DETERMINATION OF ACTUAL SOIL WATER CONTENT, MATRIX POTENTIAL AND WATER REPELLENCY IN SANDY SOIL DURING A DEHYDRATION EXPERIMENT

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Soil water repellency (SWR) diminishes the affinity of soils towards the water and may resist wetting for durations ranging from a few seconds to hours or days depending on its persistence. It has been proposed that the origin of natural SWR is caused by organic compounds released from different plant species and sources, due to resins, waxes and other organic substances in their tissues. SWR may vary nonlinearly with soil moisture content (SMC), showing complex responses. It has been observed that small variations in water potential may have significant impacts on the wettability of water-repellent soils, and concluded that maximum soil water repellency does not necessarily occur in oven-dry soils, but at certain specific soil water potentials. The aims of this work were: i. to determine the values of SMC and corresponding values of soil matrix potential and persistence of SWR in forest soil samples during the drying process under laboratory conditions; ii. graphically analyze and quantify the drying process of the water-repellent soil surface.

KEY WORDS: soil water repellency, soil moisture content, soil matrix potential, dune sand

Introduction

Soil water repellency (SWR) has been observed in forest soils under different climatic conditions, soil types and vegetation covers (Doerr et al., 2000). It has been proposed that the origin of natural SWR is caused by organic compounds released from different plant species and sources, due to waxes and other organic substances in their tissues. SWR diminishes the affinity of soils towards the water and may resist wetting for durations ranging from a few seconds to hours or days depending on its persistence (Doerr and Thomas, 2000). SWR is normally characterized by a high spatial variability in persistence, with wettable and water repellent patches next to each other (Lozano et al., 2013).

SWR can alter infiltration and water storage capacity of soils. Reduced infiltration increases the surface runoff generation (overland flow) and associated erosion, and uneven wetting leads to the development of fingered flow (Keizer et al., 2005; Leighton-Boyce et al., 2007; Ritsema and Dekker, 1994; Shakesby et al., 1993; Kobayashi and Shimizu, 2007).

A large number of authors have indicated a variety of factors influencing SWR, such as soil moisture content (SMC) (Chau et al., 2014; Ferreira et al., 2016), incidence of fires (DeBano, 2000; Mataix-Solera and Doerr, 2004), presence of fungi and bacteria species (Schaumann et al., 2007), soil texture and structure (Urbanek et al., 2007; Giovannini and Lucchesi, 1983), surface roughness (Shirtcliffe et al., 2006), aggregation (Jordán et al., 2011; Mataix-Solera et al., 2011; Zavala et al., 2010), organic matter content and chemical composition (Atanassova and Doerr, 2010), acidity, soil type and mineralogy of the clay fraction (Dlapa et al., 2004; Mataix-Solera et al., 2008; Zavala et al., 2009), microbiology (Jex et al., 1985; Savage et al., 1969), and soil organic carbon content (Wijewardana et al., 2016).

Under high SMC, SWR is reduced, and a critical soil moisture threshold exists above which the soil becomes wettable. This threshold ranges from 5% (sandy soils) to >30% (clay soils) (Bodí et al., 2012; Poulenard et al., 2004; Regalado and Ritter, 2005). According to Dekker and Ritsema (1994) the critical soil water content varies between 4.75% at 5–10 cm and 1.75% at 45–50 cm depth in this sandy soil.

As the soil dries out, SWR tends to be restored, which causes intra-annual, short-term variations in SWR driven by SMC (Keizer et al., 2008). The temperature both in situ and in the laboratory con-
ditions affects also water repellent characteristics of soils. Dekker et al. (1998) reported that potential water repellency was greater after drying soils at 65°C relative to those drying at 25°C. In contrast, some soils show higher water repellency at low temperature (20°C) conditions than those at comparatively high temperature (40°C) conditions (Whelan et al. 2014).

The aims of this work were: i. to determine the values of SMC and corresponding values of soil matrix potential and persistence of SWR during the drying process in water-repellent soil columns under laboratory conditions; ii. graphically analyze and quantify the drying process of the water-repellent soil surface.

Material and methods

Field-soil and soil sampling

The experimental area Pine 1 was located near Sekule (48°37'10'' N, 16°59'50'' E) in the Borská nížina lowland (southwest Slovakia). The altitude of study site is 150 m above sea level. The climate is continental with less annual temperature fluctuations than on the neighboring Podunajská nížina lowland. Mean annual temperature is 9°C. Mean annual precipitation is 550 mm, and it is mainly summer-dominant (Klimatický atlas Slovenska, 2015). Aeolian sandy soil from these sites is classified as an Arenosol (WRB, 2006) and sandy texture was measured for whole soil profile (Soil Survey Division Staff, 1993).

The experimental site was the stand of about 20-year old pine trees (*Pinus sylvestris*), under which occurred bryophytes (*Polytrichum piliferum*), followed by lichens (*Cladonia sp.*) and sporadically occurred also higher plants (*Corynephorus canescens*). The growth of mosses and lichens was evenly covered with fallen needles. The soil was known to be severely to extremely water repellent during dry periods (Lichner et al., 2005; Šurda et al., 2013).

Disturbed soil samples were taken from depth 0–10 cm in 1.5 m vertical transect on 20 August, 2019, after a period of 4 days without rainfall. Soil was sampled using little gardening steel shovel with a 5 cm blade and transported in closed plastic bag. In laboratory was sandy material homogenized and spreaded as a 5 cm layer. Four Kopecký steel cylinders (100 cm$^3$) were filled with same weight of sandy material and had been oven-dried and weighed to calculate actual volumetric SMC.

Soil columns preparation and hydration

Four soil columns with bulk density 1.625 g cm$^{-3}$ were prepared in laboratory, using 800 ml transparent plastic cylinders with a height of 13 cm (height of sand in cylinder was 11.1 cm) and diameter of 10 cm. The lower parts of the cylinders were perforated to ensure water drainage. 300 ml of water was applied on each of soil column surface in 3 x 100 ml irrigation doses. Applied water entered the soil through the process of falling head ponded infiltration. Water leakage through the bottom part of soil column was measured after each irrigation dose.

| Depth [cm] | Sand [%] | Loam [%] | Clay [%] | CaCO$_3$ [%] | C [%] | pH H$_2$O | pH H$_2$O |
|-----------|----------|----------|---------|--------------|------|----------|----------|
| Pine 1    | 0–10     | 95.1     | 2.3     | 2.6          | <0.05| 0.83     | 5.65     | 4.39     |

**Table 1. Physical and chemical properties of the top (0–10 cm) soil taken from the experimental site Pine1 (stand of pine trees) near Sekule, Slovakia**

![Fig. 1. Experimental area Pine 1 near Sekule.](image-url)
Measurement of matrix potential and SMC during dehydration

Two of these columns were equipped with moisture probes STM (Decagon Devices, Inc.) and two others with matrix potential sensors MPS6 (Decagon Devices, Inc.). Continuous measurements at 5 minute intervals were recorded using EM50 data loggers (Decagon Devices, Inc.). SMC of all soil columns during drying process was determined gravimetrically. Prepared columns were dried in a laboratory oven at 35°C. The drying process of soil column surfaces was captured using a Canon EOS 600d camera.

Water drop penetration time (WDPT) test

The stability or persistence of the repellency was measured by the water drop penetration time (WDPT) test – a measure of the time required for the drop to enter the soil. Five drops of distilled water from a standard medicine dropper were placed on the surface of a soil sample, and the time that elapsed before the drops were absorbed was registered. We measured the persistence of water repellency of the soil samples in the laboratory under controlled conditions at a constant temperature of 22°C.

In general, a soil is considered to be water repellent if the WDPT exceeds 5 s. Soils with WDPT=5–60 s were considered slightly water repellent, WDPT=60–600 s strongly water repellent, WDPT=600–3600 s severely water repellent, and WDPT≥3600 s extremely water repellent (Bisdom et al., 1993).

Image analysis

For the digital photo analysis we used GIMP and also ImageJ (http://imagej.net/ImageJ), open source Java image processing program inspired by NIH Image. JPEG digital photography was calibrated through the function “Set scale”. Defined number of pixels was assigned to a real known distance on picture. Then it was transformed into 8 bit format (black and white). Next step was a use of "Bandpass filter" function, which filtered structures smaller or bigger as defined size in pixels. Then we used a "Threshold" function which gives us images, usable for counting black and white pixels within the 10 cm diameter of soil surface.

Results and discussion

Soil moisture content and matrix potential in the soil columns during dehydration

The persistence of SWR at the initial air-dried conditions of the all prepared soil columns surface was determined through WDPT test and soil was classified as extremely water repellent in all cases. The results of WDPT test and hydration process of four soil columns are in Table 2.

According to the Table 2, soil samples were able to hold only very limited amount of water from the applied irrigation dose. Applied water entered the soil columns through the process of falling head infiltration (which lasted overall ca. 12 hours). After each application of 100 ml irrigation dose, a 1 cm water layer was formed on the surface. Water percolated through the soil columns through the process of preferential (fingered like) flow and the SMC increased only in the spaces around the preferential flow paths. Maximal amount of applied water held the Column 1 (61 ml), the smallest amount Column 3 (13 ml). The surface layers of soil columns were exposed to water, which reduced the SWR and thin surface layer of soil (with thickness of 2–3 mm) becomes wettable. Analysis of the soil surface drying process results are stated in next subchapter.

Drying process of soil samples started at various initial SMC (from 0.11 to 0.051). Decrease in SMC over time is shown in Figure 2. As it can be seen at the Fig. 2, the curve of SMC decrease can be divided into two parts according to the slope; to the first part with higher rate of evaporation (from 0.47 ml h⁻¹ in Column 1 to 0.26 ml h⁻¹ in Column 3) and second part with lower evaporation intensity (from 0.08 ml h⁻¹ in Column 1 to 0.03 ml h⁻¹ in Column 3). Breakpoint between two slopes of curve, or threshold value, approximately coincides with the time when SWR of the whole soil surface was restored. The decrease in evaporation rate is mainly due to a decrease in SMC, but since the initial SMC level is also low, the recovery of the surface SWR can also be important.

SWR of whole sample soil surface in all columns was recovered after 42 hours of drying process by constant temperature of 35°C and decrease of SMC by 0.027 in 1, 0.020 in 2 and 0.015 in 3.

Relation between measured values of SMC and soil matrix potential is displayed at Fig. 3. The authors do not

Table 2. Persistence of SWR of prepared samples (examined through the WDPT test with five repetitions) at the initial air-dried conditions (= represents standard deviation); values of SMC before wetting (SMC0ML); applied irrigation dose; leakage through the bottom and SMC after application of 300 ml of water (SMC300ML)

| Soil column | WDPT [s] | SMC0ML [m³ m⁻³] | Applied water [ml] | Leakage [ml] | SMC300ML [m³ m⁻³] |
|-------------|----------|-----------------|--------------------|--------------|-------------------|
| 1           | 10200 ±1296 | 0.035          | 300                | 239          | 0.1118            |
| 2           | 13200 ±1132 | 0.035          | 300                | 272          | 0.0705            |
| 3           | 10800 ±1836 | 0.035          | 300                | 287          | 0.0511            |
| 4           | 11400 ±2452 | 0.035          | 300                | 282          | 0.0573            |

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**Fig. 2.** Decrease of soil moisture content during dehydration of soil columns (1, 2, 3 and 4); dotted line represents the threshold, beneath which are whole surfaces of soil columns water repellent.

**Fig. 3.** Values of soil matrix potential (kPa) and soil moisture content $[m^3/m^3]$, measured during drying experiment.

consider the depicted potential – SMC dependence a retention curve, nor have they attempted to fit it with existing models.

Soil columns under the conditions of the experiment cannot be fully saturated and the authors believe that this does not happen even in normal filed conditions in the top layer (10 cm) of the extreme repellent soil profile. Therefore, the highest measured potential was $-9.8$ kPa in 3 and $-9.7$ kPa in 2, which corresponds with the value of SMC of 0.051 in 3 resp. 0.071 in 2. Minimal values of matrix potential, $-47.6$ kPa in 3 and $-16.7$ kPa in 2, corresponding with the SMC of 0.034 resp. 0.037, were measured after 5 days (119 hours) resp. after 12 days (293 hours) of drying process.
Drying process of the water-repellent soil surface

After infiltration process, whole surface area of soil columns (with thickness of 2–3 mm) became wettable. The drying process of the wettable soil columns surfaces are displayed in Fig. 4 (first pictures were taken after ca 30 minutes of drying). The surface of each soil column was visually dried (according to analysis of photographs) approximately two and a half hours after the start of dehydration. All dark (wetter) surfaces were always wettable (WDPT < 5 s). Visually lighter and drier part of the surface behaved differently; some of them act as wettable and some as water-repellent. SWR was completely restored (WDPT > 5 s) after 42 hours of dehydration at the entire surface of the all soil columns. Enlargement of the dry area during the dehydration process was evaluated from the binary pictures made from sequence of photographs displayed in Fig. 4. Increasing ratio of white pixels (dried area) to the total number of pixels (surface of soil column) during drying process is shown in Figure 5. According to Fig. 4 and 5, enlargement of the dried surface area of the soil columns during the drying process was relatively uniform. The largest relative increase in the dried area was detected after ca. two and a half hours in all soil columns. The surface of columns 1 and 2 dried slowly, while the strong and severe SWR at surface of these columns was recovered faster than in columns 3 and 4. This may be related to the delay of the water layer (and hence the exposure time to water) on the soil surface which could be caused by the different rate of the hydraulic conductivity (Ks) of the prepared soil columns. The necessity of the Ks measurement is important for the realization of the future experiments.

Conclusions

The values of SMC and corresponding values of soil matrix potential and persistence of SWR were measured in sandy soil columns under laboratory conditions. Drying process of samples started at various initial SMC (from 0.11 to 0.051). The curve of SMC decrease can be divided into two parts according to the slope; to the first part with higher rate of evaporation (from 0.47 ml h⁻¹ to 0.26 ml h⁻¹) and second part with lower evaporation intensity (from 0.08 ml h⁻¹ to 0.03 ml h⁻¹).

![Fig. 4. Sequence of photographs graphically depicting the drying process of soil samples surface (brown color represents wettable parts of surface, white area represents dried part of soil surface, below is time the photo was taken).](image-url)
Proportion of wet and dry areas of the total soil surface (%)

Time: 9:52, 10:24, 10:57, 11:31, 12:02

Dry, Wet

Frequency of WDPT class (%)

Time: 9:52, 10:57, 12:02

< 5 s, 5-60 s, 60-600 s, 600-3600 s

Fig. 5. Proportion of wet and dry areas of the total soil surface on the five measuring dates and relative frequency of the persistence of actual water repellency (WDPT class) on the three measuring dates (N=5) of the column 1 (a, b), column 2 (c, d), column 3 (e, f) and column 4 (g, h).
Soil columns under the conditions of the experiment were not fully saturated, due to the extreme SWR. Therefore, the highest measured potential was -9.8 kPa, which corresponds with the value of SMC of 0.05. Minimal value of matrix potential, -47.6 kPa, corresponding with the SMC of 0.03 was measured after 5 days (119 hours) of drying process.

The surface of each soil column was visually dried approximately two and a half hours after the start of dehydration, while the enlargement of the dried surface area was relatively uniform. The surface of columns 1 and 2 dried slowly, while the strong and severe SWR at surface of these columns was recovered faster than in columns 3 and 4.

Acknowledgement

This work was supported by the Slovak Scientific Grant Agency VEGA Project 20189/17.

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