Geoderma 221–222 (2014) 121–130

Contents lists available at ScienceDirect

Geoderma

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

A novel approach to quantify the impact of soil water repellency on run-off and solute loss

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ARTICLE INFO

Article history:
Received 24 April 2013
Received in revised form 8 January 2014
Accepted 10 January 2014
Available online 4 February 2014

Keywords:
Soil water repellency
Ethanol solution
Run-on
Run-off coefficient
Solute transport
Multivariate regression analyses

ABSTRACT

We developed a laboratory-scale *r*un-*o*ff *m*easurement *a*pparatus (ROMA) to quantify for the first time directly the impact of soil water repellency (SWR) on run-off from undisturbed soil slabs in the laboratory. We tested and evaluated the performance of ROMA with multiple consecutive run-off experiments using water followed by a fully-wetting liquid, namely an ethanol solution. We found that a 30% (v/v) ethanol solution was needed to ensure that the soil hydrophobicity had no influence on the infiltration rate of the liquid. The results demonstrated the ROMA is a robust and reproducible tool that performs at a high standard with instrument errors below 2%. We conducted ROMA run-off experiments with air-dried soil slabs (480 mm long × 190 mm wide × 50 mm deep) collected from four pastoral sites, representing three major soil orders in the North Island, New Zealand. They were the Kashmir-Recent Soil (Fluvisol), Hawke's Bay-Recent Soil (Fluvisol), Taranaki-Gley Soil (Gleysol), and Taranaki-Organic Soil (Histosol). These soils had a high degree and persistence of SWR. The contact angles were 97, 97, 98 and 104°, the potential water drop penetration times (WDPT) were 4, 42, 54 and 231 min, and the run-off fractions were 16, 19, 28, and 96% respectively. However, even the extremely hydrophobic Taranaki-Organic Soil, which had a runoff coefficient of 96%, only lost 13% of the applied bromide via run-off. This demonstrates that run-off occurred in rivulets covering only a small fraction of the surface. Multivariate regression analyses showed that the soil organic carbon content and the degree of SWR explained 89% of the variability of the run-off coefficients. We identified difficulties around the meaningfulness of the persistence of SWR, as determined by the WDPT test, since it just measures SWR at a single point. Alternatively, our ROMA experiments integrate the spatial variability of SWR of an undisturbed soil slab. In addition, the method is faster for extremely hydrophobic soils once the ROMA is set up.

1. Introduction

Surface run-off is a fraction of the rainfall or irrigation that does not infiltrate the underlying soil. Instead this water more rapidly reaches rivers, streams, storm sewers and other conveyance systems. The environmental impacts of enhanced run-off can contribute to flooding, accelerated soil erosion, and nutrient and pesticide export. These can lead to the polluting of water resources, reduced seed germination and crop growth. Enhanced run-off also reduces groundwater recharge, subsequently lowering water table recharge and enhancing drought. For example, Bot and Benites (2005) reported that up to 40% of rainfall may disappear as run-off in drylands, contributing to low crop yields. This poor utilization of rainfall is partly the result of natural phenomena (soil type, topography, and rainfall intensity), but it is also related to inadequate land management practices (such as trampling livestock, burning of crop residues, excessive tillage, eliminating hedges). These can degrade soil structure, reduce organic matter, and eliminate beneficial soil fauna, thereby reducing water infiltration rates. In New Zealand, run-off and its significant impact on soil health and water quality have been well identified (Cooper et al., 1992; Müller et al., 2010a; Pennington and Webster-Brown, 2008). New Zealand's hilly topography amplifies the risk of run-off generation, but farming practices like land clearance and over-grazing continue to be a leading cause of run-off problems. Many studies have been conducted on run-off and its environmental and economic impacts in New Zealand farming systems (Drewry, 2006; McDowell, 2006; McDowell et al., 2003; Nguyen et al., 1998). Some studies have indicated a negative relationship

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http://dx.doi.org/10.1016/j.geoderma.2014.01.008

between run-off and soil moisture content (Gillingham and Gray, 2006), which has been attributed to soil conditions like water repellency.

Soil water repellency (SWR) has been reported worldwide in pastoral and cropping systems (Dekker and Ritsema, 1996), forests (Ferreira et al., 2000; Miyata et al., 2007), and shrublands (Ferreira et al., 2005). Several studies have reported soil water repellency in New Zealand (Horne and McIntosh, 2000; Müller et al., 2010b; Wallis et al., 1991). Most recently, Deurer et al. (2011) conducted a survey on the SWR occurrence of soils across 50 sites under pastoral land-use in the North Island of New Zealand. They found that 49 out of 50 sites (98%) will become hydrophobic when they dry out, and that 35 out of 50 sites (70%) were hydrophobic at the time of sampling, in summer 2009/10. Many studies have shown the relationship between run-off and SWR (Cerdà and Doerr, 2007; Doerr et al., 2003; Leighton-Boyce et al., 2007). However, most previous studies on surface run-off generation on water-repellent soils have used an indirect method to attribute the increase of run-off to an increase in SWR (Frasier et al., 1998; Gomi et al., 2008). This means, for example, that statistical correlations between run-off and SWR have been used. Only a few studies have attempted to study the impact of SWR on run-off directly. For example, Leighton-Boyce et al. (2007) compared the run-off of water with the run-off of water plus a wetting agent at a rate of 4 mL L^{-1} water in simulated rainfall experiments in eucalyptus plantations on water-repellent soils. The wetting agent was assumed to generate hydrophilic soil conditions. They reported 16 and 100 times higher run-off coefficients (33 and 70% of rainfall) under repellent than wettable conditions for the same soils on small plots of lower and higher water-repellent terrains respectively. However, a potential disadvantage of using a wetting agent to simulate hydrophilic conditions is that it is unknown whether the infiltration behaviour of water mixed with concentrated wetting agent mimics the infiltration behaviour of pure water in hydrophilic soils. In addition, some concentrated wetting agents may cause toxic effects on plants (Sunderman, 1983). Philip (1969) defined the intrinsic sorptivity of a liquid as the function of dynamic viscosity, surface tension and the sorptivity of the liquid. Tillman et al. (1989) suggested that the ratio of the apparent intrinsic sorptivity of ethanol to that of water, the so-called repellency index, quantifies the impact of water repellency on water absorption. They found that in a hydrophilic soil, the repellency index cannot be greater than 1.95, and this is a useful index of sub-critical repellency. Wallis et al. (1991) showed that the repellency index was higher than 1.95 in most of New Zealand soils tested. Recently, Miyata et al. (2007) measured the effect of SWR on run-off generation by comparing the run-off generated by spraying a 36% ethanol solution and water on micro-plots of 30 × 30 cm^2 in the field. They demonstrated that SWR of surface soils caused overland flow despite the soil's high saturated hydraulic conductivity measured under hydrophilic conditions. Even though they used a fully wettable ethanol solution as a proxy measure of hydrophilic condition, they only conducted a spray demonstration experiment with an intensity of 182–335 mm h^{-1} over a period of 40 s. Further, these experiments were conducted in situ, but to our knowledge, no laboratory-scale measurements to measure directly the impact of SWR on run-off have yet been conducted.

The wettability of topsoils can be quantified by determining the persistence and the degree of SWR. The persistence of SWR is measured using the water drop penetration times (WDPT) test (King, 1981) and the degree of SWR can be indirectly derived using the molarity of ethanol-droplet (MED) test (Roy and McGill, 2002). These measurements are point measurements, but SWR, and especially its persistence, has a large spatial variability (Lemmnitz et al., 2008). The spatial heterogeneity of SWR has been reported at different scales, ranging from centimetres to the decimetre or metre scale (Gerke et al., 2001; Lemmnitz et al., 2008). The high spatial variability of SWR in dune sands under grass, as reported by Jungerius and Ten Harkel (1994), was partly explained by differing vegetation forms and the different thicknesses of the litter cover (Buczko and Bens, 2006; Crockford et al., 1991; Doerr et al., 2000; Witter et al., 1991). Gerke et al. (2001) linked the high spatial variability of water repellency to the heterogeneous spatial distribution of lignite and minerals within the soil. Biemelt et al. (2005) found that hydraulic properties and erodibility of soils were closely related to the spatial pattern of water repellency among the micro-topographic structures of ridges and gullies. These studies question the relevance of measuring the persistence of SWR at the field scale using the WDPT test. In addition, Graber et al. (2006) pointed out the potential impact of sample preparation for the measurement of the persistence of SWR.

Therefore, in order to better define the dynamics of run-off generation from water-repellent soils, and to propose an alternative method to predict the persistence of SWR, we developed a '*r*un-*o*ff *m*easurement *a*ppliance (ROMA)' to quantify the impact of SWR on run-off using undisturbed soil slabs in the laboratory. The objectives of this study were to (a) evaluate the technical performance of ROMA for assessing run-on (constant application of a liquid across the upper end of a soil slab) and run-off rates of water and ethanol solution, and (b) quantify the impact of SWR on run-off and loss of agrichemicals in run-off from different soil types.

2. Materials and methods

2.1. Design and functional features of ROMA

We developed our ROMA to assess how SWR affects the run-off behaviour of an undisturbed soil slab subjected to run-on applied to the top of the soil slab at a specified rate (Fig. 1a and b). The soil slab (480 mm long × 190 mm wide × 50 mm deep) is fitted tightly onto a perforated sample tray that can be adjusted to the different slopes of 5, 10 and 20°. We used rubber-foam liners and expanding foam (Orica NZ Ltd, Auckland) between the soil slabs and the side plates to prevent any leakage along the sides of the soil slabs. The perforated sample tray accommodates drainage from the soil and retains the soil slab.

Water or ethanol is applied as run-on to the top end of the soil slab at a rate simulating typical run-on volumes during a natural rainfall event on a hill-slope. Based on a literature review of the rainfall-run-off experiments carried out in New Zealand and elsewhere (Elliott et al., 2002; Lei et al., 2006; Leighton-Boyce et al., 2007), a rainfall intensity range of 45 to 60 mm h^{-1} was used for the ROMA experiments. A polycarbonate manifold with eight hypodermic needles (BD PrecisionGuide™ Needle, Australia) is connected to a storage tank providing a constant run-on rate of water or ethanol solution. A pressure head is maintained by a floating switch, controlled by a solenoid switch powered with a 12 V battery to ensure a steady run-on rate.

When the water reaches the soil surface, the local infiltration capacity of the soil controls whether the water infiltrates into the soil or ponds locally on the surface of the soil and eventually runs off the soil surface or re-enters the soil somewhere else. If the infiltration capacity of the soil is smaller than the rainfall intensity then surface run-off 'infiltration-excess' occurs (Beven, 2001). The total run-off volume is collected at the bottom of the soil slab in an 'overland flow trough' (Fig. 1) allowing the determination of run-off rates. Parallel to the perforated sample tray is a second tray, the 'drainage collection tray', which is connected to a separate trough (Fig. 1). This allows measuring of water volumes and rates drained below a soil depth of 50 mm. We conducted all run-off experiments with water followed by a fully-wetting liquid, namely the ethanol solution. We determined that the 30% (v/v) ethanol solution was necessary to overcome the impact of SWR on infiltration via a preliminary study using the MED test (Roy and McGill, 2002). This test can determine whether the contact angle (CA) is larger than 90°, the threshold for occurrence of hydrophobicity. In the MED test, the surface tension of the wetting liquid, an aqueous ethanol solution, is varied to the point where the soil spontaneously (<10 s) adsorbs the liquid and where the contact angle between soil surface and the liquid is 90°. Soil samples (~60 g) from a range of hydrophobic soils