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

Monica Ndolo[1], Patrick Home[1], and James Messo[1]

[1]Jomo Kenyatta University of Agriculture and Technology

November 22, 2022

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 is important in understanding and predicting its effects on the soil hydrological processes to optimize plant growth. Therefore, this study aimed at characterizing the persistence of SWR using 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 (SWRAREA and Wc) and soil properties (TOC, 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). The total SWR (SWRAREA) was calculated as the trapezoidal area under the SWR-w curve. A total of 37% of the soils investigated were water repellent. The soils investigated had a wide range in clay (10-40%) and TOC (0.67-6.08%). The SWR-w curves were either single or double peaked. SWRAREA ranged from 8.38 second/%soil moisture content to 24.91 seconds/%soil moisture content. TOC was the most important soil property in explaining the total degree of SWR(SWRAREA) and Wc. Inclusion of Clay and silt in the Multiple Linear Regression (MLR) expression of SWRAREA significantly improved the prediction of SWRAREA to 85%. Further, an upper limit critical water content was derived from the simple relationship between the Wc and TOC, which could be applied to improve irrigation practices of agricultural soils of Murang'a County in Kenya. It is however advisable to develop soil type specific models for Wc as a function of TOC when more comprehensive data is available for each soil type.

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

Ndolo M. M*, Home P. G and Raude J. M.

Department of Soil Water and Environmental Engineering

Jomo Kenyatta University of Agriculture and Technology

P.O. 62000-00200, Nairobi

*Author for correspondence. Email: monicah.mwikali@jkuat.ac.ke, Tel:+254707843662

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 is important in understanding and predicting its effects on the soil hydrological processes to optimize plant growth. Therefore, this study aimed at characterizing the persistence of SWR using 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 (SWRAREA and Wc) and soil properties (TOC, 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). The total SWR (SWRAREA) was calculated as the trapezoidal area under the SWR-w curve. A total of 37% of the soils investigated were water repellent. The soils investigated had a wide range in clay (10-40%) and TOC (0.67-6.08%). The SWR-w curves were either single or double peaked. SWR_{AREA} ranged from 8.38second/%soil moisture content to 24.91 seconds/%soil moisture content. TOC was the most important soil property in explaining the total degree of SWR(SWR_{AREA}) and Wc. Inclusion of Clay and silt in the Multiple Linear Regression (MLR) expression of SWR_{AREA} significantly improved the prediction of SWR_{AREA} to 85%. Further, an upper limit critical water content was derived from the simple relationship between the Wc and TOC, which could be applied to improve irrigation practices of agricultural soils of Murang'a County in Kenya. It is however advisable to develop soil type specific models for Wc as a function of TOC when more comprehensive data is available for each soil type.

Key words: Total organic carbon; Soil Water Repellency; total soil water repellency (SWR_{AREA}); water drop penetration time (WDPT); soil water content(w) ; critical soil water content (Wc)

Introduction

Soil water repellency (SWR) is a property of the soil that significantly reduces the functionality of the soil 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 ground water sources (Dekker and Ritsema,1995), increased overland flow, soil erosion and decreased soil water storage (Doerr et al., 2000). Primarily, the main cause of soil water repellency is thought to be coating of soil particles by the 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 reorientation 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; Roy and McGill, 2000; Graber et al., 2009).

The persistence of SWR can be described by a SWR-w characteristic curve, where soil water repellency is expressed as function of gravimetric soil water content (de Jonge et al., 2007; Regalado et al., 2008; Regalado and Ritter, 2009b) or volumetric soil water content (Regalado and Ritter, 2009a; Karunarathna et al., 2010a), or in terms of pF values (de Jonge et al., 2007; Karunarathna et al., 2010b). The SWR-w curve can either start from zero (0kg/kg) water in the oven dry soil conditions or at air-dry state of the soil (de Jonge et al., 2007; Karunarathna et al., 2010a; Karunarathna et al., 2010b) and the continue until the soil turns wettable at Critical moisture content (Wc). The area underneath the SWR-w curve represents the total SWR of a soil (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 the oven-dry conditions but the persistence of SWR decreases with increasing soil water content to a local minimum but still maintaining hydrophobicity or becomes temporarily wettable (de Jonge et al., 1999; 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 can be hydrophilic at oven-dry soil conditions.

Monitoring the change in soil water repellency with soil water content is a very time-consuming procedure. 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 easily measurable soil properties (Regalado et al., 2008). SWR_{AREA} and Wc are the key parameters that are used for characterizing 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, 2007; 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 Water Drop Penetration Time test (WDPT), Molarity of ethanol droplet (MED) method and Sessile Drop Method (SDM). WDPT tests the persistence of drop of water on the surface of the soil, hence SWR persistence (King, 1981; Van't Woudt. 1959). MED measures the severity of SWR which describes how strong the soil repels water (De jonge et al., 1999, Kawamoto et al., 2007). It only works for the repellent soils with contact angles greater than 90°.In contrary, the SDM is measures all ranges of SWR that is 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 is important in understanding and predicting its effects on the soil hydrological processes to optimize plant growth. However, there exist limiting 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 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). For these reasons, there is therefore a need to assess the distribution and persistence of SWR of the agricultural soils of Murang'a County, Kenya. This would be advantageous if SWR_{AREA} and Wc are derived from pedotransfer functions based on soil properties that are easily measurable.

The aims of this study were to (i) characterize the persistence of SWR using Water Drop Penetration Time (WDPT) test, (ii) To evaluate the SWR curve as a function of gravimetric water content from the WDPT results and (iii) to develop relationships between SWR parameters (SWRAREA and Wc) and soil properties (TOC, Sand, Silt, Clay)

MATERIALS AND METHODS

Study area

52 soil samples were collected from two soil profiles of depths 0-15cm and 15-30cm from 26 sampling sites which 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 Ferralic Cambisols as shown in Figure 1. These soil types are classified according to FAO UNESCO Soil Map of the World (1988) and were complemented with soil layers from Kenya Soils and Terrain Database (KENSOTER, 2004).

The sampling unit boundaries were mapped in ArcGis (ArcMap 10.5) such that each soil unit represented a sampling unit. Judgmental sampling was used to select the soil type that were most relevant to the study and this was based on 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)

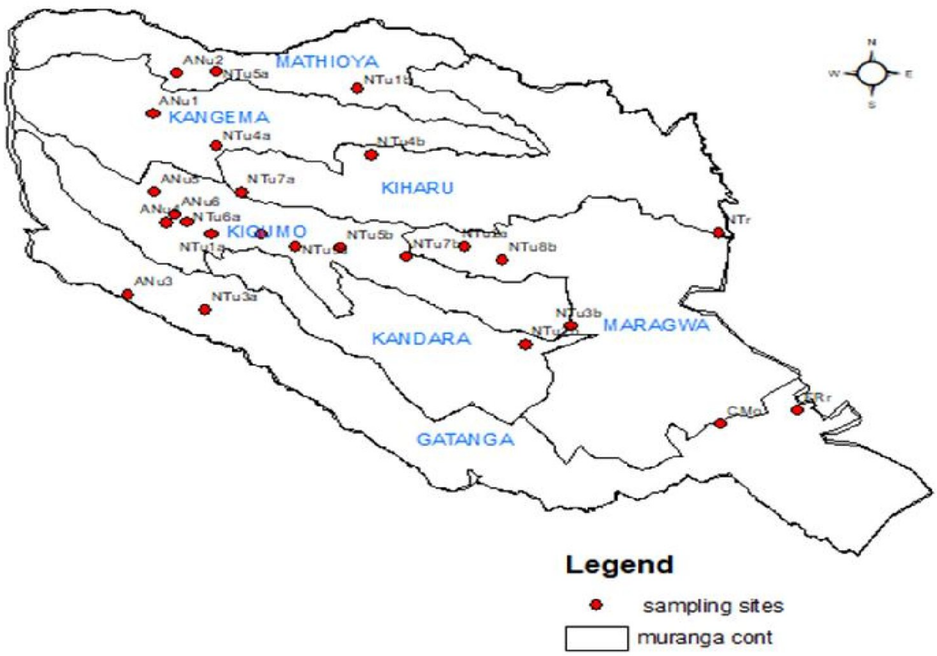

Figure 1: Map Showing Location of the 26 Sampling Sites Distributed Across Murang'a County in Kenya. The Samples Represent the Six Soil Types; Humic Nitisols UP(NTua), Humic Nitisols IB2 (NTub), Umbric Andosols (ANu), Rhodic Nitisols (NTr), Rhodic Ferralsopls (FRr) And Ferralic Cambisols (CMo)

In this case, the average effective rooting depth of most of the 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. Two disturbed and two undisturbed soil samples were collected at a depth of 0-15cm and 15-30cm from each sampling site. From each sampling site approximately 1kg of each soil sample was collected into sampling bags and the bag labelled with the GPS location of sampling site, type of soil and the depth of sampling. The samples were then transported to the laboratory in sealed bags for analysis.

Laboratory Methods

The soil texture was determined in the laboratory using the hydrometer method (Bouyoucos, 1962) while Gravimetric Oven drying Method was used to determine the soil moisture content and the bulk density from which the porosity of the soil was calculated. Total organic carbon (TOC) content was determined by the wet-digestion method (Walkly and Black, 1934).

Soil preparation and water repellency measurements

Soil samples were mixed thoroughly at their field moist conditions before the actual soil water repellency was measured. The soil samples were then oven dried at 60^{o} C to determine their potential/current risk persistence of soil water repellency. This gives an estimate of the potential soil water repellency, and it is the highest level that it can reach when the soil dries out completely (Ritsema & Dekker,1994 and Deurer et al.,2011). Estimation of the potential soil water repellency provides an insight into the potential consequences of soil hydrophobicity in case of a drought. On the other hand, it is only the insitu measurements at the field moist conditions that gives the actual soil water repellency (Muller et al., 2014). High drying temperatures have been observed to influence the formation of organic materials coatings responsible for water repellency (Dekker et al., 1998). Therefore, drying of soils at 105^{o}C can give an incorrect estimate of repellency. Air drying was suggested as the best approach to study the soil water repellency-moisture relationship in different studies (Stefan,2000).

Soil water repellency was monitored with changes in the soil moisture content during the air dying process. This was conducted in two phases: wet and dry phase.

Wet phase: The Actual soil water repellency was determined by performing Water Drop Penetration Time Test (WDPT) on the field moist soil samples before oven drying them at 60^{0}C for 48hours after which the soil moisture content reduced to absolute zero (Crockford et al. (1991); Berglund & Persson (1996); De Jonge at al.1999). The oven dried soil samples were then divided into three replicates before saturating them 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 (24^0C-39^0C) 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 soils dry weight.

Data analysis

Soil water repellency was estimated as a function of the actual gravimetric soil moisture content and SWR-w curve plotted. 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 resolved as the soil water content at which soil turned hydrophilic. The average Soil water repellency function was determined from Integrative Repellency Dynamic Index(IRDI), which gives a measure of the mean water repellency in the soil moisture interval between zero(at oven dry condition) to critical soil moisture content(when soil turns hydrophillic) (Regalado and Ritter, 2005). This average is calculated as shown in equation (1) and tabulated in Table 1

$$IRDI=\frac{SWRAREA}{Wc} \qquad (1)$$

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)

Soil samples which were hydrophilic 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, TOC) to SWR_{AREA} and Wc.

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

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

Where;

K is the number of input variables

N is the number of samples

di is the residual value between the measured and obtained value from the model

Results and Discussion

Soil water repellency persistence

The actual soil water repellency of the field moist samples varied between 1second and 355seconds which means that according to Doerr et al.(2000) classification of the water repellency, SWR ranged from wettable to strongly repellent. Among the 52 soil samples investigated from Murang'a, ninteen(19 out of 52)samples i.e. 37% were hydrophobic. The hydrophobic soils from Murang'a showed an actual water repellency(SWR_{ACT}) of between 5 and 355seconds and had a total organic carbon range between 1.38 and 6.08% . These soils were classified into sand clay loam (13 samples), clay (2samples) and sandy loam (4 samples) textural classes. Generally, Humic Nitisols,UP showed a 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.

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	Ferralic 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
SWR_{60}(seconds)	mean	2.78	11.22	2.10	3.35	2.65	5.59
	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

The potential water repellency(SWR_{60}) of the samples was also measured at 60^0C 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. Although high temperatures have been observed to influence hydrophobicity due to reorientation of the hydrophobic molecules (De jonge et al.,1999,Doerr et al.,2000), these particular soils studied here, had lower soil water repellency at oven dry state(60^0C). 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 is bacause the soil organic carbon tends to loose its stabilising effect during drying (Urbanek et al., 2014). The relationship between the potential and the actual soil water repellency is however not evident and therefore actual soil water repellency cannot be derived from the potential soil water repellency as it has also be stated by Graber et al. (2006).

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 behaviours (Fig.3). It is clear that from Fig.3 a wide range of SWR-W curve shapes published in literature (de Jonge et al., 1999, 2007; Karunarathna et al., 2010a; Regalado and Ritter, 2009; Regalado et al., 2008) were confirmed. The curves includes single peak (A,B,G,P,Q,R,S)and double peak(C,D.E,F,H,I,J,K,L,M,N) SWR-w were observed. The curves were either raising from a repellent or a wettable state at oven dry conditions(60^{0}C).The curves raising from a repellent state are shown in Fig .3(D,H,I,J,L,M,N) while those rising from a wettable state are as shown in Fig. 3(A,B,C,E,F,G,O,P,Q,R,S). The soils with bimodal curves were either repellent or hydrophillic at oven dry condition. However, the degree of soil water repellency for the bimodal curves decreased to a local minimum with an increasing moisture content but still retaining some degree of hydrophobicity like shown in Fig.3(I,M). In addition, there are also some bimodal SWR-w curves whose repellency decreased with an increase in soil moiture content to become temporarily wettable(WDPT<5seconds) before rising to a maximum repellency from oven dry conditions Fig.3(C,D,E,F,H,K,N). Some soils exhibited water repellency near their field capacity Fig.2(I). The soil sample represented in Fig.2(I) showed repellency of 5.1seconds 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.

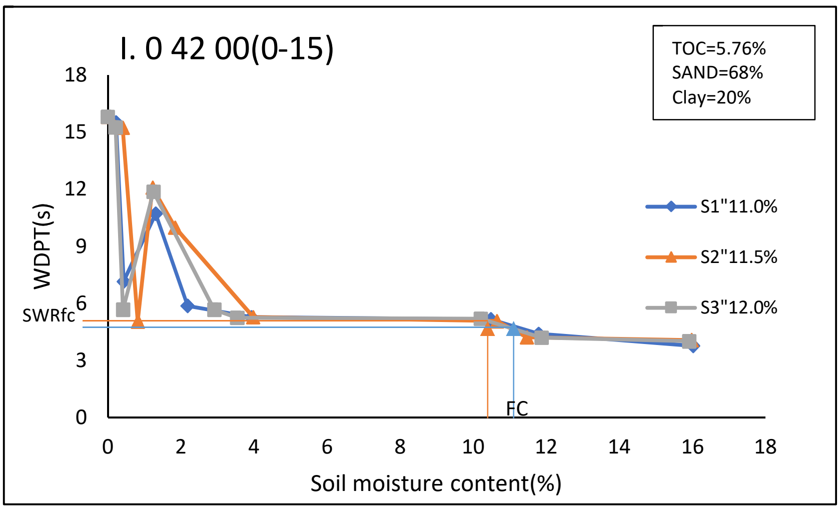

Figure 2: Soil water repellency (SWR) near field capacity. FC denotes the Field capacity (SMC=11.8%) and SWRfc represents the interpolated SWR near the field capacity (SWRfc=5.1 seconds at 11% moisture content).

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 content as it has been observed by DeJonge et al. (1999). Some possible processes and mechanisms have been proposed to explain this unusual behavior. Jex et al., (1985) and Roberts&Carbon,(1971) attributed the behavior to enhanced microbial activity with increasung relative humidity. Solvent-induced changes in molecular conformation of soil organic matter is also accountable for increased soil watre repellency at increasing soil moiture content levels (Mc Gill, 2000). Doerr et al.(2002) also attributed the same behavior to reorientation of hydrophobic functional groups that had been previously disrupted during 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 increase in soil moisture content, the repellency first decreased and then increased again to an intermediate soil water content up to a second peak after which it decreases again until the soil becomes wettable above the critical moisture content. For the double peaked curves, the behaviour of the first peak is attributed to the reorientation of the hydrophobic molecules due to water loss associated to the temperature treatment during oven-drying (De Jonge et al., 1999; Doerr et al., 2000).

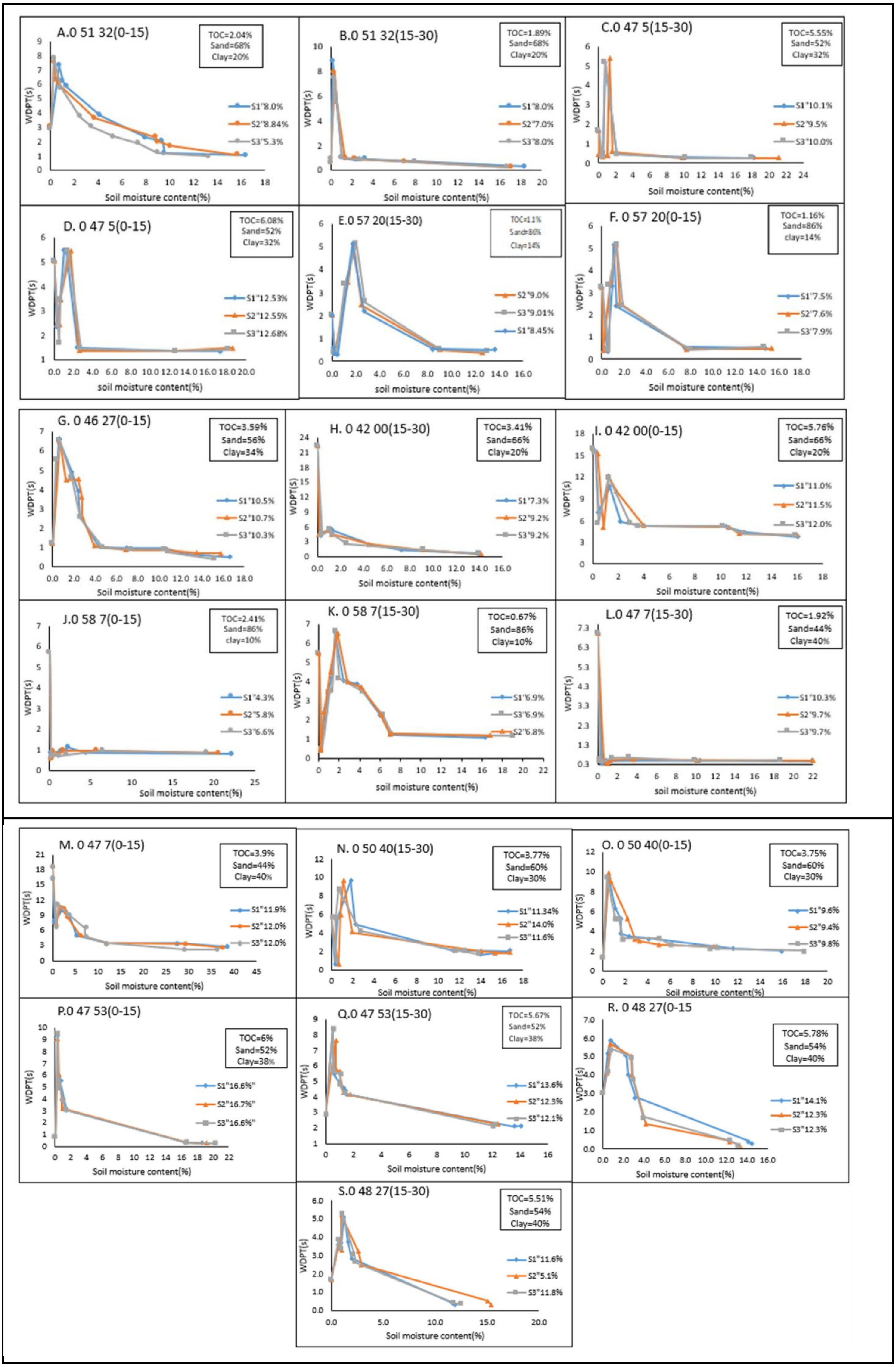
A.0 51 32(0-15)
TOC=2.04%
Sand=68%
Clay=20%
S1"8.0%
S2"8.84%
S3"5.3%
WDPT(s)
Soil moisture content(%)
B.0 51 32(15-30)
TOC=1.89%
Sand=68%
Clay=20%
S1"8.0%
S2"7.0%
S3"8.0%
C.0 47 5(15-30)
TOC=5.55%
Sand=52%
Clay=32%
S1"10.1%
S2"9.5%
S3"10.0%
D. 0 47 5(0-15)
TOC=6.08%
Sand=52%
Clay=32%
S1"12.53%
S2"12.55%
S3"12.68%
E.0 57 20(15-30)
TOC=1.1%
Sand=86%
Clay=14%
S2"9.0%
S3"9.01%
S1"8.45%
F. 0 57 20(0-15)
TOC=1.16%
Sand=86%
clay=14%
S1"7.5%
S2"7.6%
S3"7.9%
G. 0 46 27(0-15)
TOC=3.59%
Sand=56%
Clay=34%
S1"10.5%
S2"10.7%
S3"10.3%
H. 0 42 00(15-30)
TOC=3.41%
Sand=66%
Clay=20%
S1"7.3%
S2"9.2%
S3"9.2%
I. 0 42 00(0-15)
TOC=5.76%
Sand=66%
Clay=20%
S1"11.0%
S2"11.5%
S3"12.0%
J.0 58 7(0-15)
TOC=2.41%
Sand=86%
clay=10%
S1"4.3%
S2"5.8%
S3"6.6%
K. 0 58 7(15-30)
TOC=0.67%
Sand=86%
Clay=10%
S1"6.9%
S3"6.9%
S2"6.8%
L.0 47 7(15-30)
TOC=1.92%
Sand=44%
Clay=40%
S1"10.3%
S2"9.7%
S3"9.7%
M. 0 47 7(0-15)
TOC=3.9%
Sand=44%
Clay=40%
S1"11.9%
S2"12.0%
S3"12.0%
N. 0 50 40(15-30)
TOC=3.77%
Sand=60%
Clay=30%
S1"11.34%
S2"14.0%
S3"11.6%
O. 0 50 40(0-15)
TOC=3.75%
Sand=60%
Clay=30%
S1"9.6%
S2"9.4%
S3"9.8%
P.0 47 53(0-15)
TOC=6%
Sand=52%
Clay=38%
S1"16.6%"
S2"16.7%"
S3"16.6%"
Q.0 47 53(15-30)
TOC=5.67%
Sand=52%
Clay=38%
S1"13.6%
S2"12.3%
S3"12.1%
R. 0 48 27(0-15
TOC=5.78%
Sand=54%
Clay=40%
S1"14.1%
S2"12.3%
S3"12.3%
S.0 48 27(15-30)
TOC=5.51%
Sand=54%
Clay=40%
S1"11.6%
S2"5.1%
S3"11.8%

Figure 3: Soil water repellency as a function of soil water content in Murang'a soils. In each graph, three curves shown represent the three replicates examined for each soil sample at depths of (0-15cm) and (15-30cm).

It was evident that 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 inorder 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 therefore determined from Integrative Repellency Dynamic Index(IRDI), which gives a measure of the mean water repellency in the soil moisture interval between zero(at oven dry condition) to critical soil moisture content(when soil turns hydrophillic) (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 24.91sec/%moisture content and 132.3 to 65.6g/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 which had lowest and highest SWR_{AREA} also had a corresponding 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 inturn influenced the total soil water repellency (IRDI). Generraly, Humic Nitisols,IB2 and Umbric Andosols recorded a maximum IRDI (Integrative Repellency Dynamic Index) of 2.25 and 2.33 seconds respectively while Rhodic Ferralsols had a IRDI of 1.14 seconds. This could be attributed to the differences in the amount and types of Total organic carbon which brought about variations in the SWR_{AREA}(trapezoidal integrated area under the SWR-w curve) for the various soil types. This was supported 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, the severity of SWR in terms of SWR_{AREA} decreased in the following order; Umbric Andosols> Humic Nitisols,IB2> Rhodic Nitisols > Humic Nitisols,UP> Rhodic Ferralsols> Ferralic Cambisols.

Critical soil moisture content

The critical soil moisture content at which soil water repellency is broken is determined as a transition zone rather than a sharp threshold (Doerr et al, 2001). In this transition zone the soil can act either hydrophobic or hydrophilic depending on the wetting history. 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 hydrophillic at higher average critical moisture content of 13.23% (132.3g/kg soil) while on the other hand, Ferrallic Cambisols turned wettable at a lower soil moisture content level of 6.56% (65.6g/kg soil). The critical water contents ranged between 95.0g/kg and 114.8g/kg for Umbric Andosols, 80.0g/kg and 119.7g/kg for Humic Nitisols,Up, 117.3g/kg and 166.7 g/kg for Humic Nitisols,IB2, 100.4g/kg and 125.4g/kg for Rhodic Nitisols, 75.3g/kg and 90.1g/kg for Rhodic Ferralsol and 61.8g/kg and 69.4g/kg of soil for Ferrallic Cambisols as presented in Table 1 and 2. The average critical water content values were way higher than the mean permanent wilting point and but closer to 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 found that the critical soil moisture contents of Umbric Andosol , Rhodic Ferralsols and Rhodic Nitisols were very close to the field capacities of these soils. This could be attributed to overestimations of the critical water content due to inhomogeneous moisture distribution during the wetting-drying regime in these soils (Dekker et al., 2001). Furthermore, it is also thought to depend on the soil texture because of the huge differences in available surface area between clay and sand particles (Doerr & Thomas, 2000).

Taking the critical water contents of all replicate samples from all other soil types, an ANOVA test was performed (Table 3). There is a significant difference ($p=0.006<0.05$) between the critical water contents for the different soil types.

Table 3:ANOVA Results, Comparison of Critical Water Contents for Different Soil Types

ANOVA

Wc	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	74.560	5	14.912	5.580	.006
Within Groups	34.741	13	2.672		
Total	109.300	18			

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 R^2 of 0.82(Figure 4) (equation 3) therefore a simple linear regression utilizing $SWR_{AREA,}$ and TOC only resulted in a RMSE of 3.07sec/% soil moisture content. This high correlation agrees with other studies which also found a similar positive correlation between SWR_{AREA} and TOC (De jonge et al., 1999; Kawamoto et al., 2007; Regalado et al., 2008)

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

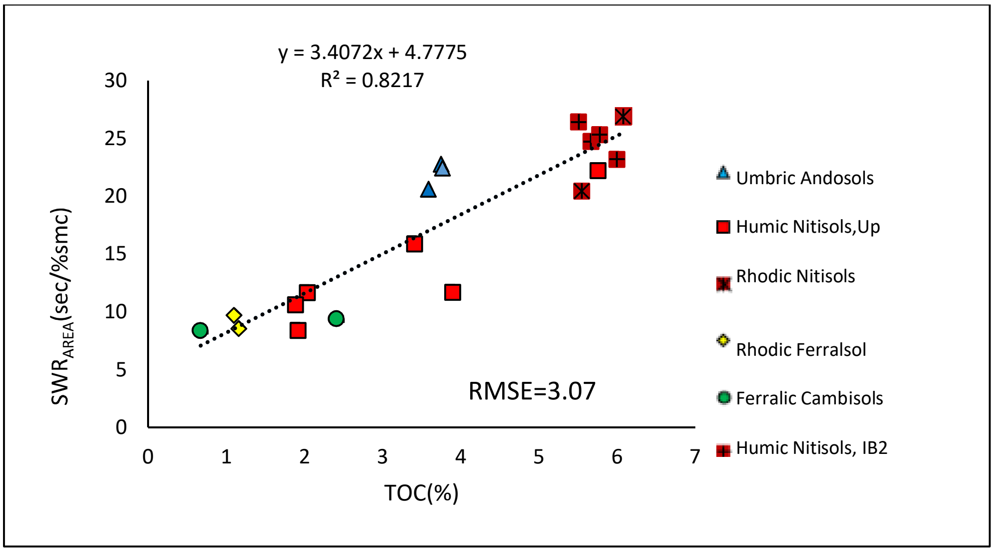

Figure 4:The total degree of soil water repellency (SWR_{AREA})

The results of this study support that the SWR_{AREA} depends on the total amount of TOC present in the soil. Similarly, critical soil moisture content was found to be strongly correlated with Total Organic Carbon (R= 0.86, P<0.01) with R^2 of 0.73 and RMSE of (1.04) 10.4g/kg of soil. This soil property can be described by a linear expression using TOC as the variable (Figure 5) and equation 4. Similarly, a linear regression(r=0.80) between Wc and Organic Carbon 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.

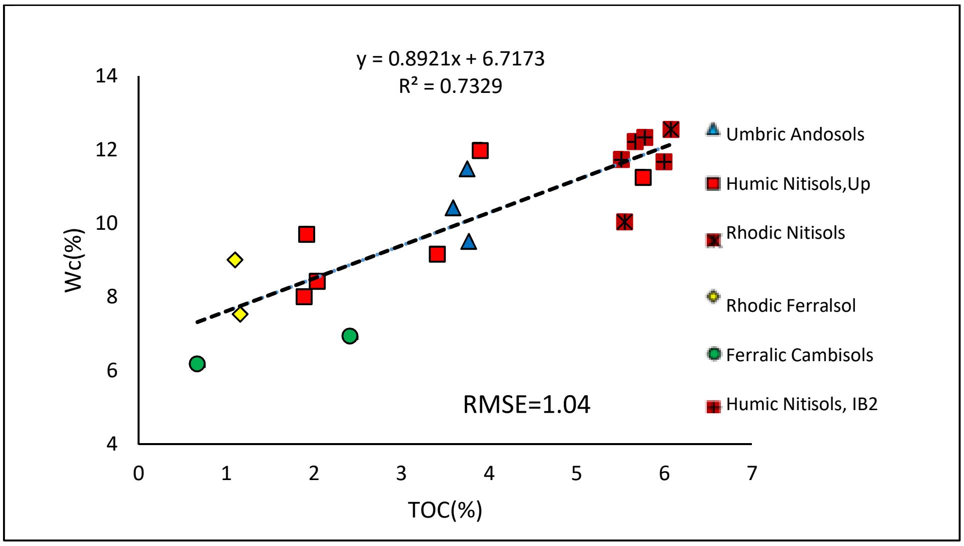

Figure 5: The critical soil water content (Wc) as a function of Total Organic Carbon

Wc= 0.8921TOC+6.7173 (4)

The critical soil moisture content shows an important soil moisture level above which onset of soil water repellency can be avoided. For practical purposes an 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 6.

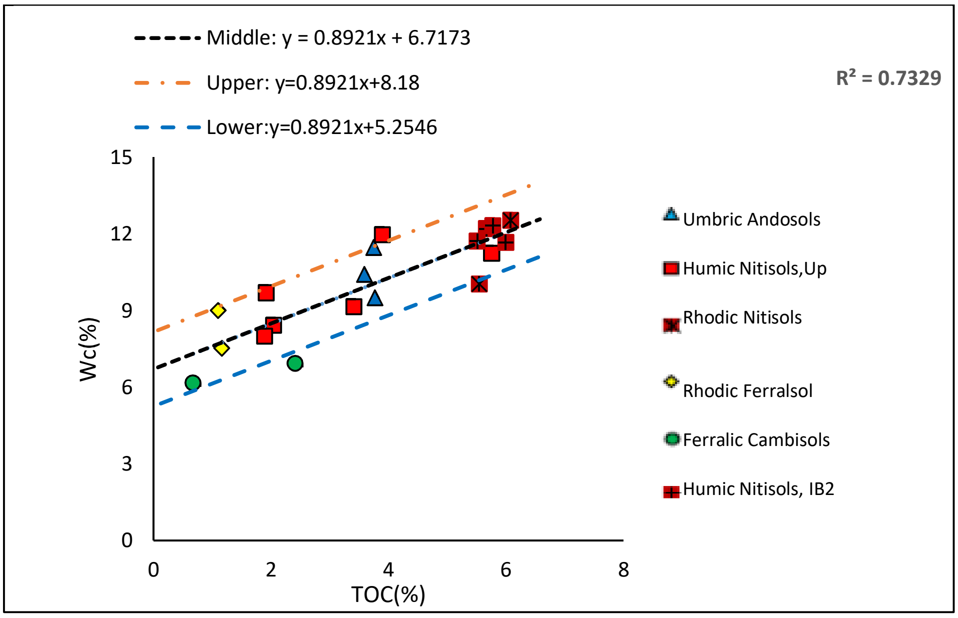

Figure 6:An upper and lower control limits to represent the spread around the regression coefficient

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 means that they require 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 moisture content. However, the general behaviour of the six soil types suggests that the overall irrigation support model; Wc= 0.89TOC+6.7183 can be utilized to avoid water repellency in those soils. It is also advisable to develop soil type specific models for Wc as a function of TOC when more comprehensive data is available for each soil type.

The correlation between SWR_{AREA} with soil texture and TOC are as presented in Table 4. Sand content was however not included in the regression analysis. This 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% of clay changes soil from a hydrophobic to hydrophilic state.

Table 4:Pearson product moment correlation matrix of Total organic carbon, clay, silt, sand, IRDI, Wc, SWRarea, SWR105 and SWR60 for 19 hydrophobic soil samples in Murang'a

	Sand	Clay	Silt	TOC	Wc	IRDI	SWRarea	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)

Clay content however correlated positively and significantly to SWRAREA and Wc (r=0.62 and 0.77, respectively) ($P<0.01$) as shown in Table 4. Clay content further improved the relationship between Wc and SWR_{AREA} to TOC in the forward multiple linear regressions (Fig 7 and 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 utilizing TOC, Silt and Clay which significantly explained 85 % of the variation in SWR_{AREA} (RMSE=3.02sec/%Soil moisture content) as shown in Figure 7 and an expression of SWR_{AREA} as a function of the three parameters is shown in equation 5.

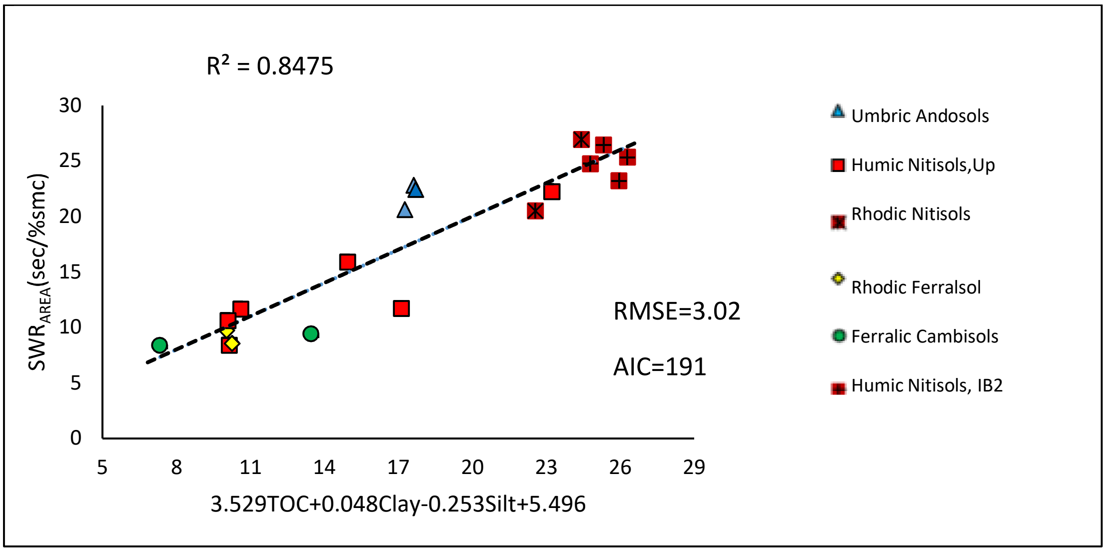

Figure 7:Multiple Linear Regression (MLR) for Trapezoidal Integrated Area under the Soil Water Repellency Curve (SWRAREA)

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

Concerning the critical soil moisture content, MLR was performed utilizing the same factors i.e. Silt, Clay and TOC (Figure 8)

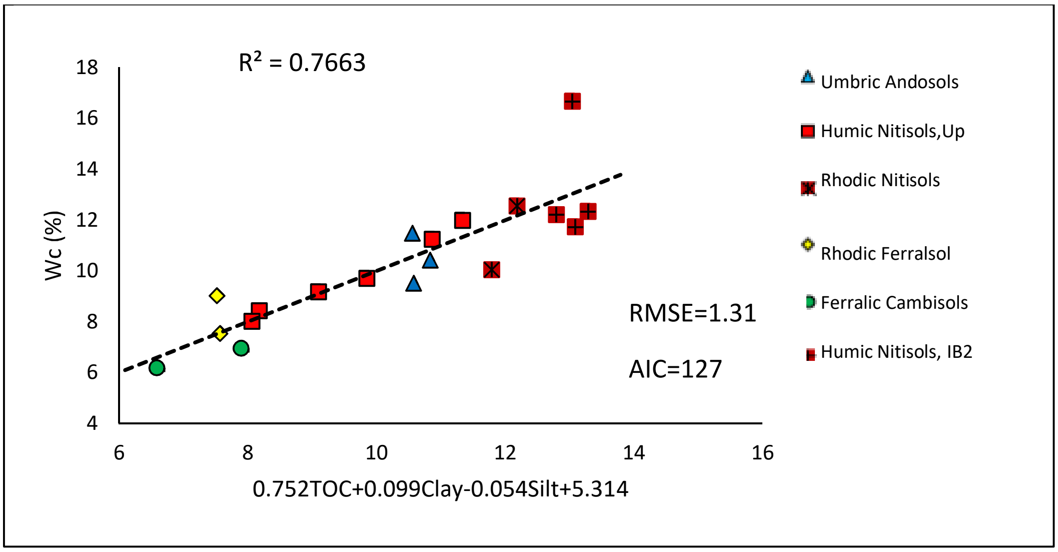

Figure 8:MLR for critical soil water content using TOC, Silt and Clay as input variables

Similarly, 77% of the variations in the critical soil moisture content could be attributed to the Clay, silt and TOC contents in the soil (RMSE=13.1g/kg of soil). Also, a high correlation between SWR_{AREA} and Wc was found (R=0.74; p<0.01) (Table 5) as already found by Kawamoto et al. (2007). On addition of Wc as an input variable, the MLR expression of SWR_{AREA} resulted in R^2 of 0.85 (Figure 9) and the expression of SWR_{AREA} as a function of TOC, sand, silt and Wc is as presented in equation 6.

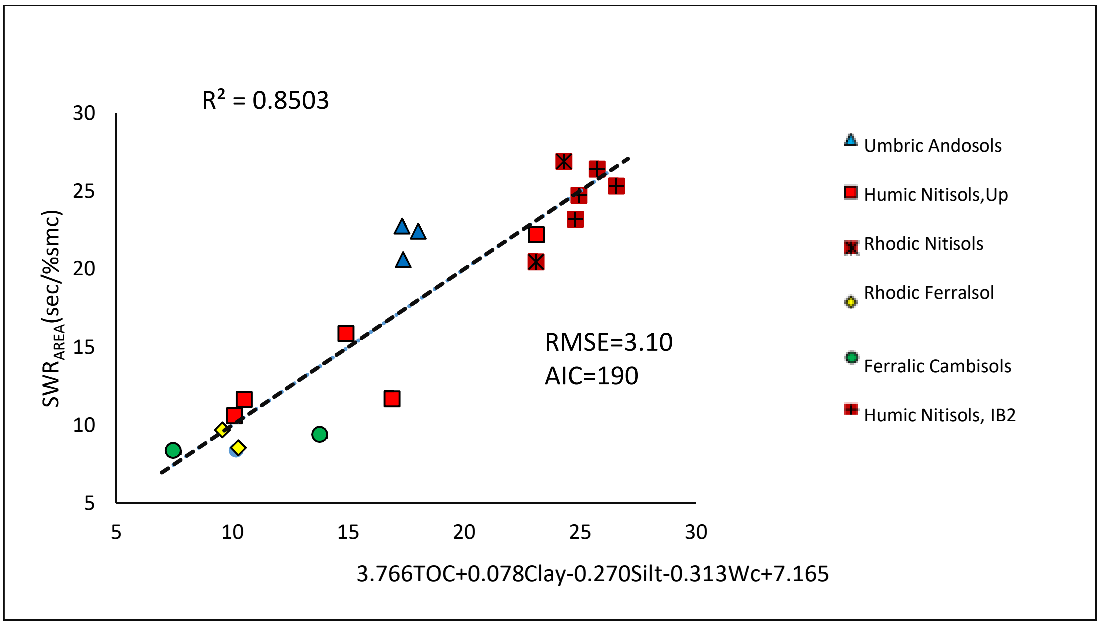

Figure 9:MLR for SWRAREA using TOC, Sand, Silt and Wc as the input variables

SWRAREA=3.766TOC+0.078Clay-0.270Silt-0.313Wc+7.165 (6)

Addition of Wc as an input variable contributed to a slight positive variation in SWRAREA. Similarly, Regalado et al. (2008) also utilized TOC and Wc to improve the prediction of SWRAREA other than utilizing only organic carbon.

Conclusions

About 37% of the soil samples collected from the 26 sampling sites were hydrophobic. Humic Nitisols, IB2 exhibited the highest SWR_{AREA} and Wc within the 6 soil types studied. 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. The SWR_{AREA} and the Wc were highly linearly correlated to TOC which was identified as the best predictor of these two repellency 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 respectively. Inclusion of Clay and silt in the MLR expression of SWR_{AREA} significantly improved the prediction of SWR_{AREA} to 85%. Concerning Wc and TOC relationship, a safety margin of 1.46% moisture content was added to obtain the upper and lower limit Wc. This upper limit critical water content could be used to derive a threshold water content above which SWR and the related degradation in soil functions could be eliminated. The overall model suggested as a guide to irrigation practices in this region was Wc= 0.89TOC+6.7183.

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.

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.

Czachor H., 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

de Jonge, 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/10.1097/SS.0b013e318065c090.

de Jonge, 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. doi: 10.1097/Ss.06013e318065c090

de Jonge, 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. Potential and actual water repellency. *Water Resources Research*, **30**, 2507-2517.

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.

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.

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.

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.

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.

Doerr, S.H., Dekker, L.W., Ritsema, C.J., Shakesby, R.A., Bryant, R., 2002. Water repellency of soils: the influence of ambient relative humidity. Soil Sci. Soc. Am. J. 66 (2), 401–405. https://doi.org/10.2136/sssaj2002.4010.

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.

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. doi:10.2136/ sssaj2008.0131

Hamparsum, B., Jhun, M., Milligan, G. W., & Cooper, M. C.,1987. CLUSTER ALGORITHMS. *Journal of Classification*, *4*, 279-281.

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

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

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.

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. doi:10.2136/sssaj2005.0060

Regalado, C.M., and A. Ritter. 2009a. A soil water repellency empirical model. Vadose Zone J. 8:136–141. doi: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. doi: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

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. II. Some chemical characteristics of the hydrophobic skins. Australian Journal of Soil Research, 10, 35-42.

Roy J.L, McGill W.B.,2000. Flexible conformation in organic matter coatings: An hypothesis about soil water repellency. *Canadian Journal of Soil Science*, **80**, 143-152.

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. doi:10.4141/S98-093

Roy, J.L., W.B. McGill, 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.

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.

Stefan, D., 2000. The role of soil moisture in controlling water repellency: New evidence from forest soils in Portugal. J. Hydrol. 231, 134.

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't Wouldt, B.D., 1959. Particle coatings affecting the wettability of soils.J.Gephyls.Res.64, 263-267.

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.