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Compatibility of methods used for soil water repellency determination for organic and organo-mineral soils

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ABSTRACT

Soil water repellency (i.e. hydrophobicity, SWR) is a common soil phenomenon inhibiting water infiltration and water movement in the soil. SWR has significant hydrological implications for enhanced overland and preferential water flows and erosion. Several methods are used to determine the degree of SWR. The methods are typically chosen based on their suitability for field or laboratory work, as well as time and resources availability. Unfortunately, each measurement method has a different analytical approach, hence the direct comparison between results from different methods is not possible. A faster and statistically sound technique for converting results is needed, especially to convert results from field applicable techniques to contact angle (CA) value, which is a valuable parameter for soil hydraulic modelling. The aim of this paper is to define a reliable compliance between methods defined on a statistical approach basis (weighted kappa coefficient κ_w), which will allow to determine the CA value based on straightforward tests, such as water drop penetration time (*WDPT*) and molarity of an ethanol droplet (*MED*). For this purpose, we measured SWR in 106 organic and organo-mineral soils collected from different locations in North East Poland using four common methods. The sessile drop and Wilhelmy plate laboratory-based methods were used to determine the CA between water and the solid phase. The other two tests are common field methods for assessing SWR by measuring water infiltration time (*WDPT*) and the highest surface tension of ethanol-water droplet infiltration into the soil (*MED*). The results revealed that the weighted kappa coefficient, when assumed as a measurement of an observer's compliance, indicates a strong relationship ($\kappa_w = 0.84$) between the average CA (CA_{av}), measured with the sessile drop method, and the median value of the *WDPT* ($WDPT_{me}$). Based on the results, we can conclude that hydrophilic samples with $WDPT < 5$ s have the average CA values below 40°, while extremely hydrophobic samples with *WDPT* above 3600 s have CA values higher than 130°. This is a proof that these tests can be a good estimator of CA value for SWR determination in the laboratory or the field.

1. Introduction

The correct estimation of SWR is essential to anticipate and prevent its negative environmental effects. SWR persistence and severity can also be taken into account (Chau et al., 2014). These parameters can be estimated by measuring the CA (e.g. Doerr, 1998), by *MED* (Letey et al., 2000) and *WDPT* (Doerr, 1998) tests or by water repellency index (RI) (Tillman et al., 1989). RI being the estimated ratio of soil-water to soil-ethanol sorptivities. Water repellency is a very important soil property, as it has crucial implications for environmental processes related to

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Abbreviations: CA_{in}, initial contact angle ($t = 1$ s) obtained by the sessile drop method (°); CA_{fin}, final contact angle ($t = 15$ s) obtained by the sessile drop method (°); CA_{av}, average contact angle obtained by the sessile drop method (°); CA_A, advancing contact angle obtained by the Wilhelmy plate method (°); CA_R, receding contact angle obtained by the Wilhelmy plate method (°); CA_M, average contact angle obtained by the Wilhelmy plate method (°); *WDPT*, water drop penetration time (s); $WDPT_{av}$, average value of water drop penetration time (s); $WDPT_{me}$, median value of water drop penetration time (s); *MED*, molarity of an ethanol droplet (%)

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water management in the soil profile (Doerr et al., 2000). Water repellency of soils limits their water sorptivity (Carrick et al., 2011) and results in uneven moisture distribution, forming preferential water flow in the soil profile. Water moves from zones of less repellent soil, leaving other areas completely dry for long periods (Ritsema et al., 1993; Dekker and Ritsema, 2000) or along pathways resulting from cracks, root channels and other types of macropores (Urbanek and Shakesby, 2009; Urbanek et al., 2015). Therefore, SWR has a significant impact on the phenomenon of water penetration into the soil (DeBano, 1981; Feng et al., 2001). In case of ponded infiltration in hydrophobic soils, the infiltration rate increases with time, contrary to wettable soils, in which the infiltration rate declines over time. In the absence of ponding conditions, a layer of water quickly forms on the surface of hydrophobic soils, which, in the case of heavy rainfall and a steep slope, flows from the ground surface, resulting in erosion (Imeson et al., 1992; Doerr et al., 2000; Schnabel et al., 2013; Butzen et al., 2015). The phenomenon of SWR can also reduce the height of the capillary rise (Scott, 2000) and limit the evaporation (Shokri et al., 2008; Kim et al., 2015), which leads to negative effects on germination and plant growth (Gupta et al., 2015). A highly hydrophobic soil delays the germination process and reduces the germination rate, which may lead to a decrease in crop yields (York and Canaway, 2000; Müller et al., 2014). SWR also affects the soil moisture retention curve (Liu et al., 2012) and soil water conductivity (Lamparter et al., 2010). SWR has typically been associated with dry environments, but research in the last two decades has shown the occurrence of SWR in many different soils under various climatic conditions and vegetation types (DeBano, 2000). Furthermore, the development of SWR in organic rich soils is still far less understood and investigated in comparison to mineral soil, with only a few studies concentrating on peat soil hydrophobicity (Hewelke et al., 2016).

In order to evaluate SWR, fast, simple and inexpensive methods are preferred, such as *WDPT* test (Bisdom et al., 1993; Doerr et al., 1996; Doerr, 1998; Letey et al., 2000; Jaramillo et al., 2000) or the molarity of an ethanol droplet (*MED*) test (Letey et al., 2000; Roy and McGill, 2002). Methods involving the determination of the CA value are less frequently selected (Bachmann et al., 2003; Ellies et al., 2005; Ramírez-Flores et al., 2008). Knowledge of the CA allows for the surface free energy of soils to be determined (Hajnos et al., 2013) and the impact of water repellency on soil water sorptivity (Cosentino et al., 2010) or the soil water retention curve to be estimated (Czachor et al., 2010). Moreover, it is also important for geotechnical engineering because it can offer novel solutions to the design of systems in order to cover overlying municipal or mine waste storage facilities or for other applications (Beckett et al., 2016).

The statistically robust conversion of data from different methods is urgently needed therefore in this paper we test the use of the pedotransfer functions (PTF) to transform SWR results obtained from the field test to mathematically meaningful CA values. PTFs are often defined as predictive functions of important soil properties from easily, routinely or cheaply measured ones (McBratney et al., 2002). The majority of PTFs have been developed to predict soil water retention and soil hydraulic properties (Schaap et al., 2001; Wösten et al., 2001; Manyame et al., 2007; Hewelke et al., 2015; Ghanbarian et al., 2017). Some PTFs have also been advanced to estimate soil physical (Martín et al., 2017; Schjønning et al., 2017), chemical (Valadares et al., 2017; Fernández-Ugalde and Tóth, 2017) and biological (Ebrahimi et al., 2017) properties. A few studies have already applied PTFs to predict SWR (Harper and Gilkes, 1994; Regalado et al., 2008; Lachacz et al., 2009). The aim of this study is to test whether it is possible to predict CA values based on the simple measurements of SWR using *WDPT* and *MED* tests.

Many authors have dealt with the comparison of methods to assess soil hydrophobicity (Buczko and Bens, 2006; Leelamanie et al., 2008a and b; Cosentino et al., 2010; Deurer et al., 2011). However, linear and non-linear regression equations proposed in the literature are not universal for all types of soils, nor widely used. In this paper, we introduce an original approach to determine the CA value based on two simple tests (*WDPT* and *MED* tests). For this purpose, we propose the use of a statistical technique called *rater agreement analysis* for estimating the compatibility degree between experts evaluating the same objects (popularly known as *agreement between observers*). As a measure of agreement between the analysed methods, the weighted kappa coefficient is applied. This statistical technique has not been previously used in SWR studies. We hypothesize that, with a high value of kappa coefficient, which means reliable compatibility between methods, it is possible to estimate the CA value on the basis of simple test (*WDPT* or *MED*) results. These tests, contrary to methods of CA measurements, do not require expensive equipment, and can be easily and quickly performed under both field and laboratory conditions.

2. Materials and methods

The study was conducted on 106 soil samples collected from 15 locations and 41 soil profiles located in North East Poland. The examined soils were classified according to the following five reference soil groups (IUSS Working Group, 2014 (updated 2015)): Histosols, Gleysols, Fluvisols, Arenosols and Podzols. Soil samples were collected from organic rich soils, mainly from surface horizons (0–30 cm), but samples from Histosol subsurface horizons (up to 100 cm) were also included. The soils from which samples were collected were formed from fen peats of various botanical origins (sedge, reed, moss, woody/alder) and represented various degrees of decomposition. Some surface horizons of peat soils had undergone secondary transformation and were therefore classified as mursh formations. Similar to murshes, but containing less soil organic matter (SOM) and substantial admixtures of sand fractions, were the semimursh formations (10–20% SOM) and postmursh formations (3–10% SOM). Examined gyttja, which represented bottom lake deposits, were mainly detritus (organic) and calcareous, while silty telmatic muds occurring in river valleys contained over 20% SOM (similar to muds, but containing < 20% SOM, are muddy formations). Ectohumus formations and A horizons of forest soils, composed of coniferous trees (*Pinus sylvestris* and *Picea abies*), were also included in the study (Arenosols and Podzols).

Soil samples with a defined mineral part, which were included in the study, had the lowest SOM contents and their texture was classified as sandy. As a result of various types of origin and composition, the studied soil formations varied greatly in respect of pH (H_2O), ranging from 3.32 to 8.41 (Table 1).

2.1. Samples preparation

Bulk soil samples, after being collected with a shovel at different

Table 1
Soil groups selected physical and chemical properties.

Reference soil groups	Number of samples	Value	SOM content (%)	OC (%)	N (%)	C:N (−)	pH in H_2O
Arenosols	14	Min	2.1	0.97	0.47	2.25	3.32
		Max	68.03	44.13	0.04	37.4	6.57
		Average	15.59	9.32	1.55	19.6	4.38
Fluvisols	11	Min	3.99	2.11	0.14	8.23	5.39
		Max	39.23	14.3	0.99	15.20	7.38
		Average	14.79	6.70	0.57	11.50	6.25
Gleysols	15	Min	3.88	1.55	0.17	9.24	3.6
		Max	89.60	42.75	2.67	20.52	6.41
		Average	35.07	15.82	1.11	13.72	5.24
Histosols	61	Min	4.15	2.27	0.1	9.75	4.78
		Max	94.06	50.60	4.75	93.71	8.41
		Average	59.85	30.07	1.64	25.85	6.19
Podzols	5	Min	6.86	3.83	0.16	15.05	3.4
		Max	73.83	36.32	1.63	24.39	3.8
		Average	27.61	13.17	0.66	19.19	3.52