ORIGINAL RESEARCH ARTICLE

Soil Water Repellency Characteristic Curves for Selected Agricultural Soils with Different Ranges in Total Organic Carbon in Murang'a, Kenya.

Monica Mwikali Ndolo [1] **,*Home Patrick. G***[1]**, *Raude J. Messo***[1]

[1]*Department of Soil Water and Environmental Engineering, Jomo Kenyatta University of Agriculture and Technology, P.O. 62000-00200, Nairobi*

**Corresponding email:* monicah.mwikali@jkuat.ac.ke

ABSTRACT

Soil water repellency (SWR) is a temporary property of the soil that changes the functionality of the soil across a soil-specific range in soil moisture content (W). The severity and persistence of soil water repellency in agricultural soils are important for understanding and predicting their effects on the soil hydrological processes that optimise plant growth. Therefore, this study aimed at characterising the persistence of SWR using the Water Drop Penetration Time (WDPT) test, evaluating the SWR curve as a function of gravimetric water content from the WDPT results, and finally developing relationships between SWR parameters, i.e.; total SWR (SWR_{AREA}), critical moisture content (Wc), and soil properties (total organic carbon, sand, silt, clay), to understand the persistence of SWR and its effect on water flow. The degree of SWR as a function of soil moisture content was measured and monitored from oven-dry conditions to the water content at which the soils turned hydrophilic (Wc). SWR_{AREA} was calculated as the trapezoidal area under the SWR-w curve. A total of 37% of the soils representing the six dominant soils investigated were water-repellent and expressed wide ranges in clay (10–40%) and TOC (0.67–6.08%). The SWR-w curves were either single or double-peaked with SWR_{AREA} ranging from 8.38 seconds/%W to 24.91 seconds/%W. The most important soil property in explaining SWR_{AREA} and Wc was TOC. The inclusion of clay and silt in the multiple linear regression (MLR) expression of SWR_{AREA} significantly improved the prediction of SWR_{AREA} to 85%. Furthermore, an upper limit for critical water content was derived from the simple relationship between Wc and TOC, which could be used to improve agricultural soil irrigation practises in Murang'a County, Kenya. When more comprehensive data for each soil type is available, it is recommended to develop soil type-specific models for Wc as a function of TOC.

Key words: Soil texture; hydrophobic; water drop penetration time (WDPT); critical soil water content (Wc).

1.0 Introduction

Soil water repellency (SWR) is a property of the soil that significantly reduces its functionality, thereby reducing agricultural production (Müller et al., 2010, de Jonge et al., 2009). The effects on soil hydrological functions include reduced water infiltration (Doerr et al., 2000; Leighton-Boyce et al., 2007), increased leaching risk of fertilizers and pesticides to groundwater sources (Dekker and Ritsema, 1995), increased overland flow, soil erosion, and decreased soil water

URL: https://ojs.jkuat.ac.ke/index.php/JAGST
ISSN 1561-7645 (online)
doi: 10.4314/jagst.v22i1.5

storage (Doerr et al., 2000). Primarily, the main cause of soil water repellency is thought to be the coating of soil particles by organic substances originating from vegetation (Franco et al., 2000), organic contaminants from raw sewage and oil spills (Roy et al., 2003), and soil microorganisms (Dekker and Ritsema, 1996; Schaumann et al., 2007). However, the governing mechanism of soil water repellency formation is associated with the re-orientation and reconfiguration of hydrophobic substances when they interact with water (Leelamanie and Karube, 2007; Regalado et al., 2008).

Soil water repellency is a transient property and is only exhibited across a soil-specific water content (W) (Graber et al., 2009). However, the severity of repellency varies non-linearly with the soil water content. Soil water repellency occurs within a transition zone of water content that is delimited by an upper critical water content (Wc), above which the soil becomes hydrophilic (de Jonge et al., 2007; Kawamoto et al., 2007; Regalado et al., 2008). Wetting patterns in repellent soils can reorient the hydrophobic substances in the soil and expose their ends, which in turn changes the surface tension of the soil and shifts between hydrophobic and hydrophilic conditions in the soil (de Jonge et al., 1999; Doerr et al., 2000; Graber et al., 2009).

The persistence of SWR can be described by an SWR-w characteristic curve, in which soil water repellency is expressed as a function of gravimetric soil water content (de Jonge et al., 2007; Regalado et al., 2008; Regalado and Ritter, 2009a; Karunarathna et al., 2010a) or in terms of pF values. The SWR-w curve can either start from zero (0 kg/kg) water in oven-dry soil conditions or at an air-dry state of the soil (de Jonge et al., 2007; Karunarathna et al., 2010a, 2010b) and continue until the soil turns wettable at the critical moisture content (Wc). The area underneath the SWR-w curve represents the total SWR of soil (SWR_{AREA}), as shown in Figure 1.

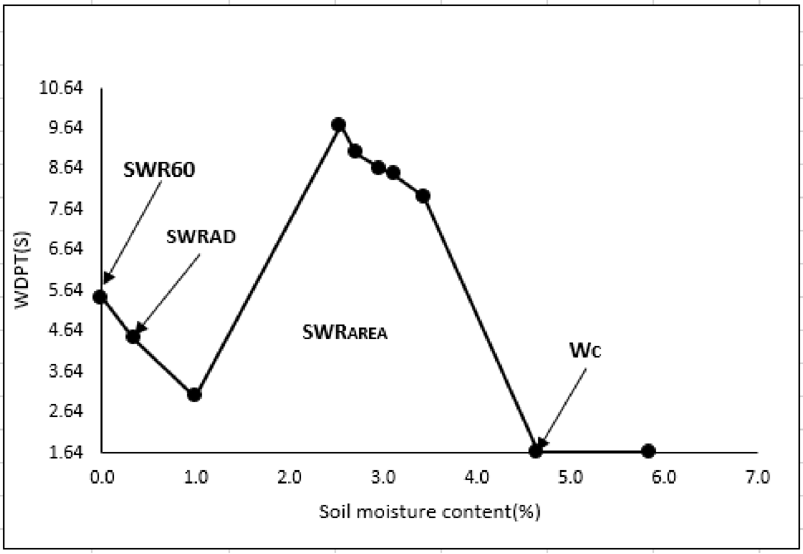


Figure 1: Soil water repellency (SWR) as a function of soil-water content and the derived parameters. SWR_{60} are determined after oven-drying soil samples 60 °C. The SWR AD is

URL: https://ojs.jkuat.ac.ke/index.php/JAGST
ISSN 1561-7645 (online)
doi: 10.4314/jagst.v22i1.5

determined at airdried conditions. Finally, Wc is the critical soil-water content at which the soil turns hydrophilic, and the area the curve represents the total degree of SWR (SWR_{AREA}).

SWR-w curves for water-repellent soils are non-linear and are either bimodal (double peak) or unimodal (single peak). The double-peaked curves usually show repellency at oven-dry conditions, but the persistence of SWR decreases with increasing soil water content to a local minimum while still maintaining hydrophobicity or becoming temporarily wettable (Wijewardana et al., 2016; de Jonge et al., 2007). Afterwards, the persistence of SWR increases again to a local maximum (second peak) and again decreases towards Wc. On the other hand, the unimodal curves can either exhibit hydrophobicity or are hydrophilic at oven-dry soil conditions.

Monitoring the change in soil water repellency with soil water content takes a long time. Nevertheless, the procedure can be used to estimate SWR parameters such as the integrated trapezoidal area under the SWR-w curve (SWR_{AREA}) and Wc, which are easily derived from the measurable soil properties (Regalado et al., 2008). SWR_{AREA} and Wc are the key parameters that are used for characterising the persistence or severity of SWR in the soil. On the other hand, soil organic carbon has been reported as the primary soil property controlling the severity and persistence of SWR across several ranges of soil moisture contents. Therefore, SWR_{AREA} and Wc increase with increasing soil organic carbon (de Jonge et al., 1999; Hermansen et al., 2019; Regalado and Ritter, 2005). Hermansen et al. (2019) suggested a linear relationship between Wc and soil organic carbon to prevent the onset of SWR and the associated effect on the soil hydrological process as a guide for irrigation practices.

Various methods are used in measuring soil water repellency, which include the Water Drop Penetration Time (WDPT) test, the Molarity of Ethanol Droplet (MED) method, and the Sessile Drop Method (SDM). WDPT tests the persistence of a drop of water on the surface of the soil, hence SWR persistence (King, 1981; Van'tWoudt, 1959). MED measures the severity of SWR, which describes how strongly the soil repels water (De Jonge et al., 1999; Kawamoto et al., 2007). It only works for repellent soils with contact angles greater than 90°. On the contrary, the SDM measures all ranges of SWR that are in soils with soil-water contact angles between zero degrees and ninety degrees (Chau et al., 2014).

The severity and persistence of soil water repellency in agricultural soils are important in understanding and predicting their effects on the soil hydrological processes that optimise plant growth. However, there is a limited understanding of the persistence (measured by WDPT) of SWR and its effect on water flow. Although it is very well known that SWR decreases with an increase in soil moisture content, little is known about the threshold soil moisture conditions needed for braking SWR (Ganz et al., 2013; Jordan et al., 2013). Murang'a County falls in agro-climatic zone III, which is characterized by different climatic conditions ranging from rainfall, evapotranspiration, and temperatures. All these factors influence the soil-forming process, which means that the soils in this study area differ in their hydrophysical properties. The soil formation factors, such as the parent material, vegetation, and land use

URL: https://ojs.jkuat.ac.ke/index.php/JAGST
ISSN 1561-7645 (online)
doi: 10.4314/jagst.v22i1.5

(Muller and Deurer, 2011), are also varied, and therefore the physical factors that influence soil water repellency, such as soil texture, bulk density, and organic matter, also vary. Given the agricultural significance of Murang'a County in Kenya and bearing in mind the negative impacts of soil water repellency in agriculture, it was necessary to study the soil hydrological behavior, especially the development, distribution, and persistence of soil water repellency in this setting.

Total organic carbon (TOC) has been reported to be the most important soil property that controls the severity and persistence of soil water repellency in most soils (Hermansen et al., 2019). However, soil organic carbon controls soil water repellency with other soil constituents such as soil texture and microbial organisms. Thus, this paper aims at examining the basic relationship between soil water repellency and soil water content from oven-dry to wet conditions for the soils sampled across Murang'a County and further obtain a critical moisture content from the basic properties that can be advantageous in preventing the occurrence of soil water repellency in agricultural soils.

2.0 Materials and methods

2.1 Study area

Murang'a County is in the central region of the Republic of Kenya, bordering Nyeri to the north, Kirinyaga, Embu, and Machakos to the east, Kiambu to the south, and Nyandarua to the west. It has a total area of 2,558.8 km^2 and is situated between latitudes 0^0 34' and 10 7' South and 36^0 00' and 37^0 27' East (Murang'a CIDP, 2018–2022). The county has three distinct climate zones, including equatorial, sub-tropical, and semi-arid zones. Its two rainy seasons are March-April-May (MAM) and October-November-December (OND). Kangema, Gatanga, and the higher parts of Kigumo and Kandara are generally humid and wet due to the influence of the Aberdares. The eastern region receives minimal rainfall, and crop production requires irrigation.

The geology consists of volcanic rock structures, and most of the soils have developed from volcanic activities. The soils are generally fertile and have good drainage. The soil types that dominant in the county and are closely related to agricultural production, as mapped by Kenya Crop Land Layer, were considered for sampling. These soil types are Umbric Andosols, Humic Nitisols, Rhodic Ferralsols, Chromic Cambisols, Haplic Lixisols, Haplic Acrisols, Dystric Cambisols, and Humic Cambisols, as classified by the 1988 FAO-UNESCO Soil Map of the World. The common crops grown in this study area, especially by irrigation, include cabbage, spinach, kale, onions, tomatoes, beans and maize, or field corn.

Fifty-two (52) soil samples were collected at two soil depths 0–15 cm and 15–30 cm from 26 sampling sites and were spread across the dominant soil types under agriculture in Murang'a County, Kenya. These soil types included Humic Nitisols UP (NTua), Humic Nitisols IB2 (NTub), Umbric Andosols (ANu), Rhodic Nitisols (NTr), Rhodic Ferralsopls (FRr)and Ferrallic Cambisols, as shown in Figure 2. These soil types were classified according to the FAO/UNESCO Soil Map

URL: https://ojs.jkuat.ac.ke/index.php/JAGST
ISSN 1561-7645 (online)
doi: 10.4314/jagst.v22i1.5

of the World (1988) and complemented with soil layers from the Kenya Soils and Terrain Database (KENSOTER).

The sampling unit boundaries were mapped in ArcGis (ArcMap 10.5) such that each soil type represented a sampling unit. Judgmental sampling was used to select the soil types that were most relevant to the study, and this was based on the rooting depth of most crops grown in the areas. Judgmental sampling involves the selection of sampling units based on expert knowledge or professional judgment. It is useful when there is reliable historical and physical knowledge about a relatively small feature or condition to develop an efficient sampling design (QA, 2002).

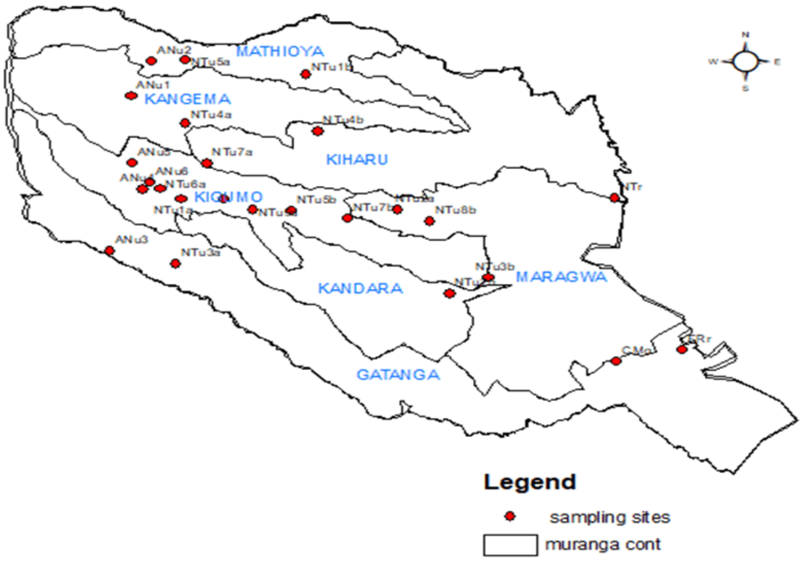


Figure 2: Map Showing Location of the 26 Sampling Sites Distributed Across Murang'a County in Kenya. The samples represent the six soil types: Humic Nitisols UP(NTua), Humic Nitisols IB2 (NTub), Umbric Andosols (ANu), Rhodic Nitisols (NTr), Rhodic Ferralsols (FRr) and Ferralic Cambisols (CMo)

In this case, the average effective rooting depth of most common crops grown in the area was used to select the soils that were deep enough to allow effective exploitation of water and nutrients by crop roots. Random sampling was then used to select the sampling sites in each of the study areas across all the selected soil types. From each sampling site, approximately 1 kg of disturbed and undisturbed soil samples was collected into sampling bags, which were then labelled with the GPS location of the site, soil type and depth of sampling. The samples were then transported to the laboratory in sealed bags for analysis.

2.2 Laboratory methods

The soil texture was determined in the laboratory using the hydrometer method (Bouyoucos, 1962), while the gravimetric oven drying method was used to determine the soil moisture

URL: https://ojs.jkuat.ac.ke/index.php/JAGST
ISSN 1561-7645 (online)
doi: 10.4314/jagst.v22i1.5

content and bulk density, from which the porosity of the soil was calculated. Total organic carbon (TOC) content was determined by the wet-digestion method (Walkley and Black, 1934).

2.3 Soil preparation and water repellency measurements

Before measuring soil water repellency, soil samples were thoroughly mixed in their moist field conditions. The soil samples were then oven-dried at 60°C to determine the potential or current risk of soil water repellency and persistence. This gives an estimate of the potential soil water repellency and it is the highest level of repellency that can be reach when the soil dries out completely (Ritsema & Dekker, 1994; Deurer et al., 2011). Estimated soil water repellency provides insight into the potential consequences of soil hydrophobicity in the event of a drought. In situ measurements in field moist conditions, on the other hand, provide the actual soil water repellency (Müller et al., 2014). High drying temperatures have been observed to influence the formation of organic material coatings responsible for water repellency (Dekker et al., 1998). Therefore, drying soils at 105°C can give an incorrect estimate of repellency. In different studies (Doerr and Thomas, 2000), air drying was suggested as the best approach to studying the soil water repellency-moisture relationship. This was the approach adopted for this study.

Changes in soil moisture content during the air-drying process were used to monitor soil water repellency. This was conducted in two phases: a wet phase and a dry phase. Wet phase: The actual soil water repellency was determined by performing the Water Drop Penetration Time Test (WDPT) on the field-gathered moist soil samples before oven-drying them at 60°C for 48 hours, after which the soil moisture content reduced to absolute zero (Crockford et al., 1991; Berglund & Persson, 1996; De Jonge et al., 1999). The oven-dried soil samples were then divided into three replicates before being saturated for 24 hours in the laboratory. The samples were then exposed to air-dry conditions in a greenhouse to simulate the ideal field conditions.

Dry phase: Soil samples were left uncovered under greenhouse conditions (24°C-39°C) to allow for gradual drying. Soil moisture loss was determined by weighing the samples each day before the soil water repellency measurements were taken. This was done for seven consecutive days. WDPT was carried out on each soil sample by placing 5 drops of deionized water on a smoothed soil surface and recording the full drop penetration time in seconds (Doerr, 1998). Three replicates were done for each soil sample until the soil moisture content reached a stable minimum, i.e., the samples attained a constant weight. Air-dried samples were then oven-dried at 105°C to estimate the soil's dry weight.

2.4 Data analysis

The SWR-w curve was plotted after estimating soil water repellency as a function of actual gravimetric soil moisture content. The total SWR of each sample was determined as the trapezoidal integrated area under the SWR-soil water content curve. The critical soil water content was determined as the soil water content at which soil turned hydrophilic. The Integrative Repellency Dynamic Index (IRDI) was used to calculate the average soil water

URL: https://ojs.jkuat.ac.ke/index.php/JAGST
ISSN 1561-7645 (online)
doi: 10.4314/jagst.v22i1.5

repellency function, which gives a measure of the mean water repellency in the soil moisture interval between zero (at oven dry condition) and critical soil moisture content (when soil turns hydrophilic) (Regalado and Ritter, 2005). The average was calculated as shown in equation (1) and tabulated in Table 1.

$$IRDI = \frac{SWR_{AREA}}{Wc}$$ *Equation 1*

Where;
IRDI= Integrative Repellency Dynamic Index (seconds)
SWR_{AREA}= trapezoidal integrated area under the SWR-w curve (seconds/%soil moisture content)
Wc= critical soil moisture content at which the soil turned hydrophillic (seconds)

Hydrophilic soil samples were excluded from further examination. Linear correlations were evaluated by the coefficient of determination (R^2). Forward multiple linear regressions (MLRs) were used to correlate physicochemical properties (clay, silt, sand, and TOC) to SWR_{AREA} and Wc.

The Akaike information criterion (AIC) is a measure of the fitness of a model used to correlate data (Bozdogan, 1987). It was applied to evaluate the accuracy of the SWR and Wc correlations with soil properties. The best model is considered to be the one with a low AIC value. This value was calculated using Equation 2, given as:

$$AIC = n[ln(2\pi) + ln\,(\sum_{i=1}^{n}\frac{(di)^2}{n-K}) + 1] + K$$ *(Equation 2)*

Where;
K = number of input variables
n = number of samples
di= residual value between the measured and obtained value from the model

3.0 Results and discussions

3.1 Soil water repellency persistence

The actual soil water repellency of the field moist samples varied between 1 second and 355 seconds, which means that, according to Doerr et al.'s (2000) classification of water repellency, SWR ranged from wettable to strongly repellent. Among the 52 soil samples investigated in Murang'a, nineteen (19 out of 52) samples, or 37%, were hydrophobic. The hydrophobic soils from Murang'a showed an actual water repellency (SWR_{ACT}) of between 5 and 355 seconds and a total organic carbon range of between 1.38 and 6.08%. These soils were classified into sand-clay loam (13 samples), clay (2 samples), and sandy loam (4 samples). Generally, Humic Nitisols in UP showed the highest mean actual soil water repellency of 106.5 seconds, with Rhodic Nitisols showing the least mean actual repellency of 6.7 seconds in Murang'a, as presented in Table 1.

URL: https://ojs.jkuat.ac.ke/index.php/JAGST
ISSN 1561-7645 (online)
doi: 10.4314/jagst.v22i1.5

Table 1: Soil Characteristics: Clay, Silt, Sand, Total Organic Carbon (TOC), SWR after Oven Drying at 60°C(SWR_{60}) and 105°C, the Total Degree of Soil Water Repellency (SWR_{AREA}), the Critical Soil Moisture Content (Wc) and the Integrated Repellency Dynamic Index (IRDI) of the 19 Hydrophobic Soil Samples in Murang'a County.

Soil Unit		Umbric Andosol	Humic Nitisol, Up	Humic Nitisol, IB2	Rhodic Nitisol	Rhodic Ferralsols	Ferrallic Cambisols
n		3	6	4	2	2	2
Sand (%)	mean	58.67	59.33	53	52	86	86
	min	56	44	52	52	86	86
	max	60	68	54	52	86	86
	sd	2.31	11.91	1.16	0	0	0
Clay (%)	mean	31.33	26.67	39	32	14	10
	min	30	20	38	32	14	10
	max	34	40	40	32	14	10
	sd	2.31	10.33	1.16	0	0	0
Silt	mean	10	14	8	16	0	4
(%)	min	10	12	6	16	0	4
	max	10	16	10	16	0	4
	sd	0	1.79	2.31	0	0	0
TOC	mean	3.76	4.40	5.74	5.82	1.13	1.15
(%)	min	1.48	3.53	5.51	5.55	1.1	0.67
	max	5.04	6.03	6.00	6.08	1.16	2.41
	sd	1.98	1.11	0.21	0.38	0.04	1.23
	mean	2.78	11.22	2.10	3.35	2.65	5.59
SWR_{60}(seconds)	min	1.18	0.60	0.80	1.67	2.03	5.45
	max	5.69	22.41	3.03	5.03	3.26	5.73
	sd	2.53	8.94	1.06	2.38	0.87	0.20
SWR_{105}(seconds)	mean	1.94	1.76	1.75	1.42	0.84	1.91
	min	1.31	1.13	0.81	1.4	0.79	1.16
	max	2.42	3.06	2.63	1.44	0.89	2.65
	sd	0.57	0.77	0.77	0.03	0.07	1.05
SWR_{ACT} (seconds)	mean	9.67	106.47	7.7	6.65	7.1	8.2
	min	6.3	5	5.3	6.2	7	7.1
	max	16.3	355	10	7.1	7.2	9.3
	sd	5.75	144.34	2.55	0.64	0.14	1.56
SWR_{AREA} (sec/%smc)	mean	21.93	13.39	24.91	23.67	9.11	8.89
	min	20.61	8.38	23.19	20.46	8.54	8.38
	max	22.76	22.21	26.41	26.90	9.69	9.40
	sd	1.16	4.95	1.34	4.55	0.81	0.72
w_c(%smc)	mean	10.47	9.75	13.23	11.29	8.27	6.56
	min	9.5	8.00	11.73	10.04	7.53	6.18
	max	11.48	11.97	16.67	12.54	9.01	6.94
	sd	0.99	1.57	2.31	1.77	1.05	0.54
IRDI (seconds)	mean	2.13	1.38	1.90	2.09	1.12	1.53
	min	1.95	0.84	1.39	2.04	1.11	1.37
	max	2.33	1.98	2.25	2.14	1.14	1.69
	sd	0.20	0.48	0.37	0.07	0.02	0.23

TOC-Total Organic Carbon; IRDI- Integrative Repellency Dynamic Index; SWR_{60}- Soil Water Repellency 60°C; SWR_{ACT}- Actual Soil Water Repellency; SWR_{AREA}-Total Soil Water Repellency; SWR_{105}-Soil Water Repellency at 105 °C; WDPT-Water Drop Penetration Time; Wc-Critical Soil Water Content

URL: https://ojs.jkuat.ac.ke/index.php/JAGST
ISSN 1561-7645 (online)
doi: 10.4314/jagst.v22i1.5

The potential water repellency (SWR_{60}) of the samples was also measured at 60 ^{0}C to estimate the highest level of repellency that can be reached when the soil dries out completely. The actual soil water repellency (SWR_{ACT}) was observed to be higher than the potential soil water repellency after heating (SWR_{60}) across all the soil samples. Despite the fact that high temperatures have been shown to influence hydrophobicity due to reorientation of hydrophobic molecules (De Jonge et al., 1999; Doerr et al., 2000), the soils studied here had lower soil water repellency at oven dry state (60^{0}C). The results agreed with those observed by Crockforf et al. (1991) and Berglund and Persson (1996), who also observed that soil water repellency was lower in the soils at their oven-dry conditions and then increased to a peak at various soil moisture levels as shown in the SWR-w curves. This was because the soil organic carbon tends to lose its stabilizing effect during drying (Urbanek et al., 2014). However, the relationship between potential and actual soil water repellency is not obvious, and thus actual soil water repellency cannot be derived from potential soil water repellency, as stated by Graber et al. (2006).

3.2 Soil water repellency-soil moisture content curves (SWR-w Curves)

With respect to repellency and soil moisture content dynamics observed, the soils expressed a range of behaviors (Figure 4). It is clear from Figure 4 that a wide range of published SWR-W curve shapes (De Jonge et al., 1999; Karunarathna et al., 2010a; Regalado and Ritter, 2009b;Regalado et al., 2008) were confirmed. Single-peak SWR-w curves (A, B, G, P, Q, R, and S) and double-peak SWR-w curves (C, D, E, F, H, I, J, K, L, M, and N) were observed. The curves were either rising from a repellent or a wettable state at oven-dry conditions (60°C). The curves rising from a repellent state are shown in Figure 4 (D, H, I, J, L, M, and N), while those rising from a wettable state are shown in Figure 4 (A, B, C, E, F, G, O, P, Q, and R). The soils with bimodal curves were either repellent or hydrophilic at oven-dry conditions. However, the degree of soil water repellency for the bimodal curves decreased to a local minimum with an increasing moisture content while still retaining some degree of hydrophobicity, as shown in Figure 4 (I, M). In addition, there are also some bimodal SWR-w curves whose repellency decreased with an increase in soil moisture content to become temporarily wettable (WDPT 5 seconds) before rising to a maximum repellency under oven-dry conditions. Figure 4 (C, D, E, F, H, K and N). Water repellency was observed in some soils near their field capacity (Figure 3(I)). The soil sample represented in Figure 3 (I) showed repellency of 5.1 seconds at 11% soil moisture content, which is very close to its field capacity (11.8%). Most of the soil samples, however, reached maximum water repellency at soil moisture content levels below their wilting point.

URL: https://ojs.jkuat.ac.ke/index.php/JAGST
ISSN 1561-7645 (online)
doi: 10.4314/jagst.v22i1.5

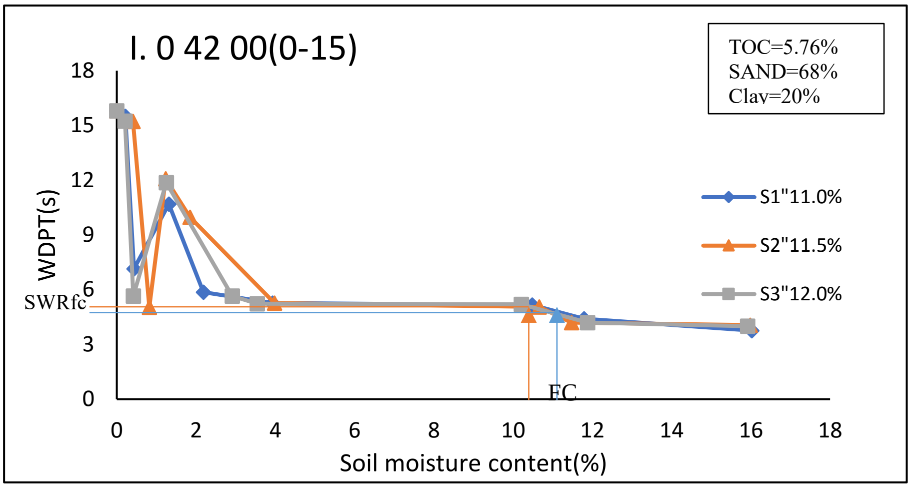
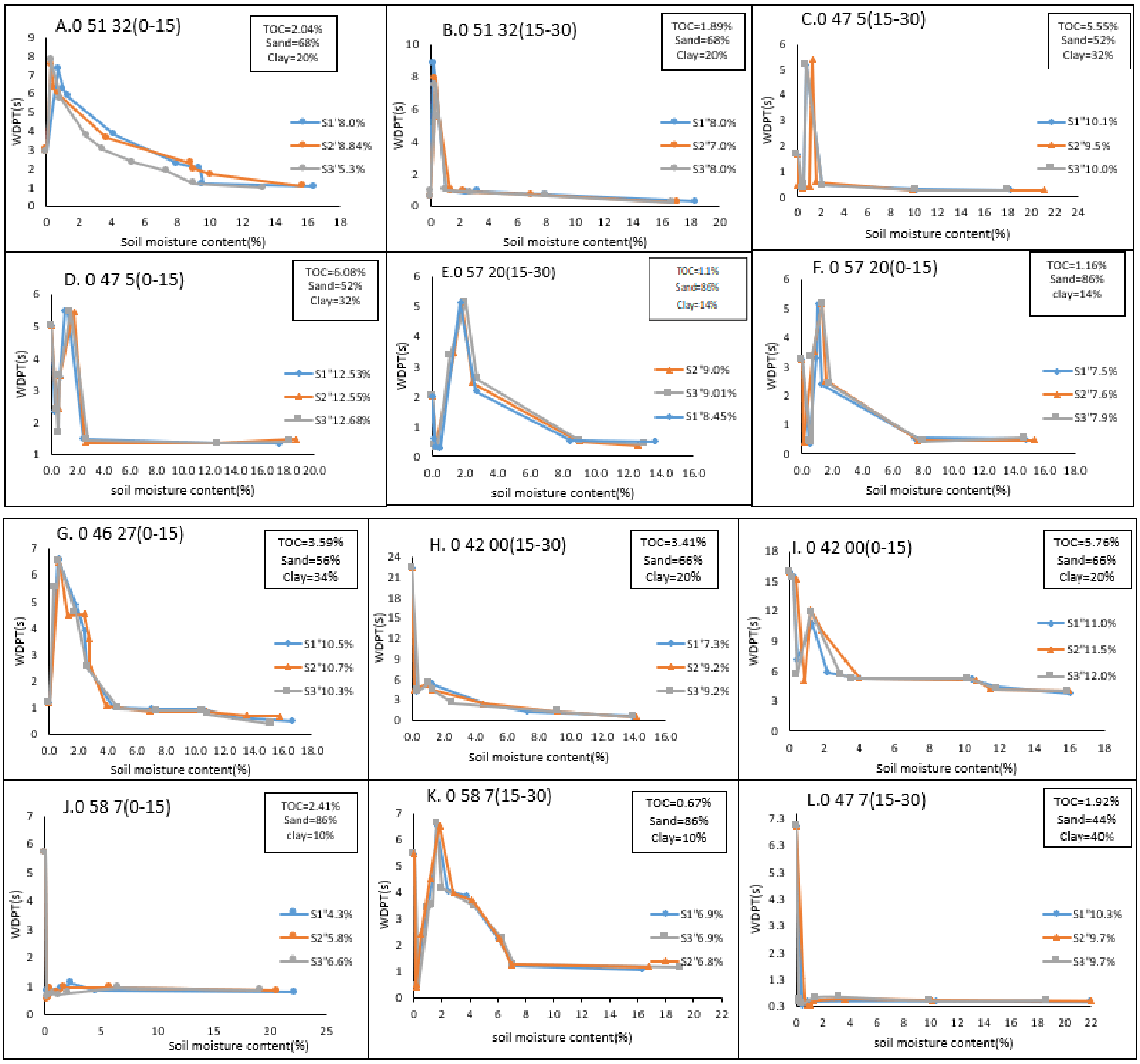


Figure 3: Soil water repellency (SWR) near field capacity. FC denotes the Field capacity (SMC=11.8%) and SWRfc represents the interpolated SWR near the field capacity (SWRfc=5.1 seconds at 11% moisture content).

Generally, it was observed that SWR first decreased from the oven-dry state of the soils to a local minimum at low soil moisture contents before again increasing at increasing soil moisture contents, as it had been observed by de Jonge et al. (1999). Some possible processes and mechanisms have been proposed to explain this unusual behavior. Jex et al. (1985) and Roberts and Carbon (1971) attributed the behavior to enhanced microbial activity with increasing relative humidity. Increased soil water repellency at higher soil moisture content levels is also caused by solvent-induced changes in the molecular conformation of soil organic matter (Roy and Mc Gill, 2000). Doerr et al. (2002) also attributed the same behavior to the reorientation of hydrophobic functional groups that had been previously disrupted during the oven-drying process. For the double peak curves, the first peak of soil water repellency occurred at low water contents, which are close to zero. However, with an increase in soil moisture content, the repellency first decreased and then increased again to an intermediate soil water content, reaching a second peak. From the second peak, soil water repellency decreases again until the soil becomes wettable above the critical moisture content (Figure 3). For the double-peaked curves, the behavior of the first peak is attributed to the reorientation of the hydrophobic molecules due to water loss associated with the temperature treatment during oven-drying (De Jonge et al., 1999; Doerr et al., 2000).

URL: https://ojs.jkuat.ac.ke/index.php/JAGST
ISSN 1561-7645 (online)
doi: 10.4314/jagst.v22i1.5



URL: https://ojs.jkuat.ac.ke/index.php/JAGST
ISSN 1561-7645 (online)
doi: 10.4314/jagst.v22i1.5

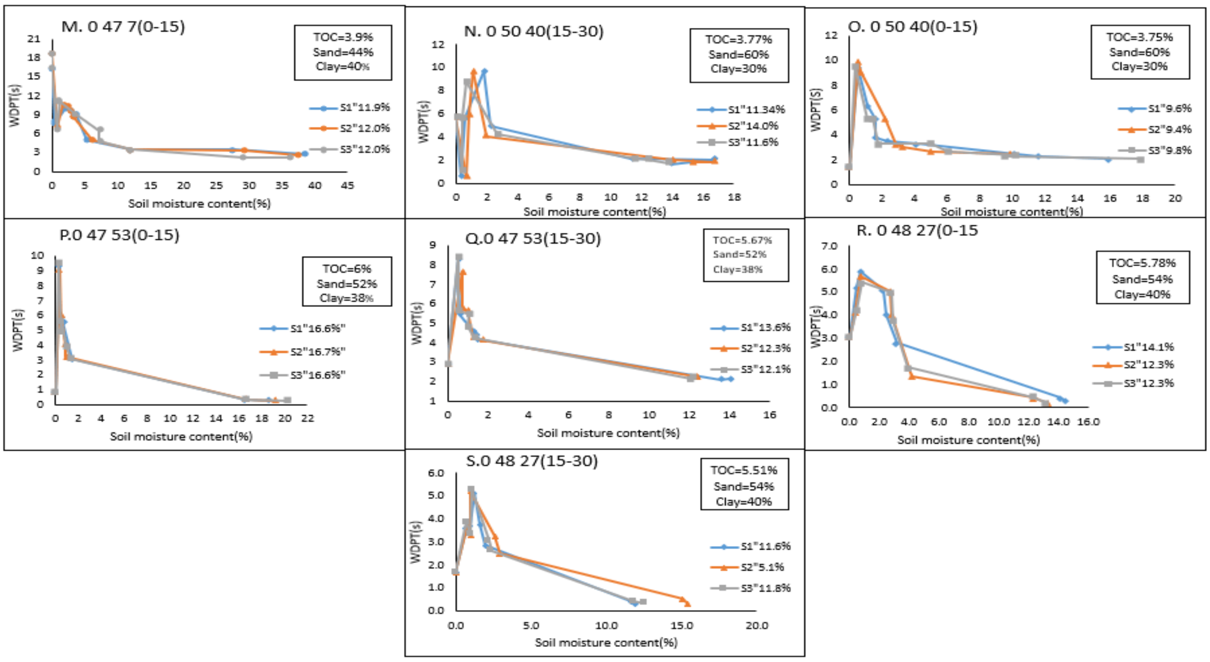


Figure 4: Soil water repellency as a function of soil water content in Murang'a soils. In each graph, three curves shown represent the three replicates (S1, S2, S3) examined for each soil sample at depths of (0-15cm) and (15-30 cm).

URL: https://ojs.jkuat.ac.ke/index.php/JAGST
ISSN 1561-7645 (online)
doi: 10.4314/jagst.v22i1.5

It was evident that in soils whose curves were bimodal, their global maximum (the largest overall value of WDPT) was observed in the second peak, and therefore, it is necessary to measure the whole SWR-w curve in order to estimate the highest degree of repellency that can be reached in the soil (Hermansen et al., 2019). The average soil water repellency function was calculated using the Integrative Repellency Dynamic Index (IRDI), which provides a measure of mean water repellency in the soil moisture interval between zero (at oven dry condition) and critical soil moisture content (when soil becomes hydrophilic) (Regalado and Ritter, 2005). This average is calculated as shown in equation (1).

The SWR_{AREA} and Wc were highly variable, ranging from a mean of 8.89 to 24.91 sec/% moisture content and 132.3 to 65.6 g/kg, respectively (Table 1). Umbric andosols exhibited generally high mean SWR_{AREA} of 22.98 sec/% smc and 22.43 sec/% smc, respectively, as presented in Table 1. Soil samples that had the lowest and highest SWR_{AREA} also had correspondingly low and high TOC contents (Table 1), depicting a strong influence of TOC on the persistence of SWR (Weber et al., 2021). The differences in total organic carbon content in the soil samples affected the SWR_{AREA} (trapezoidal integrated area under the SWR-w curve) for the various soil types, which in turn influenced the total soil water repellency (IRDI). Generally, the maximum IRDI for Humic Nitisols, IB2, and Umbric Andosols was 2.25 and 2.33 seconds, respectively, while Rhodic Ferralsols had a much lower IRDI of 1.14 seconds. This could be attributed to differences in the amounts and type of total organic carbon present in the soil which resulted in variation in SWR_{AREA} between the investigated soil types. This observation was also made by Czachor et al. (2013), who reported that even a small increase in organic matter content can change soil hydrological properties from a completely wettable to a partially water-repellent state. Among the six soil types studied, the persistence of SWR in terms of SWR_{AREA} decreased in the following order: Humic Nitisols IB2 > Rhodic Nitisols >Umbric Andosols> Humic Nitisols UP > Rhodic Ferralsols >Ferrallic Cambisol.

3.3 Critical soil moisture content

The critical soil moisture content at which soil water repellency is broken was determined as a "transition zone" rather than a "sharp threshold" (Chau et al., 2014). Depending on its wetting history, the soil in this transition zone can be either hydrophobic or hydrophilic. Two control limits can be obtained from the transition zone. An upper threshold of the transition zone indicates the absence of soil water repellency, and the lower limit indicates the re-establishment of the repellency; however, this lower limit cannot be specified well and may be an unreliable predictor of the re-establishment of soil water repellency (Doerr et al., 2000).

Soil water repellency was observed to be broken at various critical moisture content levels (W_c). Humic Nitisols, IB2, were observed to turn hydrophilic at a higher average critical moisture content of 13.23% (132.3 g/kg soil), while on the other hand, Ferrallic Cambisols turned wettable at a lower soil moisture content level of 6.56% (65.6 g/kg soil). The critical water contents ranged between 95.0 g/kg and 114.8 g/kg for Umbric Andosols, 80.0 g/kg and 119.7 g/kg for Humic Nitisols Up, 117.3 g/kg and 166.7 g/kg for Humic NitisolsIB2, 100.4 g/kg and 125.4 g/kg for Rhodic Nitisols, 75.3 g/kg and 90.1 g/kg for Rhodic Ferralsol, and 61.8 g/kg

URL: https://ojs.jkuat.ac.ke/index.php/JAGST
ISSN 1561-7645 (online)
doi: 10.4314/jagst.v22i1.5

and 69.4 g/kg of soil for Ferrallic Cambisols as presented in Table 1. The average critical water content values were way higher than the mean permanent wilting point and closer to the field capacity of the soils as presented in Table 2.

Table 2:The average Critical Soil Water Content, Field Capacity, Permanent Wilting Point (PWP), Degree of Saturation and the Moisture Content during Sampling in the Field (Field Moisture Content) for the Repellent Soil Samples in Murang'a

	Umbric Andosols	Humic Nitisols, UP	Humic Nitisols,IB2	Rhodic Nitisols	Rhodic Ferralsols	Ferraliic Cambisols
Wc (%)	10.47	9.75	13.23	11.29	8.27	6.56
Field capacity (%)	14.54	23.25	22.84	13.23	10.23	11.81
PWP(%)	6.74	6.08	8.05	6.82	3.98	3.23
Saturation(%)	25.72	35.51	39.17	22.62	22.02	28.40
Field moisture content (%)	52.8	41.5	7.05	24.25	5.25	5.95

It was discovered that the critical soil moisture contents of Umbric Andosol, Rhodic Ferralsols, and Rhodic Nitisols were very close to their field capacities. This could be attributed to overestimation of the critical water content in these soils due to inhomogeneous moisture distribution during the wetting-drying regime (Dekker et al., 2001). Furthermore, because of the large differences in available surface area between clay and sand particles, it is thought to be dependent on soil texture (Doerr & Thomas, 2000).

Taking the critical water contents of all replicate samples from all other soil types, an ANOVA test was performed. There is a significant difference ($p= 0.006 < 0.05$) between the critical water contents for the different soil types.

3.4 Relations between soil water repellency and soil properties

The soil samples investigated exhibited a strong linear relationship between SWR area and total organic carbon. The SWR_{AREA} and TOC were strongly correlated ($R = 0.90$; $p < 0.01$) with an R^2 of 0.82 (Figure 5). Therefore, a simple linear regression utilizing SWR_{AREA} and TOC (Equation 3) only resulted in a RMSE of 3.07 sec/% soil moisture content. This high correlation agrees with other studies that also found a similar positive correlation between SWR_{AREA} and TOC (De Jonge et al., 1999; Kawamoto et al., 2007; Regalado et al., 2008). The results of this study therefore support the hypothesis that the SWR_{AREA} depends on the total amount of TOC present in the soil.

$$SWR_{AREA}=3.4072TOC+4.7775 \quad (\textit{Equation 3})$$

URL: https://ojs.jkuat.ac.ke/index.php/JAGST
ISSN 1561-7645 (online)
doi: 10.4314/jagst.v22i1.5

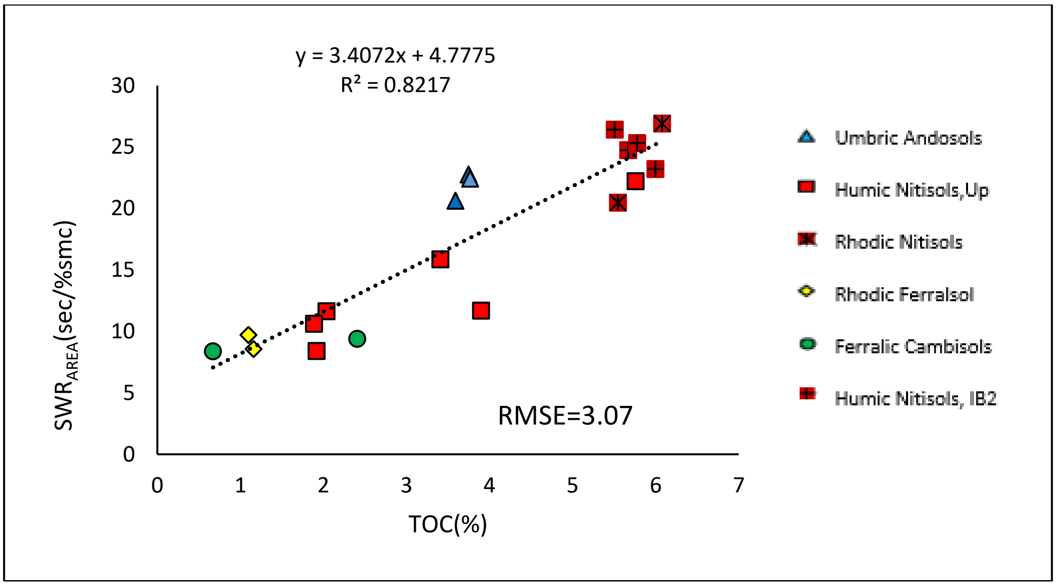


Figure 5: The total degree of soil water repellency (SWR_{AREA})

Similarly, critical soil moisture content was found to be strongly correlated with total organic carbon (R = 0.86, P < 0.01), with an R^2 of 0.73 and RMSE of 1.04 for 10.4 g/kg of soil. This soil property can be described by a linear expression using TOC as the variable (Figure 6). Notably, a strong linear regression (R= 0.80) between Wc and organic carbon (Equation 4) was found by de Jonge et al. (2007) for soils sampled from Denmark, while Kawamoto et al. (2007) developed a linear regression yielding an R of 0.87.

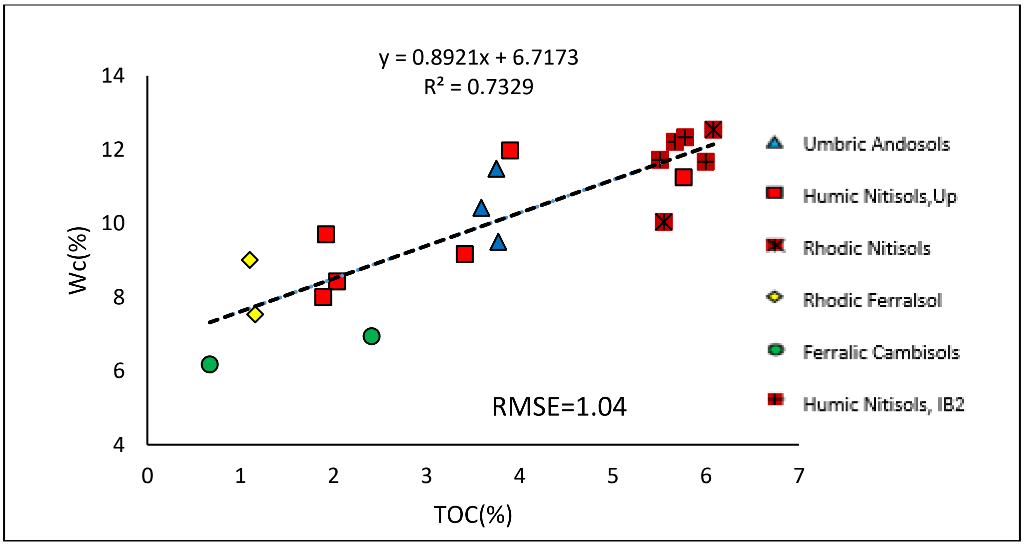


Figure 6:The critical soil water content (Wc) as a function of Total Organic Carbon

$$Wc= 0.8921TOC+6.7173 \quad \text{(Equation 4)}$$

URL: https://ojs.jkuat.ac.ke/index.php/JAGST
ISSN 1561-7645 (online)
doi: 10.4314/jagst.v22i1.5

The critical soil moisture content showed an important soil moisture level above which the onset of soil water repellency can be avoided. For practical purposes, upper and lower control limits were obtained. The upper limit is applicable in soil water repellency remediation since a safety margin will be integrated into the critical moisture content to show the level of soil water content that should be maintained to avoid soil water repellency, as shown in Figure 7.

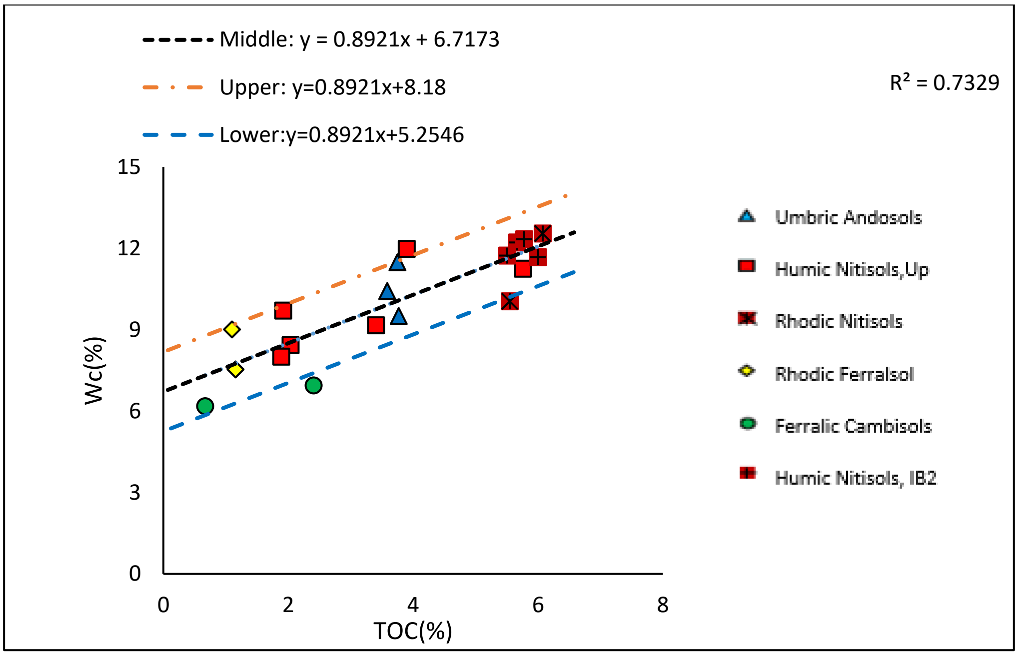


Figure 7: An upper and lower control limits to represent the spread around the regression coefficient

To get the upper control limit, a safety margin of 1.46% moisture content was added. Ferrallic Cambisols and Rhodic Nitisols appeared below the middle regression line, which implied that they require a higher extent of irrigation compared to the other four soil types to avoid the onset of SWR. This is because they are located closer to the lower control limit for moisture content. However, the general behavior of the six soil types suggests that the overall irrigation support model Wc = 0.89 TOC + 6.7183 can be utilised to avoid water repellency in those soils. However, it is advisable to develop soil type-specific models for W_C as a function of TOC when more comprehensive data is available for each soil type.

The correlation between SWR_{AREA} and soil texture and TOC is as presented in Table 3. Sand content was, however, not included in the regression analysis. This was because there existed a multicollinearity between clay, silt, and sand. The multicollinearity can be explained by the fact that clay minerals have a high specific surface area, which covers the sand surfaces. This is the same reason why claying is used as a remedy for soil water repellency in sandy soils. Harper and Gikes (1994) and McKissock et al. (2000) found that an addition of only 1–2% clay changes soil from a hydrophobic to a hydrophilic state.

URL: https://ojs.jkuat.ac.ke/index.php/JAGST
ISSN 1561-7645 (online)
doi: 10.4314/jagst.v22i1.5

Table 3: Pearson product moment correlation matrix of Total organic carbon, clay, silt, sand, IRDI, Wc, SWR_{AREA}, SWR105 and SWR60 for 19 hydrophobic soil samples in Murang'a

	Sand	Clay	Silt	TOC	Wc	IRDI	SWR_{AREA}	SWR105	SWR60
Sand	1								
Clay	0.678**	1							
Silt	0.442	0.483*	1						
TOC	1.000**	0.678**	0.442	1					
Wc	0.819**	0.770**	0.350	0.819**	1				
IRDI	0.604**	0.238	0.113	0.604**	0.252	1			
SWR_{AREA}	0.906**	0.620**	0.264	0.906**	0.735**	0.809**	1		
SWR105	0.156	0.220	0.220	0.156	0.043	0.315	0.166	1	
SWR60	0.035	-0.084	0.403	0.035	-0.018	-0.149	-0.152	0.242	1

**. Correlation is significant at the 0.01 level(2-tailed)
*. Correlation is significant at the 0.05 level(2-tailed)

Table 4 shows that clay content correlated positively and significantly with SWR_{AREA} and Wc (R = 0.62 and 0.77, respectively) ($P < 0.01$). Clay content further improved the relationship between Wc and SWR_{AREA} to TOC in the forward multiple linear regressions (Figure. 7 and Figure 8). These findings are in contrast with the findings of Hermansen et al. (2019), who did not observe any significant positive effect of clay content on Wc.

Multiple linear regression was performed utilising TOC, silt, and clay, which significantly explained 85 percent of the variation in SWR_{AREA} (RMSE = 3.02 sec/% soil moisture content) as shown in Figure 8, and an expression of SWR_{AREA} as a function of the three parameters is shown in equation 5.

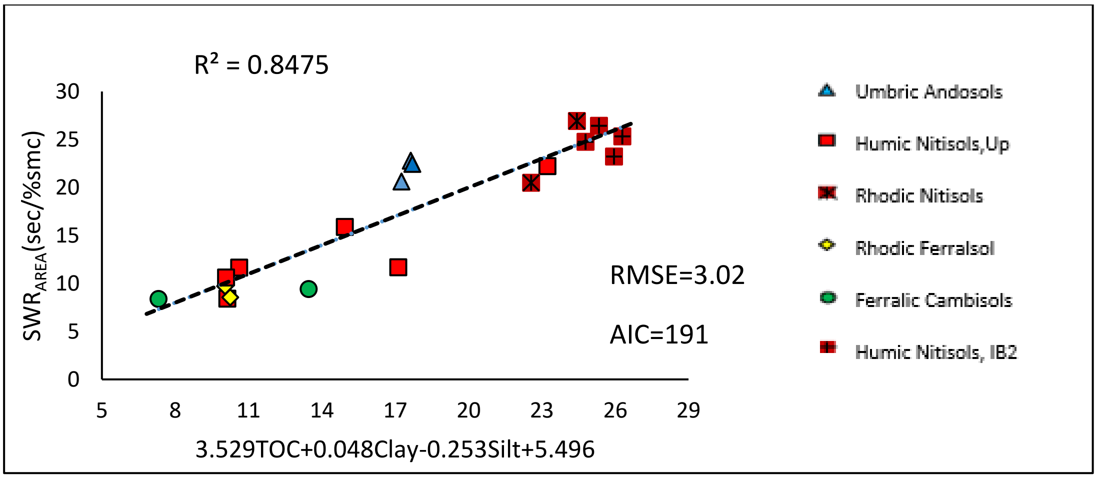


Figure 8:Multiple Linear Regression (MLR) for Trapezoidal Integrated Area under the Soil

URL: https://ojs.jkuat.ac.ke/index.php/JAGST
ISSN 1561-7645 (online)
doi: 10.4314/jagst.v22i1.5

Water Repellency Curve (SWR_{AREA})

SWR_{AREA}= 3.529TOC+0.048Clay-0.253Silt+5.496 (*Equation* 5)

Concerning the critical soil moisture content, MLR was performed utilizing the same factors i.e., Silt, Clay and TOC. The results are shown in Figure 9.

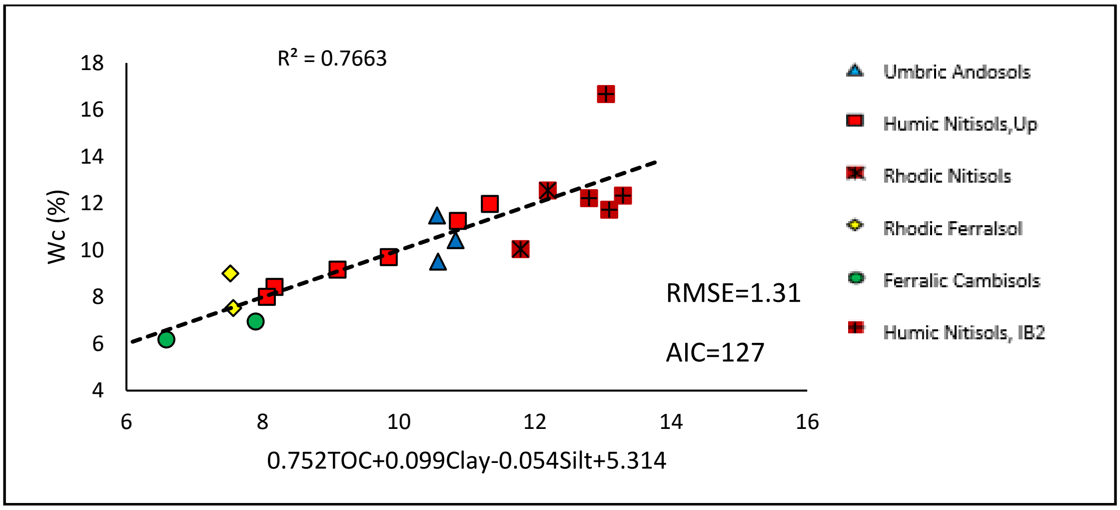


Figure 9: MLR for critical soil water content using TOC, Silt and Clay as input variables

Similarly, 77% of the variations in the critical soil moisture content for the studied soils could be attributed to the different clay, silt and TOC contents in the soil (RMSE = 13.1 g/kg of soil). A high correlation between SWR_{AREA} and Wc was also discovered (R = 0.74; p 0.01) (Table 5), as previously reported by Kawamoto et al. (2007). On addition of Wc as an input variable, the MLR expression of SWR_{AREA} yielded an R^2 of 0.85 (Figure 10), and the expression of SWR_{AREA} as a function of TOC, sand, silt, and Wc is as presented in equation 6.

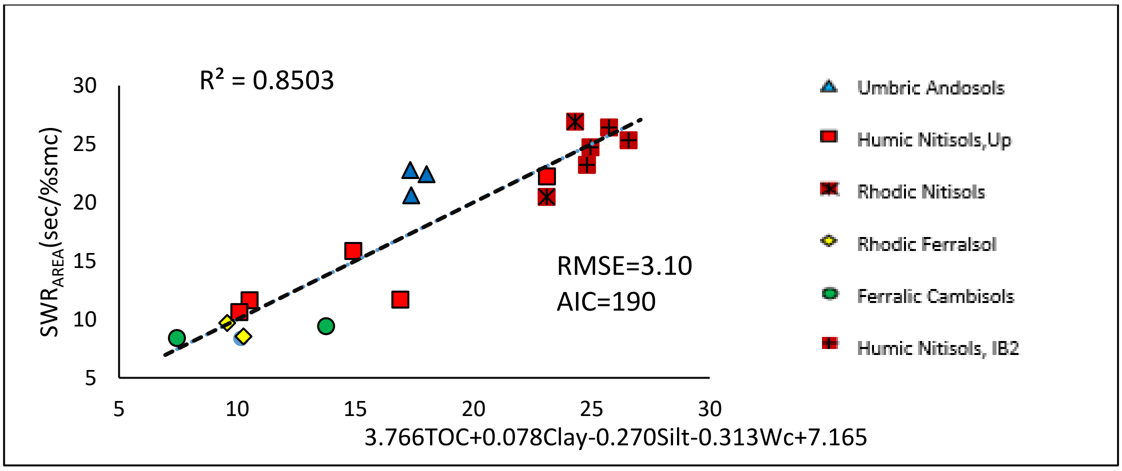


Figure 10: MLR for SWR_{AREA} using TOC, Sand, Silt and Wc as the input variables

URL: https://ojs.jkuat.ac.ke/index.php/JAGST
ISSN 1561-7645 (online)
doi: 10.4314/jagst.v22i1.5

SWR_{AREA}=3.766TOC+0.078Clay-0.270Silt-0.313Wc+7.165 (*Equation* 6)

The addition of Wc as an input variable resulted in a slight increase in SWR_{AREA}. Similarly, Regalado et al. (2008) used TOC and Wc to improve SWR_{AREA} prediction rather than only organic carbon.

4.0 Conclusion

About 37% (nineteen) of the 52 soil samples collected from the 26 sampling sites were hydrophobic. Among the six soil types studied, humic Nitisols, IB2 had the highest SWR_{AREA} and Wc. Soil water repellency was observed to be broken at various critical moisture content levels (Wc). However, there was a significant difference ($p = 0.006 < 0.05$) between the critical water contents for the different soil types in Murang'a. The SWR_{AREA} and the Wc were highly linearly correlated to the TOC, which was identified as the best predictor of these two repellency measurement parameters. TOC was the most important soil property in explaining the total degree of SWR (SWR_{AREA}) and Wc since it showed 82 and 73 % of the variability of the two parameters, respectively, in Murang'a soils. The inclusion of clay and silt in the MLR expression of SWR_{AREA} significantly improved the prediction of SWR_{AREA} to 85%. Concerning the Wc and TOC relationship, a safety margin of 1.46% (146 g of water/kg of soil) moisture content was added to obtain the upper and lower limits for Wc. This upper limit on critical water content could be used to derive a threshold water content above which SWR and the related degradation of soil functions could be eliminated. The overall model suggested as a guide to irrigation practices in this region was Wc = 0.89 TOC + 6.7183.

5.0 Recommendation

The results of this study suggested that the soils of Murang'a are suitable for agriculture. However, it is advisable to integrate a safety margin of 1.46% moisture content when determining the amount of water to apply during irrigation to prevent the occurrence of soil water repellency in agricultural soils. When more comprehensive data for each soil type is available, it could also be advantageous to develop soil-type specific models for Wc as a function of TOC.

6.0 Acknowledgement

6.1 Funding

None

6.2 Presentation of the study, findings, and a portion of the work

None

6.3 General statement and acknowledgement

None

6.4 Declaration of interest

None

URL: https://ojs.jkuat.ac.ke/index.php/JAGST
ISSN 1561-7645 (online)
doi: 10.4314/jagst.v22i1.5

6.5 Conflict of interest

The authors declare no conflict of interest.

7.0 References

Berglund, K., & Persson, L. (1996). Water repellence of cultivated organic soils. *Acta Agric. Scand*, 46.145- 152.

Bouyoucos, G.J. (1962). Hydrometer method improved for making particle size analyses of soils 1. *Agronomy journal*, 54(5), pp.464-465. https://doi.org/10.2134/agronj1962.00021962005400050028x

Bozdogan, H. (1987). Model selection and Akaike's information criterion (AIC): The general theory and its analytical extensions. Psychometrika, 52(3), pp.345-370. 10.1007/BF02294361

Chau, H.W., Biswas, A., Vujanovic, V., Si, B.C. (2014). Relationship between the severity, persistence of soil water repellency and the critical soil water content in water repellent soils. *Geoderma*221–222, 113–120. https://doi.org/10.1016/j. geoderma.2013.12.025

Crockford H, Topalidis S, Richardson D.P. (1991). Water repellency in a dry sclerophyll eucalypt forest - measurements and processes. Hydrological Processes, 5, 405-420. https://doi.org/10.1002/hyp.3360050408

CzachorH., Hallett P., Lichner L., Jozefaciuk G. (2013). Pore shape and organic compounds drive major changes in the hydrological characteristics of agricultural soils. *European Journal of Soil Science,* 64, 334–344. https://doi.org/10.1111/ejss.12052

deJonge, L.W., Jacobsen, O.H., Moldrup, P. (1999). Soil water repellency: Effects of water content, temperature, and particle size. *Soil Sci. Soc. Am. J.*63, 437–442. https://doi.org/10.2136/sssaj1999.03615995006300030003x

deJonge, L.W., Moldrup, P., Jacobsen, O.H. (2007). Soil-water content dependency of water repellency in soils: Effect of crop type, soil management, and physical chemical parameters. *Soil Sci.*172 (8), 577-588. http://dx.doi.org/10.1097/SS.06013e318065c090

deJonge, L.W., Moldrup, P., Schjonning, P. (2009). Soil infrastructure, interfaces translocation processes in inner space ('soil-it-is'): Towards a road map for the constraints and crossroads of soil architecture and biophysical processes. *Hydrol. Earth Syst. Sci.*13 (8), 1485–1502. https://doi.org/10.5194/hess-13-1485-2009

Dekker L.W, Ritsema C.J. (1994). How water moves in a water repellent sandy soil.1. Potentialand actual water repellency. *Water Resources Research,* 30, 2507-2517. https://doi.org/10.1029/94WR00749

Dekker LW, Ritsema CJ, Oostindie K, Boersma O.H. (1998). Effect of drying temperature on the severity of soil water repellency. *Soil Science*, 163, 780-796.

Dekker, L.W., Doerr, S.H., Oostindie, K., Ziogas, A.K., Ritsema, C.J. (2001). Water repellency and critical soil water content in a dune sand. *Soil Sci. Soc. Am. J.*65 (6), 1667–1674. https://doi.org/10.2136/sssaj2001.1667

Dekker, L.W., Ritsema, C.J. (1995). Fingerlike wetting patterns in two water-repellent loam soils. *J. Environ. Qual.*24 (2), 324–333. https://doi.org/10.2134/jeq1995.00472425002400020016x

URL: https://ojs.jkuat.ac.ke/index.php/JAGST
ISSN 1561-7645 (online)
doi: 10.4314/jagst.v22i1.5

Dekker, L.W., Ritsema, C.J. (1996). Variation in water content and wetting patterns in Dutch water repellent peaty clay and clayey peat soils. *Catena*28 (1–2), 89–105. https://doi.org/10.1016/S0341-8162(96)00047-1

Deurer, M., Müller, K., Van Den Dijssel, C., Mason, K., Carter, J. and Clothier, B.E. (2011). Is soil water repellency a function of soil order and proneness to drought? A survey of soils under pasture in the North Island of New Zealand. *European Journal of Soil Science*, 62(6), pp.765-779. https://doi.org/10.1111/j.1365-2389.2011.01392.x

Doerr S.H, Dekker L.W, Ritsema C.J, Shakesby R.A, Bryant R. (2002). Water repellency of soils: The influence of ambient relative. *Soil Science Society of America Journal*, 66, 401-405. https://doi.org/10.2136/sssaj2002.4010

Doerr, S. H. (1998). On standardizing the 'water drop penetration time'and the 'molarity of an ethanol droplet'techniques to classify soil hydrophobicity: a case study using medium textured soils. *Earth Surface Processes and Landforms: The Journal of the British Geomorphological Group*, *23*(7), 663-668. https://doi.org/10.1002/(SICI)1096-9837(199807)23:7%3C663::AID-ESP909%3E3.0.CO;2-6

Doerr, S.H., Shakesby, R.A., Walsh, R.P.D., (2000). Soil water repellency: its causes, characteristics and hydro-geomorphological significance. *Earth-Sci. Rev*. 51 (1–4), 33–65. https://doi.org/10.1016/S0012-8252(00)00011-8.

Doerr, S.H. and Thomas, A.D. (2000). The role of soil moisture in controlling water repellency: new evidence from forest soils in Portugal. Journal of Hydrology, 231, pp.134-147. http://dx.doi.org/10.1016/S0022-1694(00)00190-6

FAO, F. (1988). Unesco Soil Map of the World, Revised Legend, with corrections and updates. *World Soil Resources Report*, 60, p.140.

Franco, C.M.M., P.J. Clarke, M.E. Tate, and J.M. Oades. (2000). Hydrophobic properties and chemical characterization of natural water repellent materials in Australian sands. *J. Hydrol.*231–232:47–58.

Ganz, C., Bachmann, J., Lamparter, A., Woche, S. K., Duijnisveld, W. H., &Göbel, M. O. (2013). Specific processes during in situ infiltration into a sandy soil with low-level water repellency. *Journal of hydrology*, *484*, 45-54.

Graber, E. R., Ben-Arie, O., & Wallach, R. (2006). Effect of sample disturbance on soil water repellency determination in sandy soils. *Geoderma*, *136*(1-2), 11-19.

Graber, E.R., S. Tagger, and R. Wallach. (2009). Role of divalent fatty acid salts in soil water repellency. *Soil Sci. Soc. Am. J.*73:541–549. https://doi.org/10.2136/sssaj2008.0131

Harper, R.J. and Gilkes, R.J. (1994). Soil attributes related to water repellency and the utility of soil survey for predicting its occurrence. Soil Research, 32(5), pp.1109-1124.

Hermansen, C., Moldrup, P., Müller, K., Jensen, P.W., Van den Dijssel, C., Jeyakumar, P., de Jonge, L.W. (2019). Organic carbon content controls the severity of water repellency and the critical moisture level across New Zealand pasture soils. *Geoderma*338, 281–290. https://doi.org/10.1016/j.geoderma.2018.12.007.

Jex G.W, Bleakley B.H, Hubbell DH, Munro L.L. (1985). High humidity-induced increase in water repellency in some sandy soils. *Soil Science Society of America Journal*, 49, 1177-1182. https://doi.org/10.2136/sssaj1985.03615995004900050021x

Jordán, A., Zavala, L. M., Mataix-Solera, J., &Doerr, S. H. (2013). Soil water repellency: Origin,

URL: https://ojs.jkuat.ac.ke/index.php/JAGST
ISSN 1561-7645 (online)
doi: 10.4314/jagst.v22i1.5

assessment and geomorphological consequences. *Catena*, *108*, 1-5.

Karunarathna, A.K., Kawamoto, K., Moldrup, P., de Jonge, L.W., Komatsu, T., (2010a). A simple beta-function model for soil-water repellency as a function of water and organic carbon contents. *Soil Sci.*175 (10), 461–468. http://dx.doi.org/10.1097/SS.0b013e3181f55ab6

Karunarathna, A.K., Moldrup, P., Kawamoto, K., de Jonge, L.W., Komatsu, T., (2010b). Two-region model for soil water repellency as a function of matric potential and water content. *Vadose Zone J.*9 (3), 719–730. http://dx.doi.org/10.2136/vzj2009.0124

Kawamoto, K., Moldrup, P., Komatsu, T., de Jonge, L.W., Oda, M. (2007). Water repellency of aggregate size fractions of a volcanic ash soil. *Soil Sci. Soc. Am. J.*71, 1658–1666. http://dx.doi.org/10.2136/sssaj2006.0284

King, P.M. (1981). Comparison of methods for measuring severity of water repellence of sandy soils and assessment of some factors that affect its measurement. *Aust. J. Soil Res.* 19:275–285. https://doi.org/10.1071/SR9810275

Leelamanie, D.A.L., Karube, J. (2007). Effects of organic compounds, water content and clay on the water repellency of a model sandy soil. *Soil Sci. Plant Nutr.*53, 711–719. https://doi.org/10.1111/j.1747-0765.2007.00199.x.

Leighton-Boyce, G., Doerr, S.H., Shakesby, R.A., Walsh, R.P.D. (2007). Quantifying the impact of soil water repellency on overland flow generation and erosion: a new approach using rainfall simulation and wetting agent on in situ soil. *Hydrol. Processes*21 (17), 2337–2345. https://doi.org/10.1002/hyp.6744.

McKissock, I., Walker, E. L., Gilkes, R. J., & Carter, D. J. (2000). The influence of clay type on reduction of water repellency by applied clays: a review of some West Australian work. *Journal of Hydrology*, 231, 323-332. https://doi.org/10.1016/S0022-1694(00)00204-3

Müller, K. and Deurer, M., 2011. Review of the remediation strategies for soil water repellency. Agriculture, Ecosystems & Environment, 144(1), pp.208-221. https://doi.org/10.1016/j.agee.2011.08.008

Müller, K., Deurer, M., Jeyakumar, P., Mason, K., van den Dijssel, C., Green, S. and Clothier, B. (2014). Temporal dynamics of soil water repellency and its impact on pasture productivity. *Agricultural Water Management*, 143, pp.82-92. https://doi.org/10.1016/j.agwat.2014.06.013

Müller, K., Deurer, M., Slay, M., Aslam, T., Carter, J.A., Clothier, B.E. (2010). Environmental and economic consequences of soil water repellency under pasture. *Proc. N. Z. Grassl. Assoc*. 72, 207–210. https://doi.org/10.33584/jnzg.2010.72.2786.

QA, E. (2002). Guidance on Choosing a Sampling Design for Environmental Data Collection for Use in Developing a Quality Assurance Project Plan. Washington, DC, USA, *United States Environmental Protection Agency*, 166.

Regalado, C.M., and A. Ritter. (2005). Characterizing water dependent soil repellency with minimal parameter requirement. *Soil Sci. Soc. Am. J.*69:1955–1966. https://doi.org/10.2136/sssaj1995.1000er

Regalado, C.M., and A. Ritter. (2009a). A soil water repellency empirical model. *Vadose Zone J.* 8:136–141. https://doi.org/10.2136/vzj2008.0097

Regalado, C.M., and A. Ritter. (2009b). A bimodal four-parameter lognormal linear model of soil water repellency persistence. *Hydrol. Processes* 23:881–892.

URL: https://ojs.jkuat.ac.ke/index.php/JAGST
ISSN 1561-7645 (online)
doi: 10.4314/jagst.v22i1.5

https://doi.org/10.1002/hyp.7226

Regalado, C.M., Ritter, A., de Jonge, L.W., Kawamoto, K., Komatsu, T., Moldrup, P. (2008). Useful soil-water repellency indices: linear correlations. *Soil Sci.*173 (11), 747–757. https://doi.org/10.1097/SS.0b013e31818d4163

Roberts, F.J, Carbon, B.A (1971). Water repellence in sandy soils of south-western Australia. 1. Some studies related to field occurrence. Field Station Records (CSIRO Division of Plant Industry). 1971; 10:13-20. http://hdl.handle.net/102.100.100/315427?index=1

Roy, J.L., McGill W.B., H.A. Lowen, and R.L. Johnson. (2003). Relationship between water repellency and native and petroleum-derived organic carbon in soils. *J. Environ. Qual.* 32:583–590. https://doi.org/10.2134/jeq2003.5830

Roy, J.L., and W.B. McGill. (2000). Flexible conformation in organic matter coatings: An hypothesis about soil water repellency. Can. J. Soil Sci. 80:143–152. http://dx.doi.org/10.4141/S98-093

Schaumann, G.E., B. Braun, D. Kirchner, W. Rotard, U. Szewzyk, and E. Grohmann. (2007). Influence of biofilms on the water repellency of urban soil samples. *Hydrol. Processes* 21:2276–2284. http://dx.doi.org/10.1002/hyp.6746

Urbanek, E., Horn, R. and Smucker, A.J. (2014). Tensile and erosive strength of soil macro-aggregates from soils under different management system. *Journal of Hydrology and Hydromechanics*, 62(4), pp.324-333.

Van'tWouldt, B.D. (1959). Particle coatings affecting the wettability of soils. *J.Gephyls.Res*.64, 263-267. https://doi.org/10.1029/JZ064i002p00263

Walkley, A. and Black, I.A., (1934). An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil science*, 37(1), pp.29-38.

Weber, P. L., Hermansen, C., Norgaard, T., Pesch, C., Moldrup, P., Greve, M. H. & de Jonge, L. W. (2021). Moisture-dependent Water Repellency of Greenlandic Cultivated Soils. *Geoderma*, *402*, 115189.

Wijewardana, N.S., Müller, K., Moldrup, P., Clothier, B., Komatsu, T., Hiradate, S., de Jonge, L.W., Kawamoto, K. (2016). Soil-water repellency characteristic curves for soil profiles with organic carbon gradients. Geoderma 264, 150–159. http://dx.doi.org/10.1016/j.geoderma.2015.10.020

URL: https://ojs.jkuat.ac.ke/index.php/JAGST
ISSN 1561-7645 (online)
doi: 10.4314/jagst.v22i1.5