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Runoff and nutrient loss from a water-repellent soil

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ABSTRACT

The effects of soil water repellency (SWR) on runoff and nutrient losses are difficult to isolate. Hydrophobic organic substances coating soil particles can severely delay water infiltration and enhance runoff. We used a portable run-on simulator to investigate the effect of SWR on runoff and nutrient loss. Intact soil slabs, 0.48 m long and 0.19 m wide, were collected from a severely water-repellent Andosol under pasture. One day before simulating 60-min long run-on events with an intensity of 60 mm h^{-1}, superphosphate was applied at a rate of 45 kg P ha^{-1}. The effects of SWR were quantified by comparing runoff volumes and nutrient losses from run-on events conducted with water and a fully wetting aqueous ethanol solution as run-on liquids. Further, through conducting multiple consecutive water run-on events with the same soil slab, the hypothesis, that SWR is lost through the washing off of hydrophobic materials, was tested. Finally, runoff dynamics were visualised by adding a dye to the run-on water. In the first run-on experiment, 88% of the water applied was captured as runoff, while no runoff was observed when aqueous ethanol was used as run-on liquid, providing strong evidence that SWR governed runoff generation from this Andosol. In consecutive water run-on experiments, approximately 23% of the applied P was recovered in the runoff from the first event, while the cumulative P loss over ten consecutive run-on events was around 30% of the applied P. This confirms that nutrient losses were associated with SWR and the occurrence of runoff. After ten consecutive run-on events, the persistence of both actual and potential SWR in areas of the slab that had been wetted were significantly ($p < 0.5$) reduced. But the persistence of potential SWR of the soil was still classified as severe, suggesting only minor losses of hydrophobic materials from the soil surface. The persistence of potential SWR and the degree of SWR of the dry areas remained more or less unchanged. In accordance with this, visualisation of the wetted areas showed that runoff occurred as rivulets guided by surface topography, rather than as sheet flow, with the wetted area increasing from approximately 20% of the slab in the first event to around one third of the total slab area in the final event. This pattern is reflected in the cumulative pattern of the P losses over the ten events. Consequently, we conclude that SWR should be considered as a factor in hydrological modelling and should be included in models to address appropriately the risk of surface water contamination by solutes exogenously applied to water-repellent soils.

1. Introduction

The infiltration of water into water-repellent soils can be severely delayed when soil particles are coated with hydrophobic organic substances, which lower the wettability of the soil. This has implications for surface runoff and erosion, water storage and for plant growth. Many studies have suggested that surface runoff and overland flow increase with an increase in soil water repellency (SWR) (Ferreira et al., 2016; Gomi et al., 2008b; Keizer et al., 2005; Miyata et al., 2010; Valeron and Meixner, 2010). A majority of these studies focused on the impact of forest fires. Estimates of the increase in runoff and overland flow caused by SWR ranged from three (Burch et al., 1989) to 16 times (Leighton-Boyce et al., 2007). While many researchers have inferred that SWR enhances runoff and hence nutrient losses, the effect of SWR has only very rarely been isolated from other hydrological factors such as surface sealing and compaction (Keizer et al., 2005). Most attempts to quantify the effect of SWR on runoff have relied on indirect methods that attribute the increase of runoff to an increase in SWR (Gomi et al., 2008b; Leighton-Boyce et al., 2007). For example, runoff has been statistically correlated to SWR. One study measured the impact of SWR

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on runoff directly by comparing results when either water, or water plus a surfactant, was used in simulated rainfall experiments (Leighton-Boyce et al., 2007). It is a well-established method to assess the effect of SWR on infiltration by comparing the infiltration dynamics of water with those of a completely wetting liquid such as ethanol (Lamparter et al., 2010). Recently, we have adopted this method to study the effect of SWR on runoff (Jeyakumar et al., 2014).

Spatial variability of runoff connectivity and development of flow networks is directly related to rainfall intensity and soil infiltration capacity and is therefore also affected by antecedent soil moisture conditions (Cantón et al., 2011). Generally, runoff exhibits threshold behaviour such that the initiation of runoff requires a certain amount of rainfall. When the rainfall rate exceeds the rate of infiltration, excess water accumulates on the soil surface in depressions, forming puddles. Runoff starts once surface storage is filled and the puddles overflow (Horton, 1933). At a similar rainfall rate, the runoff rate depends on soil surface conditions including micro-topography, depressions, stone cover, water-repellent and surface hydraulic conditions (Gomi et al., 2008a). For example, a study analysing the temporal dynamics of runoff on forested hill slopes in Portugal found that runoff at times of strong to extreme SWR was significantly higher than when there was only slight, or no SWR (Pierson et al., 2009). The between-year variability in runoff and infiltration in soils with SWR was assessed in several burned and unburned sagebrush systems. The large variability indicated that the influence of SWR on runoff generation is quite variable, and its impact might be masked by short-term fluctuations in repellency (Pierson et al., 2008). As far as we know no studies have quantified runoff connectivity and the dynamic changes in runoff as influenced by SWR. To improve surface runoff modelling, better conceptualization of the underlying processes is necessary. Contreras et al. (2008) distinguished three runoff patterns for water-repellent soils. According to these authors all runoff hydrographs on repellent soils are characterized by the highest runoff rates at the beginning of an event. This assumes a water-repellent topsoil. The first runoff hydrograph type results from a rainfall rate exceeding the infiltration rate of the repellent topsoil layer. Runoff patterns then can be further differentiated depending on the existence of macropores and cracks or an underlying impermeable layer, which would lead to saturation-excess flow conditions. While SWR most often occurs in the topsoil, a water-repellent layer can also be sandwiched between wettable top and subsoil layers (Doerr et al., 2000). Thus, the suggested three runoff hydrograph patterns on repellent soils are not sufficient to capture the complexity of the response of water-repellent soils to rain.

Runoff studies are hampered by the unpredictability of runoff-generating rainfall events. The use of rainfall simulators is a reliable method for creating reproducible scenarios under semi-controlled conditions (Zhang et al., 1997). Major drawbacks associated with rainfall simulation studies are their small scale, the different characteristics of simulated rainfall compared with natural rainfall (Lascelles et al., 2000; Tossell et al., 1990), and high experimental costs. Rickson (2002) reviewed rainfall simulation techniques, highlighted issues related to the various approaches and techniques, and concluded that there is no ideal rainfall simulator. However, Neff (1979) concluded, 'we have no alternative' for investigating runoff processes. To avoid the discussion around the comparability of the heterogeneity and kinetic energy of natural and artificial rainfall, we decided to simulate inflow runoff (run-on) volumes to soil slabs instead of simulating artificial rainfall (Fabis et al., 1993) using our portable rainfall simulator (ROMA - RunOff Measurement Apparatus) (Jeyakumar et al., 2014). Run-on experiments allow one to exclude the kinetic impact of raindrops on the soil surface and thus, to isolate the effect of SWR on water dynamics from other processes such as surface sealing. In contrast to others (e.g., Darboux et al., 2008), we use intact soil slabs to quantify the effect of SWR on runoff.

Our main objectives were (i) to quantify the effects of SWR on runoff and phosphorus (P) losses, (ii) to assess how SWR affects runoff and infiltration dynamics during successive events, and (iii) to investigate if rainfall leaches hydrophobic organic compounds from the soil, thereby requiring the input of new hydrophobic material to re-establish SWR following substantial rainfall.

2. Materials and methods

2.1. Collecting soil samples

Soil was collected from a severely water-repellent Pumice Soil (Andosol; FAO, 2006) under permanent pasture on a beef farm near Tihoi, New Zealand (−38.394959, 175.444809; GPS coordinates). On 20 December 2013, six intact topsoil slabs from a north-facing hillslope with an average slope of 16° were collected. On 27 November 2014, three additional intact topsoil slabs from the same hillslope were collected. All collected topsoil slabs were larger than the required size for the ROMA trays (0.2 × 0.5 m) and were wrapped in plastic to reduce the risk of damage and evaporative losses during transport to the laboratory. Four soil samples (0–0.05 m depth) were taken adjacent to each slab with a spade and immediately sieved (< 5 mm) to remove the thatch, a layer of organic matter accumulated around the base of the pastoral plants; the remaining soil (designated 'disturbed' soil sample) was placed in sealed plastic bags. In addition, intact soil cores (0.05 m diameter × 0–0.03 m) were collected close to the slabs in 2014. All slabs, cores and disturbed soil samples were stored at 4 °C prior to conducting the experiments.

In November 2014, water infiltration rates into the topsoil were measured using tension disc infiltrometers at −70, −40, −20 and −10 mm tension in triplicate. Unsaturated hydraulic conductivity K was derived at each of these tensions as described by Reynolds and Elrick (2005). The infiltrometer results at a steady state, at each given tension were used to estimate the mean pore size weighted by flow, α, at this tension (Reynolds and Elrick, 1991). A large α indicated that the unsaturated flow was dominated by gravitational force, meaning that macropore flow dominated over matrix flow.

2.2. Determining physico-chemical soil properties

Approximately 100 g of each disturbed soil sample was passed through a 2-mm sieve. The gravimetric soil water content (GWC) and pH (in 1 M KCL) were measured using standard methodology (Blakemore et al., 1987). The pH meter was a Hanna HI 9812. Total soil organic carbon (SOC) and nitrogen content were analysed by the Dumas method for %C and %N using a Leco TruMac instrument (Blakemore et al., 1987). Hot water extractable carbon (HWC) was determined using the method developed by Ghani et al. (2003). Dissolved organic carbon (DOC) in the HWC extracts was determined by high temperature catalytic combustion using a Shimadzu TOC-V CSH total organic-carbon analyser (Ghani et al., 2003). For the second measurement campaign in 2015, subsamples for textural analysis were sieved to < 4 mm, air-dried and dispersed using an ultrasonic vibrator before being separated into sand, silt and clay fractions using a sieving and settling process (Gee and Or, 2002). Bulk density was determined following standard procedures (Blakemore et al., 1987).

2.3. Conducting runoff experiments

Design and performance of the ROMA have been described in detail by Jeyakumar et al. (2014), where we conducted consecutive run-on events with water and a fully-wetting liquid on the same water-repellent soil slab. ROMA allows measuring volumes and rates of the applied run-on liquid running off the soil surface and draining below the soil slap depth. The set-up is shown in Fig. 1. In brief, a polycarbonate manifold with eight hypodermic needles is connected to a storage tank to simulate a constant run-on rate of 60 mm h^{-1}. A constant pressure head is maintained by a floating switch controlled by a

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