

Field Assessment of Soil Water Repellency Using Infrared Thermography

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Received on <07-11-2016>, reviewed on <07-12-2016>, accepted on <16-01-2016>

Abstract

This study aimed to evaluate the applicability of an infrared thermography technique relying on cooling the soil surface with cold water for assessing soil water repellency (SWR) severity under field conditions.

This study is a follow-up of earlier exploratory small-scale laboratory tests, where SWR spatial variability was mapped and repellent areas could be clearly detected on the thermal imaging due to their higher temperatures, thus distinguishing them from the remaining wettable areas.

Field tests were carried out, where both natural and artificial SWR 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.

Naturally repellent soils were found in a pine and eucalyptus forest and artificial SWR was induced with a waterproofing spray.

The molarity of an ethanol droplet (MED) test was used to measure both natural and artificial SWR severity.

The technique was, in overall terms, successful in mapping SWR spatial variability, distinguishing repellent from wettable areas as well as distinguishing different levels of SWR severity.

Only extensive testing can, ultimately, validate the technique and reveal its suitability in different field conditions (e.g., surface roughness, surface cover, spatial scale).

Keywords: *soil water repellency, infrared thermography, field tests*

Rezumat. Evaluarea în teren a impermeabilității apei în sol utilizând termografia în infraroșu

Acest studiu a avut drept scop evaluarea utilizării unei tehnici de termografie în infraroșu, bazându-se pe răcirea suprafeței solului cu apă rece, pentru a evalua impermeabilitate hidrică a solului (SWR) în condiții severe de teren. Acest studiu este o continuare a testelor de laborator anterioare de explorare la scară mică, în care variabilitatea spațială a SWR a fost cartată, iar zonele de respingere a putut fi detectate în mod clar pe imagini termice datorită temperaturilor lor mai mari, ceea ce a permis distingerea de perimetrele umectate. Testele de teren SWR au fost efectuate, în regim natural cât și artificial, iar cartografierea s-a efectuat prin imagistică termică, cu o camera video portabilă în infraroșu. Apa rece a fost folosit pentru a crea un gradient termic pe suprafața solului, în scopul de a evalua SWR. În mod natural, soluri hidrofuge au fost găsite într-o pădure de pin și eucalipt și SWR artificială a fost indusă cu un spray pentru impermeabilizare. Molaritatea unui test de etanol a picăturii (MED) a fost utilizată pentru a măsura severitatea SWR atât natural și artificială. În termeni generali, tehnica a fost un succes și a permis cartarea variabilității spațiale a SWR, diferențierea perimetrelor hidrofuge de cele zone hidrofile precum și niveluri distinctiv de severitate diferită a SWR. Numai testare extinsă poate, în cele din urmă, să valideze tehnica și să dezvăluie caracterul adecvat în condiții diferite de teren (de exemplu, rugozitate de suprafață, acoperirea terenului, scară spațială).

Cuvinte-cheie: *impermeabilitate hidrică a solului, termografiere în infraroșu, testele de teren*

Introduction

Soil water repellency (SWR) is recognized as a key hydrological and geomorphological process since the earlier part of the 20th century. However, first observations of this phenomenon were reported in the later part of the 18th century (DeBano, 2000, Doerr et al., 2000). SWR is a major concern to hydrogeologists and land managers since it can alter infiltration and solute transport into the soil, enhancing surface runoff and associated erosion and affecting seed germination and plant growth, triggering land degradation processes (Keizer et al., 2005a; Leighton-Boyce et al. 2007; Ritsema and Dekker, 1994; Shakesby et al., 1993).

SWR is originated by the coating of soil particles with hydrophobic organic substances usually released by plants or decomposing plant material (Dekker and Ritsema, 1994; Keizer et al., 2005b). Repellent soils have been found in fire affected forest lands (Badía-Villas et al., 2014; Keizer et al., 2008; Mataix-Solera and Doerr, 2004), but also in pine and eucalypt forest lands not affected by fires and in agricultural lands with high soil organic matter content (Doerr et al., 2000, Keizer et al., 2007, Santos et al., 2013).

One of the most commonly used technique to measure SWR is the Molarity of an Ethanol Droplet (MED) test (Letey, 1969), which measures the surface tension between an ethanol solution and the soil surface to indirectly determine how strongly the water is repelled. It provides quantitative data, but the subsequent classification or characterization of

these data varies with the objective of the investigator and perception of what constitutes low or high SWR severity. The MED test is a practical and quick test and has therefore been widely applied in especially intensive field monitoring studies (Keizer et al., 2005b; 2007, 2008; Malvar et al., 2015; Santos et al., 2013). Other techniques used to measure SWR include measurement of the time taken by a water drop to completely penetrate into the soil, measurement of the water-soil contact angle, measurement of ethanol and water ethanol sorptivity, measurement of the water entry pressure head of a soil and the sessile drop method (King, 1981; Dekker et al., 2009). However, these techniques only provide punctual data that must be grouped or scaled to bring out spatial coherence, in order to properly map spatial variations of SWR at field and landscape scales.

Infrared thermography based methods have been used as high resolution imaging tools in hydrology (Bonar and Petre, 2015; Mejías et al., 2012; Schuetz et al., 2012) and physical geography (Dehvari and Heck, 2007; Pohl and Van Genderen, 1998; Ricchetti, 2001), in particular those using portable hand-held infrared cameras have been increasing due to recent reductions in their prices and substantial enhancements of their portability and spatial resolution. In recent studies, infrared thermographic techniques were used by the authors to assess different soil surface hydrological processes in laboratory and field conditions (Abrantes et al., 2017; Abrantes and de Lima, 2014; de Lima and Abrantes, 2014a, 2014b; de Lima et al., 2014a, 2014b, 2014c, 2015a, 2015b).

This study aimed to evaluate the applicability of a field infrared thermography technique relying on cooling the soil surface with cold water for assessing small-scale SWR severity under field conditions. This study is a follow-up of exploratory small-scale laboratory tests presented in Abrantes et al. (2017) where SWR spatial variability was mapped and repellent areas could be clearly detected on the thermal imaging due to their different coloration associated with higher temperatures, thus distinguishing them from the remaining wettable areas.

Study area and soil surface repellency

The field tests presented in this study were conducted in a Pine (*Pinus pinaster*) and Eucalyptus (*Eucalyptus globulus*) forest site located in Pinhal de Marrocos, Coimbra, Portugal, in the surroundings of the Department of Civil Engineering of the Faculty of Sciences and Technology of the University of Coimbra. The soils in this site were loamy sand soils with a surface slope between 15-20%. Soil surface was dry at the beginning of the tests.

The thermographic technique was tested in 6 areas of the study site, each with approximately $0.65 \times 0.85 \text{ m}^2$. The areas presented different characteristics (Fig. 1a), such as areas with bare soil surface in open patches of the tree canopy (i.e. wettable soil surface) and areas with soil surface covered with a thick litter layer of pine and eucalyptus residues (i.e. repellent soil surface). Some wettable areas of the soil surface were also induced with artificial repellency by applying a waterproofing spray. This allowed to test the technique in different soil surface repellent conditions, ranging from wettable to extremely repellent: scenario 1 with wettable soil surface; scenario 2 with low SWR; scenario 3 with moderate SWR; scenario 4 with severe SWR; scenario 5 with half of the area artificially induced with extreme repellency (Fig. 1b); and scenario 6 with circular areas artificially induced with extreme repellency (Fig. 1c).

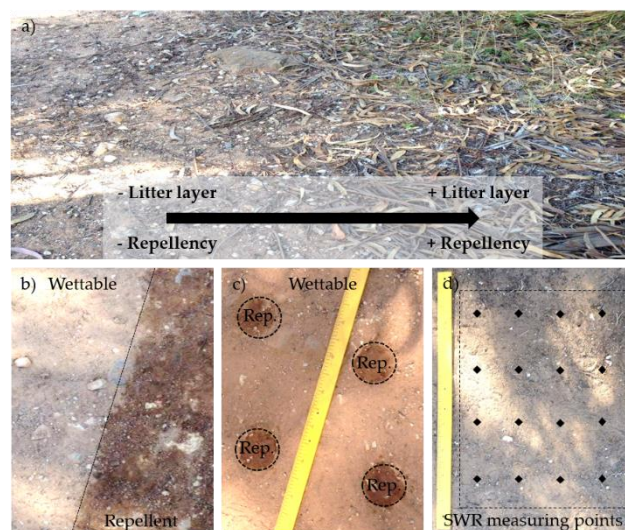


Fig. 1: Photographs of: a) study area with observation of the increasing layer of litter and, consequently, increasing SWR; b) and c) scenarios 5 and 6, respectively, with representation of the boundary between the wettable and the induced repellent areas (photographs taken immediately after application of the waterproofing spray); and d) location of the places where the MED test was used to measure the SWR in the scanned area, after removal of the litter layer

SWR severity was determined at the soil surface after removal of the litter layer, using the MED test (following proceeding used in Abrantes et al., 2017). SWR severity was divided in 5 repellency intensity classes, according the ethanol concentration, as follows (adapted from Doerr et al., 1998): class 0, wettable (0%); class 1, low repellency (1, 3 and 5%); class 2, moderate repellency (8.5 and 13%); class 3, severe repellency (18 and 24%) and class 4, extreme repellency (36, 50% and more). In each scenario, SWR measurements were conducted

randomly at the soil surface on 16 points in a regular pattern, as shown in Fig. 1d.

Materials and methods

Infrared thermographic technique

A schematic representation of the experimental setup used in this study is presented in Figure 2. The proposed thermographic technique, tested previously in laboratory (Abrantes et al., 2017), started by applying approximately 4.0 L of cold water, at a temperature of 6.3 ± 0.5 °C (cooled in a refrigerator), over the soil surface. The water was released manually by turning over a feeder box located upslope of the scanned area (Fig. 2). The feeder box was tipped in a quick and fast movement in order to achieve a uniform discharge and a flow depth uniformity over the scanned area but, at the same time, to induce minimum soil surface disturbances.

Thermal videos of the soil surface and water were recorded with an Optris PI-160 portable infrared video camera (Optris GmbH, Germany) with an optical resolution of 160×120 pixels. The camera was attached to a support structure with the focal direction perpendicular to the soil surface, at a distance of 2.15 m (Fig. 2). These videos were then analysed with the objective of distinguish repellent from wettable areas as well as identify different levels of SWR. For each scenario, two thermograms (i.e. snapshot of the thermal video) were selected and its temperatures were analysed: one corresponding to an instant just before the coldwater application; and other corresponding to an instant just after the passage of the cold water wave through the scanned area, approximately 5 s after the cold water application. This specific instant was chosen because, in general, it revealed the strongest thermal differences between wettable and repellent areas and, thus, allowed evaluating the best possible performance of the proposed technique.

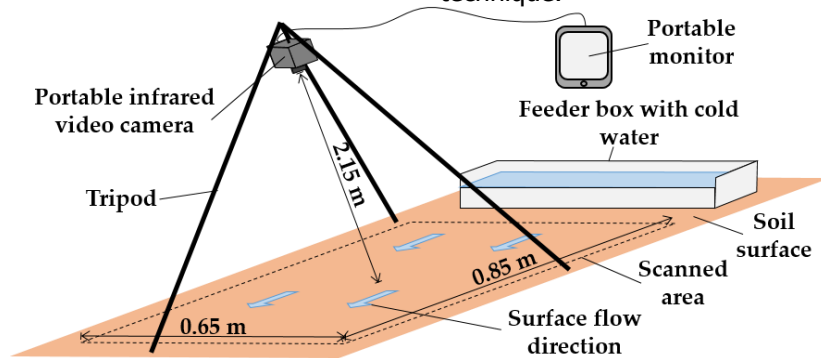


Fig. 2: Scheme of the setup used in the field tests (not at scale)

Results and discussion

Thermograms of the six scenarios studied in the field experimental tests, using the proposed infrared thermography technique, are presented in Figure 3. Each thermogram comprises a total of 19200 pixels (i.e. temperature data points), each one with a size of 28.8 mm².

At the beginning of the tests, soil surface temperature was not exactly the same in all scenarios. Average soil surface temperature of scenarios with previous presence of a litter layer of forest residues (removed at the beginning of the tests and before thermal images were captured) was lower than bare soil scenarios (average values of 22.2 and 24.0 °C, respectively). Before the application of the thermographic technique (i.e. application of the cold water on the soil surface), the extremely repellent area induced with waterproofing spray could not be distinguished from the wettable area in scenario 5 (Fig. 3e left). However, circular

extremely repellent areas, induced with waterproofing spray, in scenario 6 showed slightly lower temperatures than the remaining wettable area. Even so, these thermal differences were not significant and, by themselves, were not sufficient to identify the extremely repellent areas.

As the cold water flowed down the scanned areas, it started to be repelled in the repellent areas. Therefore, after the passage of the water wave through the scanned areas, scenarios with stronger levels of SWR presented higher average temperatures (cold water was repelled), as opposed to scenarios with no (wetable soil) and lower levels of SWR, where more cold water infiltrated into the soil, thereby cooling it.

Extremely repellent areas induced with waterproofing spray in scenarios 5 and 6 (Figures 3e and 3f) could be clearly distinguished from the wettable area, based on their lighter coloration associated with higher temperatures (also observed in Abrantes et al., 2017).

Imaging results were driven by soil water content as a result of infiltration differences (also observed in de Lima et al., 2014b). As stated before, in wettable areas more cooled water flowed into the soil, therefore these areas presented lower temperatures. Repellent areas presented higher temperatures, because less cooled water has infiltrated in these places since it was repelled. Therefore, these imaging results are a clear indicator of the drainage pattern of each studied scenario, especially Figures 3c and 3d.

Since the application of the thermographic technique only lasted 5 s (i.e. time taken from the

application of the cold water to its passage through the scanned area), temperature exchange between the soil surface (and/or water flowing at the soil surface) and the atmosphere was considered negligible. The thermogram of scenario 6 presented some deformations of the circular areas, where extreme SWR was induced, suggesting leaching of SWR from these areas in the downslope direction (also observed in Abrantes et al., 2017).

These deformations could result/reflect the transport of repellent soil particles by the water wave and/or heat diffusion, as observed in de Lima and Abrantes (2014) and in de Lima et al. (2014b).

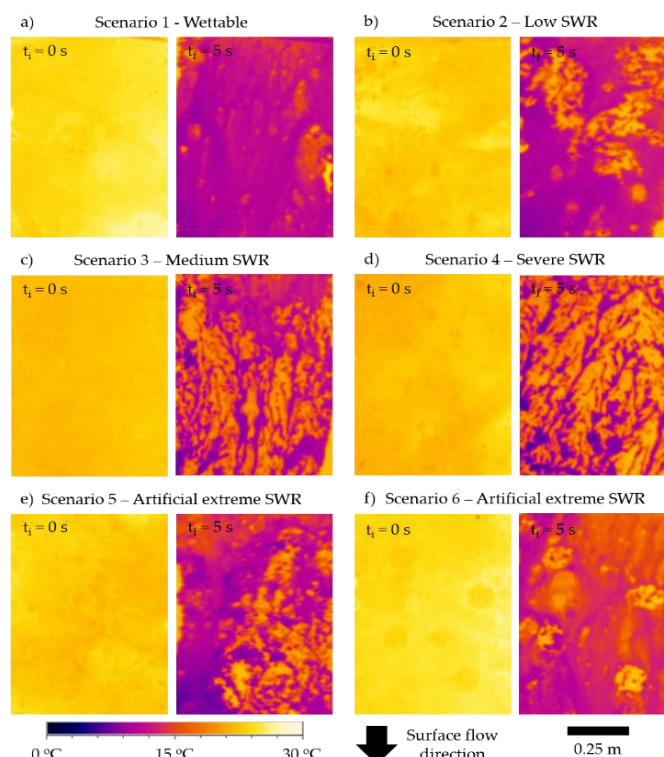


Fig. 3: Unprocessed soil surface thermograms of the six scenarios studied in the field tests, before ($t_i = 0$ s) and after ($t_f = 5$ s) the application of the thermographic technique (i.e. application of the cold water on the soil surface): a) scenario 1 with wettable soil surface; b) scenario 2 with low SWR; c) scenario 3 with moderate SWR; d) scenario 4 with severe SWR; e) scenario 5 with half of the area artificially induced with extreme repellency; and f) scenario 6 with circular areas artificially induced with extreme repellency

As stated before, soil surface temperature at the beginning of the tests (i.e. prior to cold water application) was not exactly the same in all scenarios; therefore, the temperature in the thermograms was corrected by subtracting the temperature of the thermograms before the cold water application (T_i at $t_i = 0$ s) to the temperature of the thermograms after the cold water application (T_f at $t_f = 5$ s), as schematized in Figure 4 for scenario 1.

Since the temperature of the cold water applied to the soil surface was approximately equal in all tested scenarios ($6.3 \pm 0.5^\circ\text{C}$) a correction of this temperature was not done. However, a similar

correction should be considered if the temperature of the applied water would not equal.

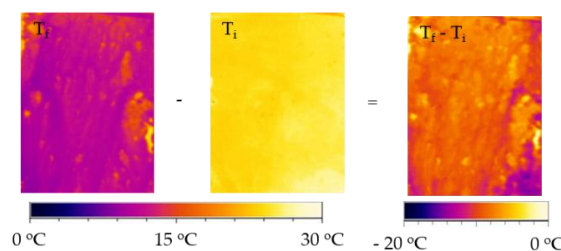


Fig. 4: Scheme of the procedure used in the temperature correction of the soil surface thermograms, for scenario 1

The correction procedure resulted in the final thermograms is shown in Figure 5, for all tested scenarios. With this correction, temperature of all thermograms can be compared without interference of the initial temperature of the soil surface. This is relevant because average soil surface temperature of scenarios with previous presence of a litter layer of forest residues was lower than bare soil scenarios.

As shown in Figure 5 (left), scenarios with stronger levels of SWR presented a corrected temperature (i.e. temperature difference) closer to 0 °C, since its final temperature was more similar to the initial temperature, due to lower cold water infiltration. By contrast, scenarios with no and lower levels of SWR presented average lower corrected temperatures, due to higher infiltration of cold water into the soil. This is shown in the graph of the

Figure 5g which presents the average corrected temperatures, extracted from the processed thermograms, and plotted against the 5 SWR severity classes measured with the MED test.

For each and every year, the values of the Figure 6 (right) shows corrected temperatures extracted from the thermograms, for some cross sections of the scanned area, for all tested scenarios. The longitudinal (Fig. 6a) as well as transversal (Fig. 6b) cross sections revealed that average corrected temperatures contrasted markedly between scenarios 1, 2, and 3-4. However, almost no difference was observed between the average corrected temperature of scenarios 3 and 4. For the induced extreme SWR scenarios (scenario 5 in Fig. 6c and scenario 6 in Fig. 6d) a clear distinction existed between the corrected temperature in the repellent and wettable areas.

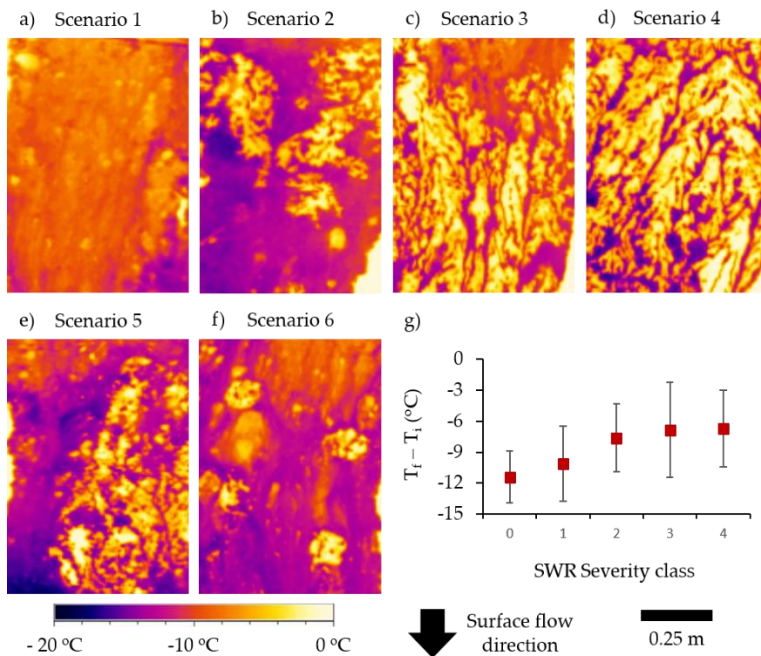


Fig. 5: a), b), c), d), e) and f) Thermograms of the soil surface after the correction procedure, for all tested scenarios; and g) Average and standard deviation (19200 data points) of the corrected temperatures plotted against the 5 SWR severity classes measured with the MED test (class 0 – wettable, class 1 - low SWR, class 2 - moderate SWR, class 3 - severe SWR and class 4 - extreme SWR)

Conclusion

In the present field study, a technique based on infrared thermography was tested for assessing water repellency at the soil surface (SWR). The technique proved to be an easy and fast way for gathering a high resolution SWR map in small scale field plots, allowing thermograms with 19200 data

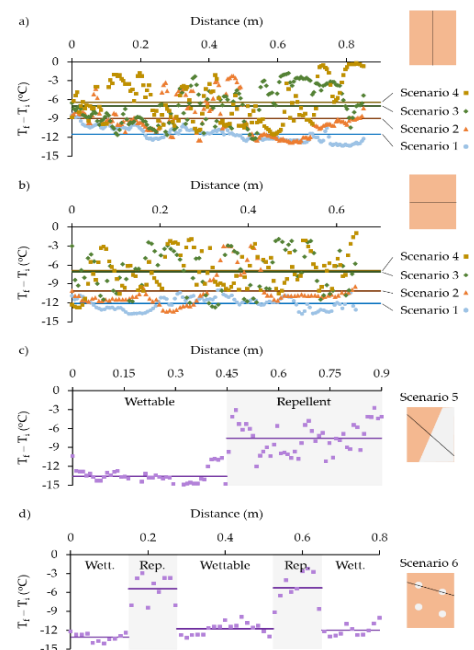


Fig. 6: Soil surface corrected temperature (data points and average lines), for some cross sections of the scanned area (shown in the right side of the plots): a) Longitudinal cross sections for scenarios 1, 2, 3 and 4 (160 data points); b) Transversal cross sections for scenarios 1, 2, 3 and 4 (120 data points); c) Cross section for scenario 5 (90 data points); and d) Cross section for scenario 6 (60 points)

points versus the 16 MED measurements. The technique was, in general, successful in distinguishing areas that were water repellent from areas that were wettable as well as in distinguishing between areas with different levels of SWR. Overall, the proposed technique apparently has high potential to contribute to a better understanding of the hydrological impacts of SWR, by also revealing the drainage pattern of the field plots.

However, the proposed technique presented some drawbacks: i) it may require measurements of SWR as a basis for accurate predictions; ii) it can only be applied to relatively flat sloping soil surfaces and its results may depend strongly on experimental aspects (e.g., temperature of applied water), as well as on local soil conditions, such as roughness, temperature, moisture and macroporosity, which could create preferential infiltration patterns even in highly repellent areas; iii) it may affect the soil surface characteristics, especially in easily erodible soils and it may alter SWR levels and, especially through leaching, SWR spatial patterns.

Results of this study suggest that is worthwhile to explore this technique. Only extensive testing can, in fact, validate the technique and reveal its suitability under different field conditions (e.g., surface roughness, surface cover, spatial scale).

Acknowledgements

This study was supported by the project "RECARÉ - Preventing and Remediating degradation of soils in Europe through Land Care" (Grant Agreement 603498) funded by the European Union (EU), through a 5 months research grant of the first author (BI/UI88/7111/2015).

This study is also in the framework of the doctoral (SFRH/BD/103300/2014) and post-doctoral (SFRH/BPD/97851/2013) grants of the first and third authors, respectively, and the project "HIRT - Modelling surface hydrologic processes based on infrared thermography at local and field scales" (PTDC/ECM-HID/4259/2014 – POCI-01-0145-FEDER-016668), coordinated by the second author and funded by the Portuguese Foundation for Science and Technology (FCT) and FEDER (*Fundo Europeu de Desenvolvimento Regional*).

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