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# Soil-water repellency characteristic curves for soil profiles with organic carbon gradients

Nadeeka Senani Wijewardana [a,g,*], Karin Müller [b], Per Moldrup [c], Brent Clothier [b], Toshiko Komatsu [a], Syuntaro Hiradate [d], Lis Wollesen de Jonge [e], Ken Kawamoto [a,f]

[a] Graduate School of Science and Engineering, Saitama University, 255 Shimo-okubo, Sakura-ku, Saitama 338-8570, Japan
[b] The New Zealand Institute for Plant & Food Research Ltd., New Zealand
[c] Department of Civil Engineering, Aalborg University, Denmark
[d] Biodiversity Division, National Institute for Agro-Environmental Sciences (NIAES), Japan
[e] Department of Agroecology, Aarhus University, Denmark
[f] International Institute for Resilient Society, Saitama University, 255 Shimo-Okubo, Sakura-ku, Saitama 338-8570, Japan
[g] Greater Kandy Water Supply Project, Katugastota, Kandy, Sri Lanka

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ABSTRACT

Soil water repellency (SWR) of soils is a property with significant consequences for agricultural water management, water infiltration, contaminant transport, and for soil erosion. It is caused by the presence of hydrophobic agents on mineral grain surfaces. Soils were samples in different depths at three forest sites in Japan and three pasture sites in New Zealand, covering soil organic carbon (SOC) contents between 1 and 26%. The SWR was measured over a range of water contents by three common methods; the water drop penetration time (WDPT) test, the molarity of an ethanol droplet (MED) method, and the sessile drop method (SDM). The aim to (i) compare the methods, (ii) characterize the soil-water repellency characteristic curves (SWRCC) being SWR as a function of the volumetric soil-water content ($\theta$) or matric potential ($\psi$), and (iii) find relationships between SWRCC parameters and SOC content. The WDPT, MED, and SDM generally agreed well in predicting the $\theta$ range where SWR occurred, and there was close agreement between SWR results determined by average MED and SDM at similar $\theta$. Generally, SWR was only found within the top 20 cm of the soil profiles. Six SWR parameters were introduced: (i) the area under the curve ($S_{WR(\theta)}$); (ii) $\theta$ at the maximum SWR ($\theta_{WR\text{-}max}$), (iii) $\theta$ where SWR ceased ($\theta_{non\text{-}WR}$), (iv) the maximum SWR ($CA_{i\text{-max}}$), (v) $pF$ at the maximum SWR ($pF_{WR\text{-}max}$) and (vi) $pF$ where SWR ceased ($pF_{non\text{-}WR}$). The relationship between the first three parameters and SOC content were best described with Langmuir type equations ($r^2$ of 0.5–0.7), while the other three parameters changed linearly with SOC contents.


## 1. Introduction

Soil water repellency (SWR) of soils is a property with significant consequences for agricultural water management (DeBano, 1975; Müller et al., 2014b), water infiltration (DeBano, 1975; Hillel and Baker, 1988), vertical soil-water transport (Nissen et al., 1999), contaminant transport (Van Dam et al., 1990; Clothier et al., 2000), and for soil erosion (Doerr et al., 2000; Hallet et al., 2001; Neris et al., 2013). It is caused by the presence of hydrophobic organic materials on soil grains and aggregate surfaces (DeBano, 2000; Doerr et al., 2000; Buczko and Bens, 2006; Urbanek et al., 2007; Ma'shum and Farmer, 1985; Horne and McIntosh, 2000; Leelamanie and Karube, 2014a), soil's water potential and aggregate size (Goebel et al., 2002; Bachmann et al., 2000; Lamparter et al., 2010), fire (Savage et al., 1972; DeBano et al., 1976), organic matter from plant litter or from microbial activity (Horne and McIntosh, 2000; Täumer et al., 2005; Badía-Villas et al., 2014), soil temperature (de Jonge et al., 1999), land uses and land management practices (Jaramillo et al., 2000; Doerr et al., 2006; Doerr et al., 2009).The severity of SWR depends primarily on the quality of the organic matter, the soil-water content (King, 1981; Dekker and Ritsema, 1997; de Jonge et al., 1999; Doerr et al., 2000) and the soils wetting and drying history (Arye et al., 2007; Lamparter et al., 2009). The governing mechanism of surface hydrophobicity is associated with the reconfiguration or reorientation of amphipathic organic matter compounds when they interact with water (Leelamanie and Karube, 2007; Regalado et al., 2008). When soils are wet, polar groups of the organic matter interact with water molecules, but as soils dry out these polar groups interact with each other (Nowak et al., 2013; Doerr et al., 2000). Vogelmann et al. (2013) found that the threshold water content below which hydrophobic soils became hydrophilic varied between 0.36 and 0.57 $cm^3\ cm^{-3}$ for subtropical humid soils under natural grassland in Brazil. Therefore, it is important to identify critical water contents (Dekker et al., 2001;

* Corresponding author at: Graduate School of Science and Engineering, Saitama University, 255 Shimo-okubo, Sakura-ku, Saitama 338-8570, Japan.
*E-mail address:* senanipdn@gmail.com (N.S. Wijewardana).

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Chau et al., 2014), which are site- and soil-specific, under which soils are water-repellent.

Different methods are used for measuring SWR, such as the water drop penetrating time (WDPT) test (King, 1981; Van't Woudt, 1959), the molarity of ethanol droplet (MED) method (de Jonge et al., 1999; Roy and McGill, 2002; Kawamoto et al., 2007) and the sessile drop method (SDM) (Bachmann et al., 2000; Subedi et al., 2012). The WDPT test assesses the persistence of SWR, and the MED is a measure for the ninety-degree surface tensions from which one may evaluate the solid-air interfacial tension. It only works for hydrophobic soils with contact angles greater than 90° (Carrillo et al., 1999). But, the SDM can be used to measure all ranges of SWR and specifically, sub-critical SWR (King, 1981; Chau et al., 2014), where the soil-water contact angle is >0° to 90° which cannot obtained from MED.

Potential correlations between measured SWR and different soil properties, such as soil organic carbon (SOC) content (de Jonge et al., 1999; de Jonge et al., 2009; Kawamoto et al., 2007; Rodríguez-Alleres et al., 2007), water content (Karunarathna et al., 2010a, 2010b; de Jonge et al., 2007; Kawamoto et al., 2007) and particle size (de Jonge et al., 1999; Rodríguez-Alleres et al., 2007) have been analyzed. The team of de Jonge et al. (1999, 2007) found single peak and double peak behavior for SWR curves in relation to water content, while Karunarathna et al. (2010a) identified three basic types of curves for single peak behaviors. Their type I curve behavior is characterized by increasing SWR with reducing $\theta$ until a maximum SWR at a certain $\theta$ ($\theta_{WR\text{-}max}$) is reached, and thereafter non-linearly decreasing SWR towards the potential SWR at air-dry $\theta$ ($\theta_{AD}$). Type II is the opposite of the type I curve: SWR ceases at a given $\theta$, which is larger than the $\theta_{AD}$. The soil is fully wettable at $\theta_{AD}$. Type III curve soils are not water-repellent at any $\theta$ between field $\theta$ to $\theta_{AD}$. The relationship between the degree of SWR and the soil volumetric water content ($\theta$) or suction is termed as soil water repellency characteristic curve (SWRCC) (Karunarathna et al., 2010a, 2010b; Kawamoto et al., 2014). Karunarathna et al. (2010a) identified SWRCC types for SWR-pF relations and found that the maximum SWR occurred at pF of 3.5 for most of the soil samples measured in their study.

Doerr et al. (2006) analyzed the relationships of SWR with clay contents, organic matter contents and soil moisture contents (%) for different soil sampling depths under different land-use systems. They concluded that land use and soil moisture contents are reliable predictors for SWR. Also, Vogelmann et al. (2013) generally concluded that in hydrophobic soils, the SWR parameters and persistence of SWR decreased with depth, reduced organic carbon contents, and increased water contents. Importantly, vegetation type, plant species (McIntosh and Horne, 1994; de Jonge et al., 2007) and the activity of fungal and microbial species (Hallett et al., 2001) could also contribute to the development of SWR in soils. Most published studies have based their conclusions on the relationship between SWR and other basic soil properties by applying only one indirect SWR characterization method. In addition, most studies did not evaluate the occurrence of sub-critical SWR. But even sub-critical SWR may reduce water infiltration and promote preferential flow and surface runoff (Clothier et al., 2000).

Japan and New Zealand have many naturally water-repellent soils. For example, in a comprehensive survey on the occurrence of SWR under pasture in the North Island of New Zealand, Deurer et al. (2011) found SWR to be widely prevalent in pastoral soils independent of soil order. Andosols, which are soils formed from volcanic tephra (USS Working Group WRB, 2006), are important in both countries. They are generally quite young and very fertile. Most Japanese forest soils are Andosols. Some of New Zealand pastoral lands are on Andosols, but Cambisols, which are medium developed and fine-textured soils (USS Working Group WRB, 2006), are also important soils for New Zealand agriculture and specially for pasture productivity (Müller et al., 2014a, 2014b).

Only a few studies on the occurrence of SWR in Andosols have been conducted (Kawamoto et al., 2007; Jordán et al., 2009; Karunarathna et al., 2010a, 2010b; Leelamanie and Karube, 2014a, 2014b; Neris et al., 2013). For example, Kawamoto et al. (2007) studied SWR in volcanic ash soil samples from Fukushima, Japan and concluded that hydrophobicity of aggregates changed with θ and with SOC gradients. Neris et al. (2013) measured infiltration and runoff in Andosols in the Canary Islands of Spain under pine forests and rainforests. The type of forest controlled the amount of infiltration and runoff. Under pine forests, infiltration was lower than under rainforest. Jordán et al. (2009) also studied the occurrence and hydrological effects of SWR in volcanic soils under different land uses. Results revealed that runoff was enhanced in water-repellent forest soils (average runoff coefficients between 15.7 and 19.9%) as compared with hydrophilic or slightly water-repellent soils, where runoff rates were lower (between 1.0 and 11.7%). Similarly, Müller et al. (2010) found that SWR reduced the infiltration rate and increased runoff in New Zealand Andosols. Moreover, Leelamanie and Karube (2007) concluded that hydrophilic organic compounds may increase water repellency when combined with hydrophobic organic compounds.

Ellerbrock et al. (2005) and Schnabel et al. (2013) studied SWR of Cambisols. Ellerbrock et al. (2005) found an exponential relationship between SWR parameters and the SOC/clay ratio. Schnabel et al. (2013) did not find a relationship between SWR and the basic physical or chemical properties of the soils, but for their study they concluded that the bare soil surface was hydrophilic independent of whether it was located below a tree canopy or in the open. Therefore, it seems necessary to discuss further the relationships between SWR and SOC for different land use types.

The objectives of this study were to (i) characterize SWR using three common methods; the water drop penetration time (WDPT) test, the molarity of ethanol droplet (MED) method and the sessile drop method (SDM) and compare the results for a range of SOC contents, (ii) evaluate the soil water repellency characteristic curve as a function of water content or matric potential with SDM results, and (iii) to find relationships between SWR parameters derived from SWRCC and SOC contents.

## 2. Materials and methods

### 2.1. Soil sampling and soil properties

Soil samples were collected from Japan (JP) and New Zealand (NZ) representing the soil orders of Andosols and Cambisols. Fig. 1 shows the distribution of the soil sampling locations in JP and NZ. The sites in JP were located in Nishigo, Fukushima (37° 08′ N 140° 09′ E), Hiruzen, Okayama (35° 16'N 133° 37'E) and Tochigi, Nikko (36° 41'N 139° 4'E),and in NZ they were in Ngahinapouri, Waikato (37° 53'S 175°12'E), Waihora, Waikato (38° 36'S 175° 74'E) and Whatawhata, Waikato (37° 28'S 175° 3'E). For the last site, high and low fertility fields were sampled. This terminology is based on a long-term phosphorus experiment: the "high fertility" field received 100 kg of phosphorus per ha and per year for 20 years, and the "low fertility" field did not receive any mineral phosphorous fertilizer during the same time period (Schipper et al., 2009). Photographs of soil profiles for each sampling site are shown in Fig. 1. All JP soil sampling locations were under forest, and the NZ sampling sites were under pasture. The dominant plant species at the sites are listed in Table 1. Table 2 tabulates the soil sampling depths, as well as the average of the measured soil physical and chemical properties. All measurements were done in triplicate.

The soil texture was determined by the hydrometer method (Gee and Or, 2002) and sieve analysis (Kettler et al., 2001). The soil organic carbon (SOC) and soil organic nitrogen (SON) contents were determined using ground samples in an automatic CN-analyzer (FLASH 2000 CHNS/O Analyzers, Thermo Scientific, Thermo Fisher Scientific, Inc. (NYSE:TMO)). Using the measured SOC and SON, the C/N ratio was calculated for all samples. The EC (1:5 solution) and pH (1:2.5 solution) were measured using a two-channel type digital meter (EC-pH meter WM-32EP, DKK-TOA Corporation, Japan), and soil core samples were used for the determination of field dry bulk density. Dry bulk