient soil condition and its effect on pasture productivity. Topsoil actual and potential SWR, water contents and pasture production were monitored at monthly to bi-monthly intervals on two hill country pastures located in Hawke's Bay and the Waikato, New Zealand, between December 2009 and March 2012. Clear seasonal dynamics of SWR were observed with peaks during dry and warm periods and breakdown of SWR after wet periods. While the actual persistence of SWR was negatively correlated with the soil water content, it was not directly related to rainfall. But it was significantly and negatively correlated to the soil moisture deficit. Low soil fertility promoted SWR. These results confirm that soil water content alone is not a reliable predictor for the appearance and disappearance of SWR. We also conclude that a large contact angle indicates not only a high degree of SWR, but also a high persistence. One potential explanation for the high variability of the potential of SWR might be that hydrophobic organic substances causing SWR are partly and periodically leached out of the soil profile. During the summer months, pasture productivity was reduced by 48% at the Hawke's Bay site, and 48% of the observed variability in dry matter production during the entire investigation period of 2 years could be explained by the degree and the potential persistence of SWR. Our results confirm that SWR is an issue for New Zealand pastoral production that requires development of mitigation strategies.

1. Introduction

Soil water repellency (SWR) can compromise the delivery of the many ecosystem services that soils provide: for example, enabling rapid infiltration of rainwater; buffering runoff and regulating flooding; providing clean water; and providing storage for nutrients, carbon and plant-available water (Wallis and Horne, 1992; Doerr et al., 2000, 2006). Potential adverse environmental consequences have been studied to some degree including the accelerated leaching of agrichemicals (Jarvis et al., 2008) and the enhanced runoff of water and solutes (Jeyakumar et al., 2014) leading to contamination of water resources. The potential resulting economic consequences of SWR for farmers have received less attention (Blackwell, 2000; Müller et al., 2010). Also, it has not been attempted to quantify the economic impact for society such as through water contamination and enhanced flood risks.

It is widely recognised that SWR is occurring worldwide in many regions (Dekker et al., 2005), under different soil types (Vogelmann et al., 2010; Deurer et al., 2011), independent of land use (Doerr et al., 2006) and poses a threat to soil quality and function. The spatial and temporal dynamics of SWR are still poorly understood. Soil water repellency is a transient soil property (Doerr et al., 2000) and its breakdown and reestablishment as soil dries out and is rewetted has not been well investigated (Jury et al., 2011). Predicting the appearance and disappearance of SWR is not yet very successful. Attempts have included simple empirical models and conceptual numerical models. The empirical models take into account the soil water content, matric potential and soil organic carbon content

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http://dx.doi.org/10.1016/j.agwat.2014.06.013

(Karunarathna et al., 2010a, 2010b), all of which have been identified early on as critical factors for the development of SWR (Dekker and Ritsema, 1994; Doerr et al., 2000). Ritsema et al. (2005) divided the soil profile into water-repellent and hydrophilic areas and assigned distinctive hydraulic properties to each. A more sophisticated modelling approach (Bachmann et al., 2007; Deurer and Bachmann, 2007) similarly considered the soil water content as the key factor. In this modelling framework, the contact angle is a dynamic property dependent on water content and time. Moreover, hydraulic properties are formulated as functions of the actual soil water repellency. However, the relationship between SWR and soil water content has proven to be more complex than previously thought (Doerr et al., 2007; Diehl, 2013). Many environmental factors have been shown to influence the breakdown and reestablishment of SWR. These include, *inter alia*, the pH of the soil (Diehl et al., 2010), the ambient air temperature (King, 1981) and drying temperature (Diehl et al., 2009), the ionic composition of the soil solution (Graber et al., 2009) and the relative humidity (Wallach and Graber, 2007). One of the reasons for the lack of progress is the knowledge gap around the root source of SWR in spite of decades of intensive research activities in this area. We know that SWR is caused by hydrophobic organic substances that cover soil particles (Bisdom et al., 1993) or exist as interstitial matter (Franco et al., 2000). These substances can be plant material, root exudates, fungal hyphae or they can be derived from the decomposition of litter, roots, fungi, bacteria or other organisms (Hallett, 2008). We have hypothesised that low soil fertility leads to a lower soil microbial activity and lower abundance, which in turn decreases the decomposition of soil organic matter and promotes the generation of water repellent topsoils (Müller and Deurer, 2011).

Over the time scale of seasons some information on the dynamics of SWR is available. Seasonal variability of SWR has been observed in forests (Burch et al., 1989; Ferreira et al., 2000; Buczko et al., 2005; Rodríguez-Alleres and Benito, 2011), under permanent pasture (Hardie et al., 2012), throughout a crop-rotation cycle with potatoes, maize and fallow (Keizer et al., 2007) and under sports turf (Kostka, 2000). But there are relatively few studies that have measured actual and potential soil water repellency throughout a year. It is still not clear if the persistence of SWR of oven-dried samples, which is commonly thought to be equivalent to the risk of SWR occurring when soils dry out, can be expected to be constant throughout a year. This knowledge gap is due to the lack of understanding of the root causes of SWR.

Grazed pasture provides the bulk of feed on New Zealand's animal production farms. The volume and nutritive value of the pasture directly influence the production and profitability of these farms. In fact, pasture-based farming is the fundamental platform for 35% of New Zealand's annual gross domestic product. In the Waikato region, low soil moisture is a major constraint to pasture production during summer, and recent droughts have highlighted the limitations of the predominant pasture species, perennial ryegrass (*Lolium perenne*). Soil water repellency has also been linked to the dry patch syndrome (DPS), the patchy occurrence of bald areas in a paddock in New Zealand, which have been estimated to cover more than 60% of individual paddocks (Deurer et al., 2007; Deurer and Müller, 2010). We consider that SWR plays a major role for reducing dry matter production during droughts, and during the rewetting of the soil afterwards. There is the need to quantify the impact of SWR on productivity to inform farmers on the economic relevance of the phenomenon, so that they might consider mitigation options.

We have investigated the temporal development of soil water repellency under permanent pasture grazed by sheep and beef in two regions of New Zealand's North Island over a period of 2 years, including three summers. The specific objectives of this research were (i) to quantify the temporal variation in soil water repellency throughout a calendar year under permanent pasture in two regions through monthly to bimonthly analyses during a period of 2 years, (ii) to assess the relationship of topsoil water content, climatic parameters and soil water repellency, and to analyse *in situ* the wetting patterns of water-repellent soils after significant rainfall events, (iii) to quantify the impact of soil water repellency on pasture productivity for a pasture exhibiting DPS during a calendar year using areas outside of the dry patches as hydrophilic control sites, and (iv) to analyse the impact of a soil's fertility status of the topsoil, here different phosphorus levels on the occurrence of soil water repellency.

2. Materials and methods

2.1. Sites and soils

During the period of 2 years from January 2010 until March 2012, we investigated the development of the characteristics of SWR and pasture growth at two hill-country sheep/beef pastoral sites in Hawke's Bay and in the Waikato at monthly to bimonthly intervals. The regions selected are both prime areas for sheep and beef farming and are located at the west and east coast of New Zealand's North Island. Both areas have a temperate climate with maximum rainfall during winter and potential summer droughts despite a high annual rainfall. The relatively calm, dry sunny climate of the Hastings District (Hawke's Bay) is characterised by long hot summers and mild winters. The average long-term (1981–2010) annual rainfall is 1694 mm with a minimum rainfall of 309 mm during summer (New Zealand National Climate Database; http://cliflo.niwa.co.nz/). The average long-term daily temperature is 11.8 °C with an average maximum temperature of 16.1 °C in summer and an average minimum temperature of 7.3 °C in winter. The Waikato region is exposed to prevailing west and southwest winds from the Tasman Sea resulting in mild, humid conditions. The average long-term annual rainfall is 1616 mm (1981–2010; meteorological station located at the Whatawhata Hill Country Station) with a long-term maximum and minimum of 516 and 303 mm during winter and summer, respectively. The average long-term daily temperature is 13.9 °C with an average maximum of 17.9 °C in summer and an average minimum temperature of 9.8 °C in winter.

The Hawke's Bay site was located near Maraetotara (39.85S, 176.87E), where we had previously established a link between the DPS and SWR (Deurer et al., 2007). The soil in the centre of dry patches (DP) showed a higher degree of SWR and a higher critical soil water content threshold than the soil outside of DP. Another site suffering from severe SWR had been identified at the Whatawhata Hill Country Station located in the Waikato Region (Aslam et al., 2009). This site is a control site in a long-term phosphorus (P) fertilisation experiment (37.48S, 175.05E). The pasture has not received any mineral phosphorus fertilisation for 30 years, which resulted in an Olsen-P of the topsoil of 17 mg/kg at the time of our study. More information on the long-term experiment can be found in Schipper et al. (2009).

Maraetotara is located in an elevated area (>2000 m AMSL) predominantly formed on limestone outcrops. The soils are generally classified as Mottled Argillic Pallic Soils (Aquic Haplustalf, USDA classification) with a light silt loam texture. The soils are imperfectly drained with a mottled profile. Soil water perches on the slowly permeable siltstone layer and runs downhill along the sandy subsurface horizons. Despite high annual rainfall, the pastures can dry off fairly rapidly during summer, or in periods with infrequent rain. The paddock located in the Waikato is a well-established ryegrass-clover pasture on a steep slope of 25–30°. The soil is classified as Mottled Yellow Ultic Soil (Aquic Hapludult, USDA classification). It developed from saprolite derived from sedimentary