Geoderma 287 (2017) 98–104

Contents lists available at ScienceDirect

Geoderma

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

Assessing soil water repellency spatial variability using a thermographic technique: An exploratory study using a small-scale laboratory soil flume

João R.C.B. Abrantes [a,*], João L.M.P. de Lima [a], Sérgio A. Prats [b], J. Jacob Keizer [b]

[a] MARE - Marine and Environmental Sciences Centre, Department of Civil Engineering, Faculty of Science and Technology of the University of Coimbra, Rua Luís Reis Santos, Pólo II – Universidade de Coimbra, 3030-788 Coimbra, Portugal

[b] CESAM - Centre for Environmental and Maritime Studies, Department of Environment and Planning, University of Aveiro, Campus Universitário de Santiago, 3810-193 Aveiro, Portugal

ARTICLE INFO

Article history:
Received 30 January 2016
Received in revised form 16 August 2016
Accepted 23 August 2016
Available online 1 September 2016

Keywords:
Soil water repellency
Infrared thermography
Spatial variability
Laboratory soil flume experiments

ABSTRACT

This exploratory study presents a technique to assess soil water repellency (SWR) spatial variability based on infrared thermography. Small-scale laboratory tests were carried out using a soil flume and a loamy-sand soil, where SWR was induced on soil surface with waterproofing spray and repellent areas were mapped through thermal imaging, using a portable infrared video camera. Cold water was used to create a temperature gradient on the soil surface in order to assess SWR. The technique was, in overall terms, successful in mapping SWR spatial variability, distinguishing repellent from wettable areas as well as distinguishing between areas with different levels of SWR severity, in particular, between areas with extreme as opposed to low to medium SWR. The proposed technique appears to have high potential to contribute to a better understanding of the hydrological impacts of different spatial patterns of SWR due to its capacity to monitor in real time the dynamics of these impacts.

1. Introduction

Soil water repellency (SWR) is now recognised as a global phenomenon with important implications for hydrology and, therefore, of major concern to both hydrogeologists and land managers over a century (DeBano, 2000b). SWR can alter infiltration and water storage capacity of soils, enhancing infiltration by preferential flow and/or surface runoff generation and associated erosion (Keizer et al., 2005b; Leighton-Boyce et al., 2007; Ritsema and Dekker, 1994; Shakesby et al., 1993). Also, by altering water availability SWR can indirectly affect seed germination, seed establishment and plant growth (Doerr et al., 2000). A large number of studies have indicated a variety of factors causing and influencing SWR, such as soil moisture (Chau et al., 2014; Ferreira et al., 2016; Keizer et al., 2005a; Leighton-Boyce et al., 2005), incidence of fires (Badía-Villas et al., 2014; DeBano, 2000a; Keizer et al., 2008; Mataix-Solera and Doerr, 2004), presence of fungi and bacteria species (Schaumann et al., 2007), soil texture and structure (Urbanek et al., 2007) and soil organic carbon content (Wijewardana et al., 2016). However, the ultimate origin of SWR is the coating of soil particles with hydrophobic organic substances usually released by plants or decomposing plant material (Dekker and Ritsema, 1994; Doerr et al., 2000; Keizer et al., 2005c).

The two most commonly used techniques to measure SWR are the Molarity of an Ethanol Droplet (MED) test, also known as Percentage of Ethanol test or Critical Surface Tension test (Letey, 1969) and the Water Drop Penetration Time (WDPT) test (van'tWoudt, 1959). The MED test uses the surface tension of an ethanol solution to indirectly measure the apparent surface tension of the soil surface, i.e. how strongly water is repelled. The WDPT determines how long SWR persists in the contact area of a water drop. Both the MED and WDPT tests provide quantitative data, but the subsequent classification or characterization of these data vary with the objective of the investigator and perception of what constitutes low or high SWR severity. Also, although SWR strength and persistence are often related somehow, this relationship is not always clear or consistent (Dekker and Ritsema, 1994; Keizer et al., 2005a). Other techniques to measure SWR include measurement of the water-soil contact angle (Letey et al., 1962), measurement of ethanol and water ethanol sorptivity and using their ratio as SWR index (Tillman et al., 1989), measurement of the water entry pressure head of a soil, which is a function of water-soil contact angle (Carrillo et al., 1999), and the sessile drop method using a goniometer-fitted microscope (Bachmann et al., 2000). Most of these techniques have been compared in various papers such as Cosentino et al. (2010); Dekker et al. (2009); King (1981) and Letey et al. (2000).

An important problem in assessing the hydrological role of SWR is that most of the existing techniques to quantify SWR require specialized equipment and are best suited for use in the laboratory (Dekker et al., 2009). Also, some of these techniques require air-dried or oven-dried samples which may not be very representative of the conditions occurring in the field. The WDPT test can be performed on field-moist samples for the actual persistence of SWR (Cosentino et al., 2010), or on

* Corresponding author.
E-mail address: jrcbrito@msn.com (J.R.C.B. Abrantes).

http://dx.doi.org/10.1016/j.geoderma.2016.08.014
0016-7061/

dried samples for the potential persistence of SWR (Dekker and Ritsema, 1994). However, while the WDPT method demonstrates infinite resolution in severe SWR assessment, it lacks the precision required to distinguish intermediate degrees of soil repellency (Dekker and Ritsema, 1994). Also, WDPT results do not have an obvious physical meaning, and the technique can be very time consuming in the presence of strong to extreme SWR such as prevailing in eucalypt plantations (e.g., Doerr et al., 1998; Keizer et al., 2005c; Leighton-Boyce et al., 2005). The MED test is usually more practical and more rapid than WDPT test and has therefore been widely applied in especially intensive field monitoring studies (e.g., Keizer et al., 2005c, 2007, 2008; Malvar et al., 2016; Santos et al., 2016). Furthermore, its results are related to the water-soil contact angle and, therefore, physically meaningful. However, MED test results poorly predict the soil wetting behaviour (Doerr and Thomas, 2000). Other problem with most of the existing techniques to quantify SWR is that they provide point data, not revealing the spatial extent of the SWR severity. At field and landscape scales, point measurements must be grouped or scaled to bring out spatial correlation, in order to properly map SWR and represent distributed patterns of variations. This presents a laborious and time consuming task. Moreover, the limited surface area sampled by the MED and WDPT tests contributes to wide variability about the mean values (Dekker and Ritsema, 1994).

Infrared thermography is a versatile, accurate and fast technique of monitoring surface temperature and has been used in a variety of fields, such as military surveillance, medical diagnosis, industrial processes optimisation and building inspections. Its use in different studies has been increasing due to recent reductions in the prices of infrared cameras and substantial enhancements of their portability and spatial resolution. In surface hydrology, it has been successfully employed as a high spatial and temporal resolution non-invasive and non-destructive imaging tool to access groundwater discharges into estuaries (Mejías et al., 2012) and streams (Chen et al., 2009), quantify thermal heterogeneity of streams (Bonar and Petre, 2015) and floodplains (Tonolla et al., 2010), and map saturated area connectivity and dynamics (Pfister et al., 2010). Combining thermal imaging with the injection of hot water, as an artificial tracer technique, Schuetz et al. (2012) characterized the spatial distribution of flow paths and assessed flow transport properties, while de Lima and Abrantes (2014b) and de Lima et al. (2015) estimated very shallow overland and rill flow velocities. Some authors developed techniques based on infrared thermography to assess different processes that occur at the soil surface level, such as crust formation (Soliman et al., 2010), evaporative fluxes (Shahraeeni and Or, 2010) microrelief and rill morphology (de Lima and Abrantes, 2014a), permeability and preferential infiltration fluxes (de Lima et al., 2014a) and macroporosity (de Lima et al., 2014b).

The main goal of this exploratory study was to investigate if infrared thermography can be used to assess SWR severity and spatial distribution.

2. Material and methods

2.1. Experimental setup

A schematic representation of the experimental setup used in this study is presented in Fig. 1. The experiments were carried out using a 1.00 m × 0.75 m free drainage soil flume, with a depth of 0.05 m, set at 10% slope gradient (used in previous studies, e.g., de Lima and Abrantes, 2014a, 2014b; de Lima et al., 2014a, 2014b). The soil used in the experiments was collected from the banks of Mondego River in Coimbra, Portugal, and was classified as loamy-sand, according Soil Survey Division Staff (1993), comprising 82.6 ± 2.4% sand (2.0–0.05 mm), 10.7 ± 0.4% silt (0.05–0.002 mm) and 6.7 ± 0.1% clay (<0.002 mm). The soil presented an organic matter content of 0.86 ± 0.05% and a saturated hydraulic conductivity of 4.51×10^{-6} m s^{-1}, for a bulk density of 1750 kg m^{-3}. A feeder box was installed at the upslope end of the flume, which allowed the uniform application of determined volumes of cold water to the soil surface.

An Optris PI-160 portable infrared video camera (Optris GmbH, Germany) was used to record soil surface and water temperatures. The infrared camera converts the invisible infrared energy (working spectral range of 7.5–13.0 μm) emitted by a surface into temperature values that are then converted into a visual image (i.e. thermogram). The camera had an optical resolution of 160 × 120 pixels, a thermal resolution of 0.1 °C, a frame rate of 100 Hz and a lens with a field of view of 23° × 17°. The camera was attached to a support structure with the focal direction perpendicular to the soil surface of the flume, at a distance of 2.0 m (Fig. 1).

A rectangular area with 0.80 m × 0.60 m was defined at the soil surface and was scanned with the infrared video camera (Fig. 1), providing thermal imaging with a pixel size of 0.005 m × 0.005 m. The scanned area was defined smaller than the soil flume to avoid border effects of the flume sides, to avoid higher turbulence near the feeder box caused by the application of cold water to the soil surface and to avoid the downstream effect of the surface excess water flowing out through the outlet.

2.2. Soil water repellency (SWR)

To test the proposed technique, 32 rectangular areas of the soil surface, each of 0.06 m × 0.04 m, were induced with different levels of SWR.

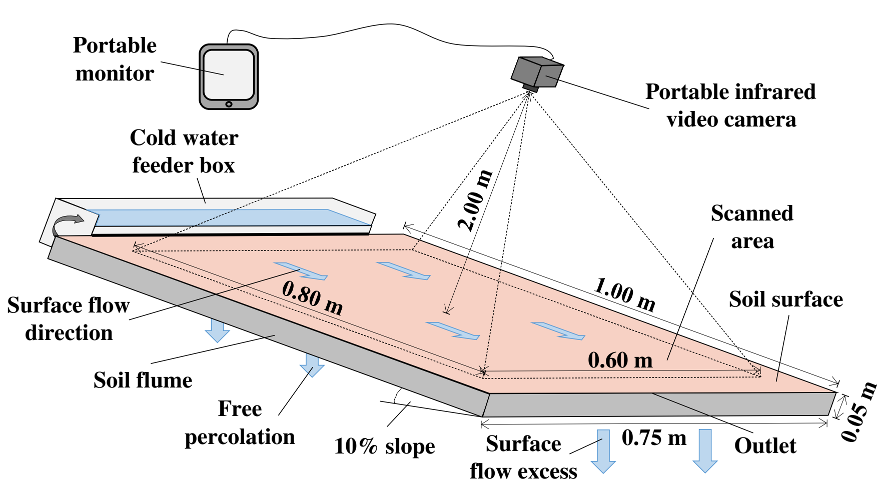

Fig. 1. Scheme of the setup used in the laboratory tests (not at scale).