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FIELD-SCALE APPARENT ELECTRICAL CONDUCTIVITY MAPPING OF SOIL PROPERTIES IN PRECISION AGRICULTURE

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ABSTRACT. The physical examination of a functioning cacao farm revealed varying pod production rates in its area. Agricultural soil nutrient assessment is usually carried out through soil geochemical/chemical analyses which are laborious and expensive, necessitating faster/cheaper alternatives. This investigation assessed the physical properties that can substitute for geochemical analysis of soil nutrient. The study was executed at 0.3 m depth. The Volumetric Water Content (VWC) and Apparent Electrical Conductivity (EC_a) of the soils were determined using a VG-meter-200 moisture meter and a earth-resistivity meter. 912 EC_a/VWC points were measured. Soil textural classes (51 samples) were established using the Bouyoucos method. The falling head permeability test was conducted on nine cored soil samples for water infiltration assessment. The distributions of the soil EC_a (10-344 µS/cm) and VWC (2-69%) showed similar variation. An increase in VWC corresponds to a rise in the EC_a value. The soil moisture aids the mobility of ions in solution and a rise in EC_a connotes the presence of more dissolved ions. The soils were classified as sandy loam, loamy sand and sandy clayey loam. Soils' permeability ranged from 4.11×10^{-5} to 3.97×10^{-3} cm/sec; the infiltration rate varied inversely with the EC_a, accounting for the moisture variation. The low permeable soil has high nutrient retention and water-holding capacities. The soil physical properties were effective in evaluating the nutrient inconsistency.

Keywords: electrical conductivity, volumetric water content, soil texture, soil permeability, soil nutrient.

INTRODUCTION

Agricultural production causes changes in soil which vary in space and time. This requires a continuous and precise spatial evaluation of physical and chemical properties of the soil. Usual farming practices often treat an agricultural farmland evenly, disregarding the innate variability of the soil and crop conditions between and within fields and a uniform management is not the most effective management plan (Corwin and Lesch, 2005a; Moral et al., 2010).

The cost of geochemical assessment is enormous. Moreover, a comprehensive soil assessment may be difficult to achieve due to the necessity of many soil samples, which invariably limits denser sampling and results in the production of less accurate assessment maps as a result of the analysis cost (Moral et al., 2010; Costa et al., 2014). Indirect approach via apparent electrical conductivity (EC_a) serves as an alternative for dense sampling and provides an avenue to lower the cost, coupled with good correlation with soil variables (Costa et al., 2014).

The apparent electrical conductivity of soil has broad relevance in the field of soil science and agronomy (Ekwue and Bartholomew, 2011; Corwin and Lesch, 2013; Molin and Faulin, 2013; Siqueira et al., 2014). The soil electrical conductivity (EC) in agriculture field assessment has been transformed from a soil salinity tool to a spatial variability mapping tool of the soil physico-chemical properties in analyzing soil quality, transport model and site specific management (Corwin and Lesch, 2005b). The electrical conductivity of soil depends on soil mineralogy, particle size distribution, porosity, salinity level, cation exchange capacity (CEC), distribution of pore size, connectivity of the pore, water content and temperature (Corwin and Lesch, 2005a; Khattak and Hussain, 2007; Bai et al., 2013; Brillante et al., 2015; Hawkins et al., 2017).

Soil texture is a vital tool that influences the relationship between soil and water, gas exchange, CEC, organic matter content and plant nutrient required for its growth (Khattak and Hussain, 2007; Ritchey et al., 2015). Soil is a permeable unit that is characterized with interconnection of voids/spaces allowing flow of fluids as a result of the difference in energy heads. Besides being evaluated in the field, soil permeability can be measured in the laboratory using constant head, falling head and also deduction from grain size analysis (Elhakim, 2016). The rate at which water infiltrates the soil unit is estimated as its capacity to absorb water during a given period (Scherer et al., 2013). Flow of fluid and passage of electrical current are controlled by the distribution and the volume of the void in the soil matrix (Kirkby et al., 2016).

Currently, there is limited documentation on using physical parameters to assess agricultural soil productivity and its long-term performance in Nigeria. On the basis of this aim, the research was focused on assessing the effectuality of the electrical resistivity technique in mapping the variability of soil properties and also on establishing the influence of soil particle sizes and soil permeability on productivity across the cacao farm.

The study was carried out on soil within a cacao farm that lies between Latitudes 7°13′15.9″N and 7°13′19.6″N, and Longitudes 3°51′40.1″E and 3°51′43″E at the Cocoa Research Institute of Nigeria (CRIN), Ibadan (Figure 1). The farm covers an area extent of 7,722 m^2. The site inspection of the farm showed that the cacao trees were characterized with different pods' production rates. The research institute is situated on a schist and migmatite gneiss complex (Figure 2).

METHODOLOGY

The visual observation of the cacao trees conducted during the peak of the dry season showed that some of the trees withered while others exhibited healthy growth. Mommer (1999) stated that 90% of cacaos' root hairs are situated within the 30 cm of soil while the remaining 10 % are found at a deeper depth (Figure 3). This depth distribution indicates the need to evaluate the root zone in which the majority of the root hairs were situated in order to attend to the impending yield limiting causes. The investigation was conducted at 30 cm below the ground surface for all techniques employed. The seasonal appraisal of the spatial inconsistency of the soils' properties in cacao was carried out in August 2016 and March 2017 to check variations during the peak of the wet and dry seasons. The following techniques were adopted for the evaluation: electrical resistivity, volumetric water content, and permeability. Electrical resistivity, volumetric water content and thermal assessment were seasonally evaluated. The Garmin global positioning system (GPS) was used to harmonize the measurement points and all maps were generated using the ARCGIS 10.2 software.

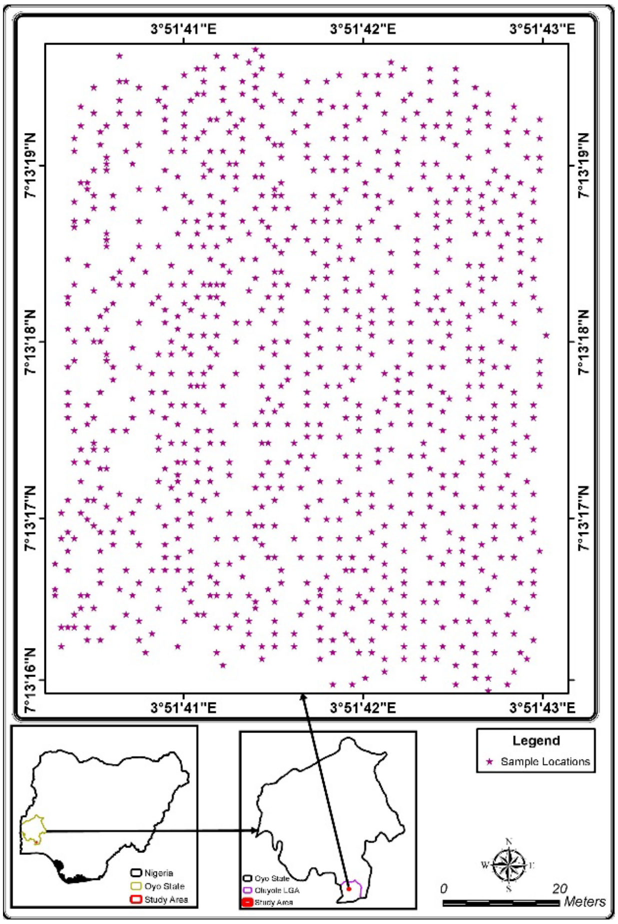


Figure 1: Spatial distribution of the data acquisition points in the study location.

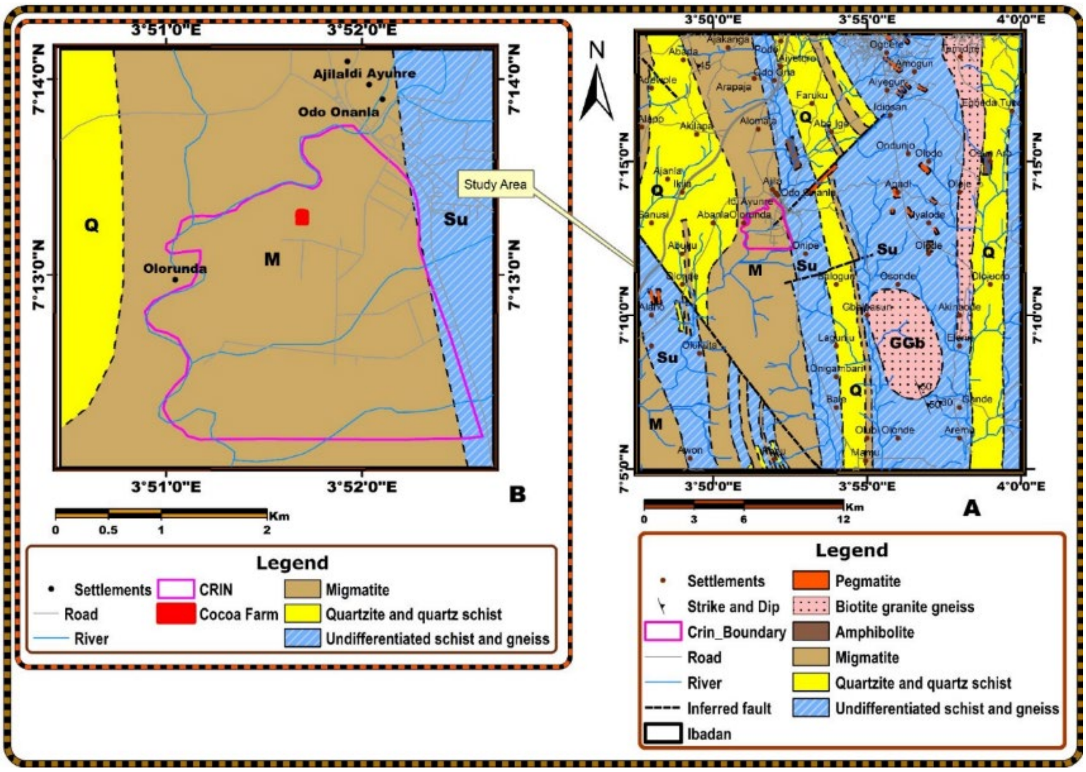


Figure 2: Geological map of the study location (adapted from NGSA, 2009).

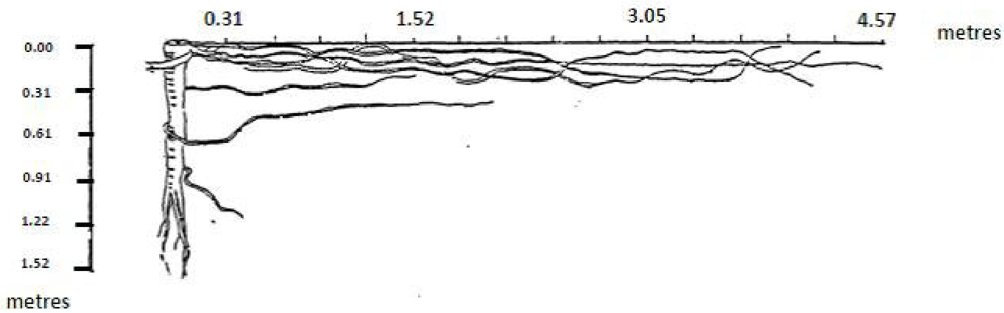


Figure 3: The root system of the cacao plant (modified after Mommer, 1999).

Electrical Resistivity

The soil apparent electrical conductivity (EC_a) was evaluated using the Allied Ohmega earth-resistivity meter, and it was employed the Wenner disposition for the resistivity measurement (Bozkurt et al., 2009) at an even inter-electrode spacing of 0.4 m. The choice of the Wenner array was based on its simplicity, ease of movement of electrodes, besides being the standard used for electrical soil testing as specified in ASTM G57 surveys (AGI, 2017). The electrodes were permanently fixed on a handy wooden frame to ensure constant spacing, equal depth of penetration and ease of data acquisition (Figures 4 and 5). Measurements were made at every 3 m along a profile and it was adopted an interline spacing of 3 m. Twenty-seven lines of measurement were established, containing 912 and 906 data points taken in the wet and dry seasons respectively.

The resistivity (ρ) measured in a homogeneous and isotropic layer is given by

$$\rho = K\frac{V}{I}, \tag{1}$$

where:

K = Geometric factor for Wenner array

V = Potential difference

I = Applied current

$$K = \frac{2\pi}{\left(\frac{2}{a} - \frac{1}{a}\right)} = 2\pi a \tag{2}$$

Note that

$$\rho = RK \text{ and } V = IR \text{ (Ohm's law)} \tag{3}$$

R = Resistance
a = Inter-electrode spacing

$$\rho = 2\pi a \frac{V}{I} = 2\pi aR \quad (4)$$

The resistivity measurements were taken at 30 cm within the root zone. Using the Wenner array, Edwards (1977) proposed the effective depth of penetration (Z_e) of the electric current as:

$$Z_e = 0.519 * a \quad (5)$$

a = 40 cm

$$Z_e = 40 * 0.519 = 20.76 \text{ cm} \quad (6)$$

The ejection of the electric current from the electrode to the ground takes place at the point source, considering an additional length of 10 cm from the electrode that has extended into the substrate; thus, the measurement of the depth is 30.76 cm. The soil apparent electrical resistivity was taken at the mentioned depth (30.76 cm) for all the sample points.

Figure 4: Electrical earth resistance measurement taken with the Allied Ohmega resistivity meter at CRIN during the wet season.

Volumetric Water Content (VWC)

The volumetric water content of the soil was quantified via the VG-Meter-200 soil moisture meter. It has the capacity of measuring the dielectric constant to infer the soil solution and it is a modification of the VH400 which has been reported to have provided accurate results (Smarsly, 2013). Shallow pits of 30 cm were dug in order to assess the soil water at the same site where the resistivity measurements were taken. Volumetric water content (Θv) is the volume of water per unit volume of soil. Volume is the ratio of mass to density (ρ) given by Bilskie (2001) as:

$$\theta_v = \frac{\text{Volume of water}}{\text{Volume of soil}} = \frac{\text{Mass of water}}{\text{Density of water}} \Big/ \frac{\text{Mass of soil}}{\text{Density of soil}} \quad (7)$$

$$\theta_v = \frac{\text{Mass of water}}{\text{Mass of soil}} * \frac{\text{Density of soil}}{\text{Density of water}} = \theta_g * \frac{\text{Density of soil}}{\text{Density of water}} \quad (8)$$

$$\theta_v = \theta_g * \text{Specific Gravity}, \quad (9)$$

where θ_g is the gravimetric water content.

Determination of Soil Particle Sizes

A total of fifty-one soil samples were collected with the aid of a hand auger from the cacao plot. They were placed in polythene bags and labeled to avoid mix-up of samples. The samples were taken at every 18 m along a profile and it was adopted an interline spacing of 9 m; the Garmin global position system (GPS) was used in taking the coordinates of the sample locations. The soil samples were air dried at room temperature and soil particles larger than 2mm in diameter were eliminated via 2 mm sieve aperture using a mechanical sieve device set to agitate the sample for fifteen minutes. It was taken 50 g of soil particles that passed through the 2 mm sieve aperture for particle size analysis to determine the proportion of clay, silt and sand using the Bouyoucos hydrometer method at the Department of Agronomy, University of Ibadan, Nigeria.

The Stokes' law is the basis for hydrometer analysis; it relates velocity of fall and diameter of particles sphere in a fluid together with density of the sphere and that of the fluid, and the fluid viscosity. The equation from Braja (2010) is given as:

$$V = \frac{2}{9} * \frac{(\rho_s - \rho_f)}{\eta} * \left(\frac{D}{2}\right)^2, \quad (10)$$

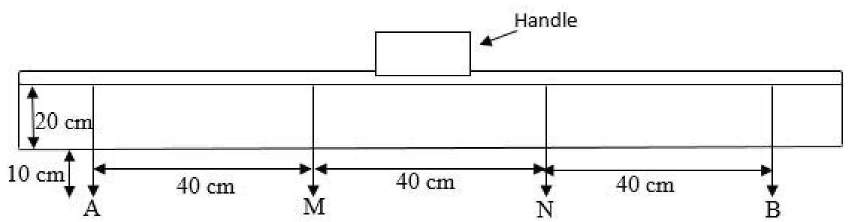


Figure 5: Schematic arrangement of the electrodes mounted on a fixed wooden frame.

where,
v = Velocity of fall of particle sphere in cm/s
ρ_s = Density of sphere
ρ_f = Density of fluid which varies with temperature
η = Viscosity of the fluid (g/(cm*s))
D = The diameter of the particle sphere in cm

Substituting ρ_f for ρ_w, which is the density of water, D can be determined from the equation as:

$$D = \sqrt{\frac{18\eta V}{(\rho_s - \rho_w)}}, \quad (11)$$

where,
$v = \frac{L}{T}$
L = Effective length in cm
T = Time taken in s

Therefore,

$$D = \sqrt{\frac{18\eta L}{(\rho_s - \rho_w)T}} \quad (12)$$

Falling Head Permeability Test

Ten undisturbed soil samples were extracted from the regions of low, medium and high conductivity/VWC using core barrels at 0.3 m below the ground surface. This was done to establish the water infiltration rate in these earth materials and the test was carried out at the Department of Petroleum Engineering, University of Ibadan, Nigeria. The approach involves measuring the drop in water level in a standpipe. The time taken by water to fall from the starting head "H_1" to final head "H_2" is "t". "H" represents the head at any intermediate time and "Q", the volume of water. Being "– *d*H" the change in head in the time interval "*dt*" with cross-sectional area (*a*) in the standpipe, Darcy's law can be used to establish the rate of flow of water and is given by Braja (2010) as:

$$Q = \frac{-dH.a}{dt} = KA\frac{\Delta H}{L}, \quad (13)$$

where,

The hydraulic conductivity (k) is given by:

$$k = \left(2.303\left(\frac{a.L}{A.\Delta t}\right)\log_{10}\frac{H1}{H2}\right) \text{ cm s}^{-1} \quad (14)$$

And the parameters to be calculated are:

Length of the sample	= L (cm)
Diameter of the sample	= D (cm)
Diameter of the standpipe	= d (cm)
Area of the standpipe	= a (cm^2) = $\pi d^2/4$
Cross-sectional area of the sample	= A (cm^2) = $\pi D^2/4$
Initial Hydraulic Head	= H_1 (cm)
Final Hydraulic Head	= H_2 (cm)

Time taken for water flow from H_1 to H_2 (change in head) = Δt (second)

RESULTS AND DISCUSSION

Electrical Conductivity of Soils

Table 1 shows the breakdown of statistical parameters generated from the field data. The variation model generated by Warrick and Nielsen (1980) was used to ascertain the degree of variability (Table 2).

The EC_a data of the Cacao field showed moderate variability (60.97 %) in the rainy period whereas the variability was slightly higher (64.11 %) in the dry period. Molin and Faulin (2013) considered the Coefficient of Variation (CV) as the first indicator in determining spatial variability of the measured parameter. Since the EC_a variability ranged between moderate and high class, it is showed that there is a variation in the measured parameter. Therefore, it would serve as a soil quality evaluator from which subsequent investigation sites could be established.

The salinity level in the cacao field during the wet and dry seasons falls within the non-saline class (Table 3), suggesting that the concentration of soluble ions in the field is not extremely high and the crops have the ability to absorb water and soil nutrient. Mean EC_a values recorded in the dry season are lesser than those of wet season which is consistent with the work of Doerge (1999).

Table 1: Exploratory statistics for soil apparent electrical conductivity (EC_a) of the cacao field.

Variable		Number of investigated points	Minimum	Maximum	Mena	Standard Deviation	Coefficient of Variation (%)
Cacao Field	**Wet Season**						
	EC_a (µS/cm)	912	13	344	68.04	41.48	60.97
	Dry Season						
	EC_a (µS/cm)	906	10	267	45.11	28.92	64.11

Table 2: Coefficient of variation, its range and classification (after Warrick and Nielsen, 1980).

S/N	Coefficient of Variation (CV)	Class
1	CV < 12 %	Low
2	12 <CV< 62 %	Moderate
3	CV>62 %	High

Table 3: Ranges of the EC value and their corresponding salinity classes (after USDA, 2011).

S/N	EC (µS/cm)	Class
1	0-2000	Non-saline
2	2000 – 4000	Very slightly saline
3	4000 – 8000	Slightly saline
4	8000 – 16000	Moderately saline
5	≥ 16000	Strongly saline

Marshall (1987) noted that water has an inherent property in which its electrical conductivity in the absence of dissolved ions is 0.055 µS/cm. Lide (2007) also reported that a rise in the concentration of electrolytes leads to an increase in the electrical conductivity. This suggests that the measured electrical conductivity values in the farm were above the absence threshold of soluble ions, thus indicating the presence of dissolved ions in the soil. The spatial distribution of the apparent electrical conductivity (EC_a) during the wet and dry seasons was used in segmenting the spatial occurrence into high, moderate, and low EC_a (Figures 6 and 7).

There is a reduction in the extent of the section covered by the moderate and high EC_a during the dry season compared to the wet period due to the decrease in soil moisture content (Figures 6 and 7).

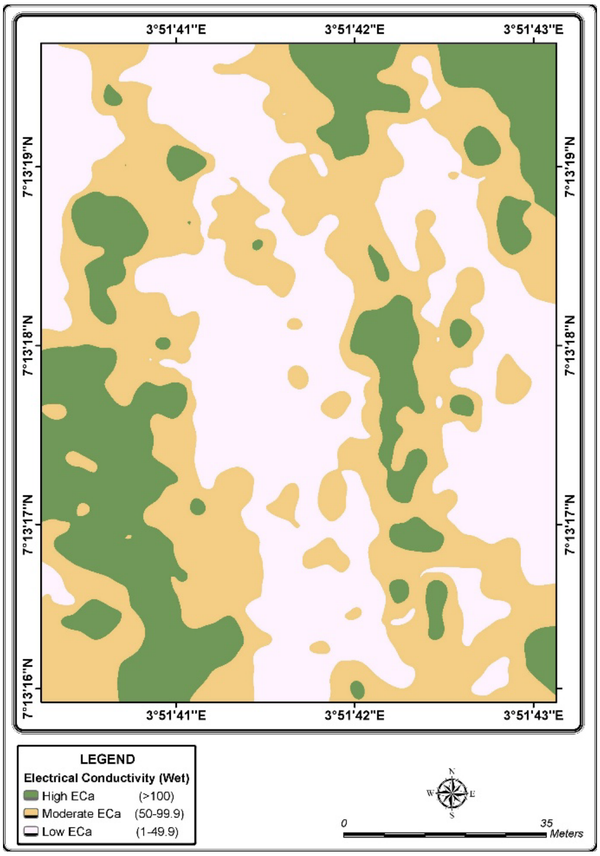


Figure 6: The spatial variation of the apparent electrical conductivity in the cacao farm during the wet season.

Volumetric Water Content (VWC) of Soils

The raw data were analyzed (Table 4) and the degrees of their variability were established by a comparison with the variation model (Table 2). The variation of VWC during the wet spell in the cacao field was moderate (53.84 %) and its variation in the dry period was also moderate (33.40 %) but there was a significant reduction in its numerical value compared with the value obtained in the wet season.

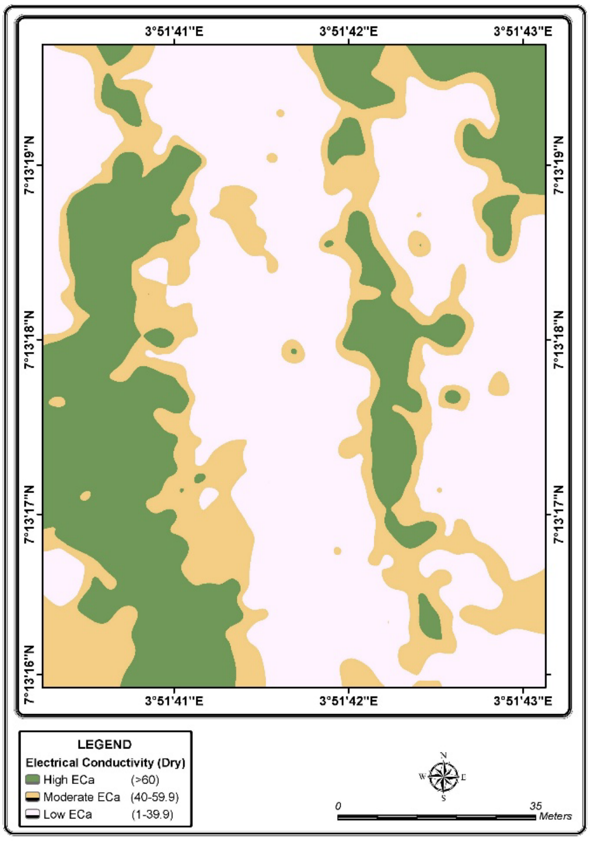


Figure 7: The spatial variation of the apparent electrical conductivity in the cacao farm during the dry season.

The prevailing VWC was approximately 26 % in the wet season while it was ~10 % at the climax of the dry time; this showed that a quarter of the soil volume was filled with water at the peak of the wet period whereas less soil water was made available for plant during the dry season. This invariably contributed to the crop yield as fewer nutrients were supplied to the plant, due to the reduction in soil moisture content and its sparse distribution (Ryšan and Šařec 2008). The spatial distribution of volumetric water content was used in classifying the zones into low, moderate, and high VWC (Figures 8 and 9). There is an increase in the area covered by low VWC during the dry season as a result of the reduction in soil moisture. This shows that the water retention capacity around this soil is low. Also, ions mobility will be reduced and this could impede availability of soil nutrient for plant consumption.

Correlation Analysis between Volumetric Water Content and Electrical Conductivity

Regression analysis has been the norm in evaluating the relationship between soil water content and apparent electrical conductivity (EC_a) values in precision agriculture in order to establish the influence of soil moisture on electrical conductivity (Brevik et al., 2006; Ali et al., 2009; Hossain et al., 2010; Ekwue and Bartholomew, 2011).

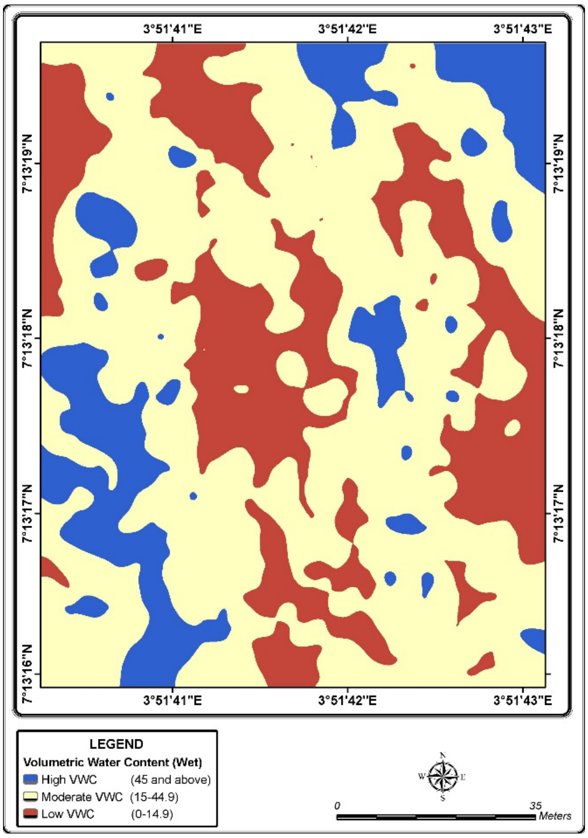


Figure 8: The spatial variation of the volumetric water content in the cacao farm during the wet season.

Figure 10 shows that VWC rises together with the EC_a and a strong correlation coefficient (0.972) was observed. A small change in moisture content leads to a greater change in conductivity. Pedrera-Parrilla et al. (2016) and Samouëlian et al. (2005) also made known that such fit exists between electrical conductivity and soil water content. The total ion constituents increase with an increase in moisture content at extraction.

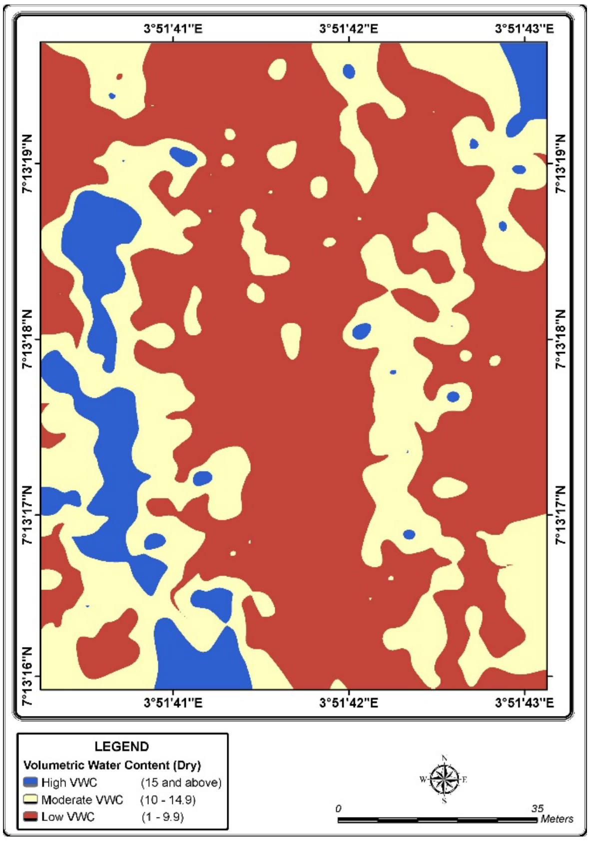


Figure 9: The spatial variation of the volumetric water content in the cacao farm during the dry season.

The capability of the soil solution to conduct electrical current depends on the concentration of ions in the solution (Ryšan and Šařec, 2008; Corwin and Yemoto, 2017). Also, the air occupying the voids is replaced with water, invariably increasing the electrical conductivity of the medium. The ions are transferred from the soil materials to the water where they contribute to the electrical conduction. Once the water is removed, they return to the particles around them (Liu et al., 2013).

During the dry season, a strong relationship was also observed from the interaction of these parameters having a coefficient of 0.807 (Figure 11). This showed that the EC_a increases as the VWC increases during the dry period and a non-linear relationship was observed between EC_a and VWC (McCutcheon et al., 2006; Bhatt and Jain, 2014; Asif et al., 2016). The soil moisture aids the mobility of ions in solution; as the soil moisture reduced, it was noted a decrease in the EC_a values and this is consistent with the works of Doerge (1999); McCutcheon et al. (2006); Kizito et al. (2008); Costa et al. (2014); and Wang et al. (2017).

Soil Textural Assessment of the Cacao Farm

Clay particles ranged from 4.8g/kg to 26.8 g/kg with a mean distribution of 12g/kg; the proportion of silt fractions ranged from 5.4 g/kg to 24.8 g/kg and its average composition was 15g/kg; the amount of sand material in soil varied from 57.8g/kg to 87.8g/kg (Table A1). Particle size data were subjected to a variability test using the Warrick and Nielsen (1980) classification (Table 2). The distribution of clay particle was within the moderate class (33%); the silt fraction was also in the class of moderate proportion (25%) while the proportion of sand size presented low variability (8%) suggesting nearly uniform distribution in the cacao farm.

Three soil texture classes were established from the grain size distribution in Table A1. They include sandy loam (41), loamy sand (9) and sandy clayey loam (1) with the following percentage: 80%, 18% and 2%, respectively (Figure 12). The region of high EC_a has soil classes ranging from sandy loam to sandy clayey loam whereas the loamy sand to sandy loam class was inherent in the moderate and low EC_a segments. Khadka et al. (2018) reported that soil with sandy loam texture is satisfactory for most of agricultural purposes.

Particle Size Variation at EC_a Sections in the Cacao Farm

In the low EC_a section, the clay distribution ranged from 6.0 g/kg to 18 g/kg; the silt component in the soil varied from 5.4 g/kg to 23.4 g/kg while its sand proportion varied between 65.8 g/kg and 87.8 g/kg. The particle size computation for the soil samples taken at the moderate EC_a section shows that the clay size was between 7.4 g/kg and 18.0 g/kg; the silt fraction varied from 9.4 g/kg to 21.4 g/kg whereas the sand fraction in soils from this segment ranged from 62.6 g/kg to 79.8 g/kg. In the region of high EC_a, the clay size varied between 9.8 g/kg and 26.8 g/kg; the silt fraction presented its content ranging from 12.8 g/kg to 24.8 g/kg whereas the sand particle size ranged from 57.8 g/kg to 73.8 g/kg. Considering the mean distribution of the soil particles (Figure 13), it revealed that areas of low EC_a are characterized with less content of finer soil textures than the moderate and high EC_a zones. They tend to be more porous and permit faster water infiltration into lower soil horizons; therefore, they are prone to low water holding capacity and less retention of soil nutrients as a result of low clay content leading to low soil fertility (Ritchey et al., 2015; Jaja, 2016; Mukungurutse et al., 2018).

Table 4: Statistical analyses of volumetric water content (VWC) in the cacao field.

Variable	Number of investigated points	Minimum	Maximum	Mena	Standard Deviation	Coefficient of Variation (%)
Wet Season VWC (%)	912	3.00	69.00	25.52	13.95	53.84
Dry Season VWC (%)	906	2.00	26.00	9.70	3.24	33.40

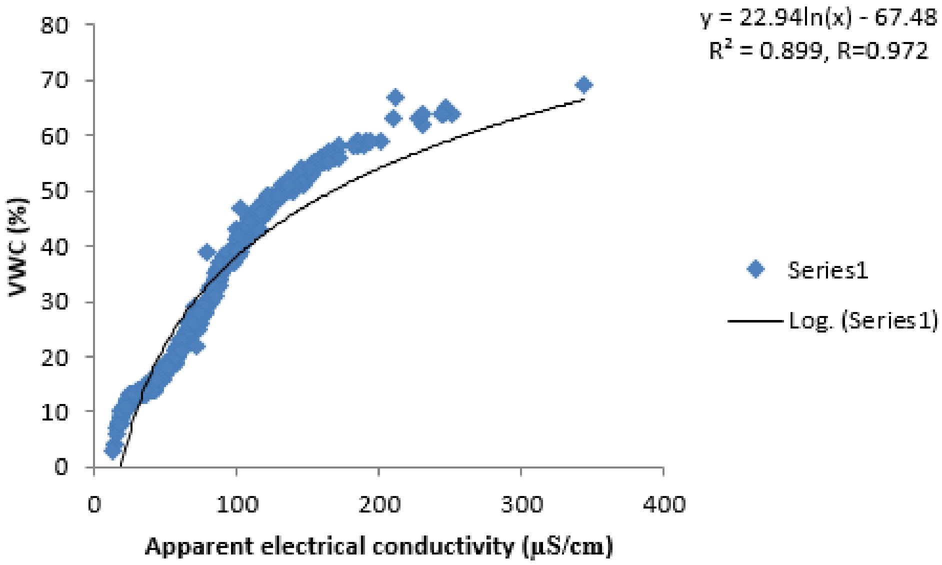


Figure 10: Relationship between VWC and the EC_a in the cacao farm during the wet season.

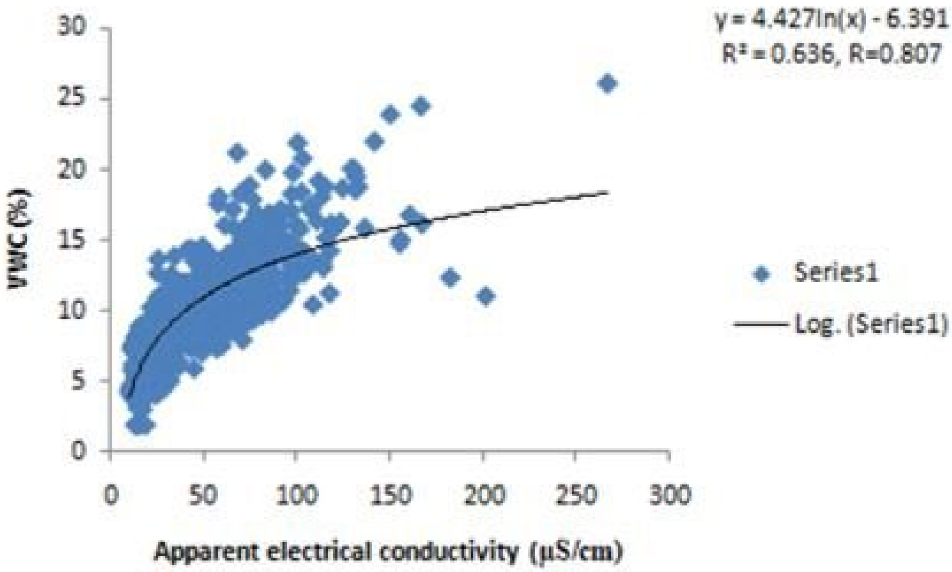


Figure 11: Relationship between VWC and the EC_a in the cacao farm during the dry season.

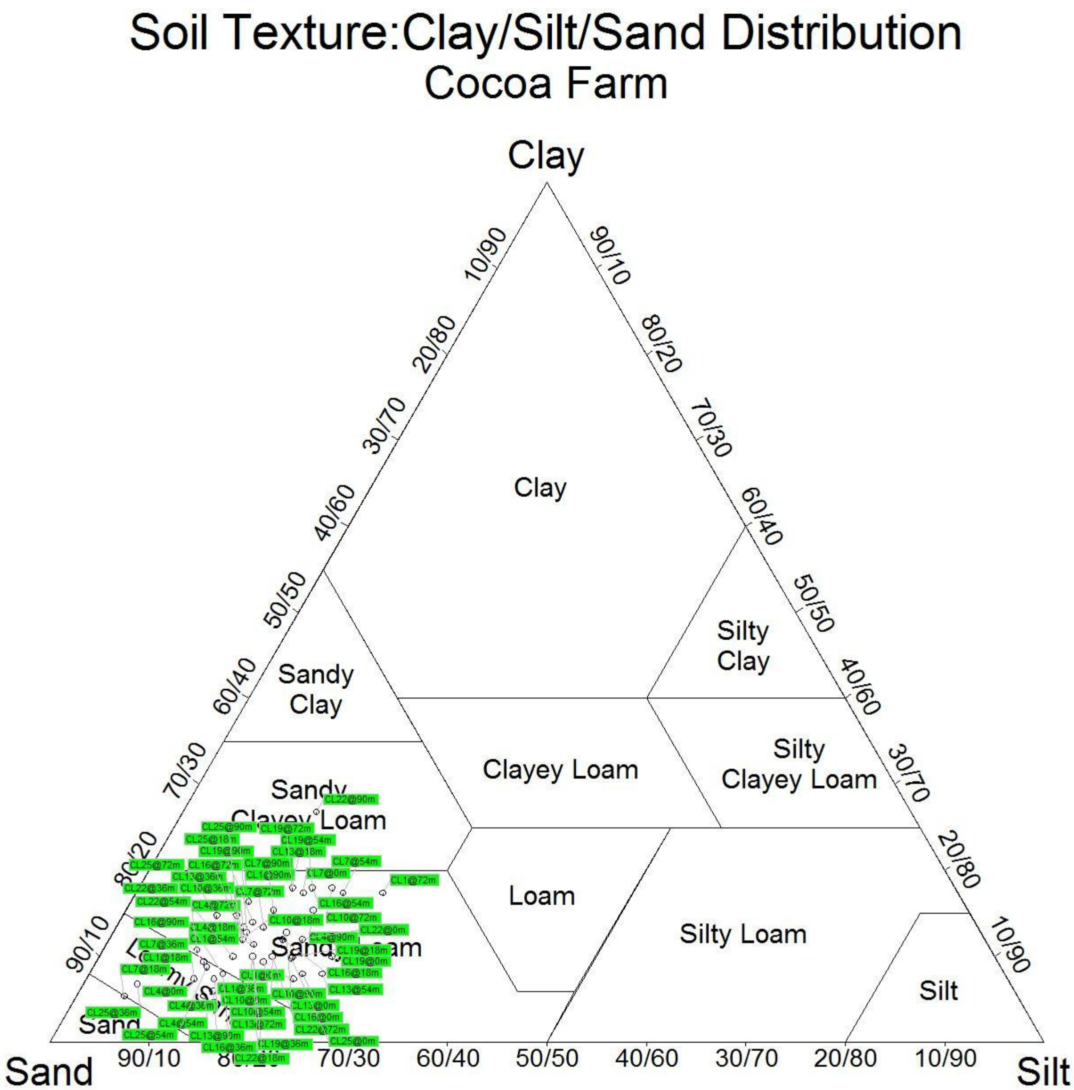
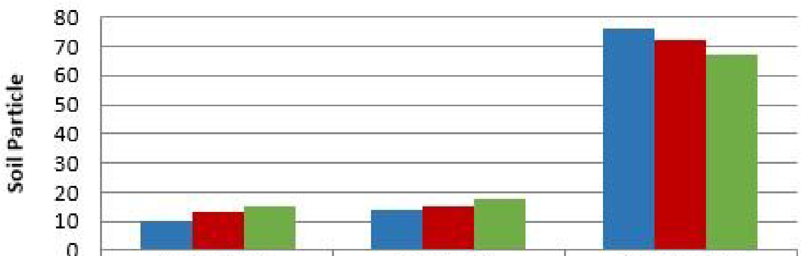


Figure 12: Textural classes of soils in the cacao farm using Schoeneberger et al. (2012) classification.



	Clay (g/kg)	Silt (g/kg)	Sand (g/kg)
LECa	10	14	76
MECa	13	15	72
HECa	15	18	67

Figure 13: Mean distribution of soil particles in different EC_a sections in the cacao farm.

Soils in the low EC_a section have sandier textures than the moderate EC_a and high EC_a sections; they hold less water and less nutrients because they are prone to nutrients' leaching (Botta, 2015). High clay content was observed in the moderate (13 g/kg) and high EC_a (15 g/kg) sections. These soil particles retain more water than the ones in the low EC_a portion due to the presence of small pores with capacity to hold more soil nutrient (Botta, 2015).

Relationship between Soil Particle Size and Apparent Electrical Conductivity (EC_a) in the Cacao Farm

An attempt was made to examine the soil particles influencing the apparent electrical conductivity of the soil measured during the wet and dry seasons.

A moderate positive correlation coefficient (0.391) was observed between clay content and apparent electrical conductivity (EC_a) in the wet period, suggesting that as the clay fraction increases, the EC_a also rises (Figure 14), in accord with the results of Gholizadeh et al., (2012). A rise in the EC_a values was also noted as the proportion of silt particle size increases across the soil unit (Figure 15) and a moderate correlation coefficient of 0.458 was generated from their relationship (Chaudhari et al., 2014). Figure 16 shows the interaction between EC_a and sand fraction to be a moderate negative coefficient (-0.562) and it can be inferred that EC_a values tend to be reduced across the soil unit with abundant sand proportion compared to the portion of lower sand quantity (Chaudhari et al., 2014). The interaction between fine fraction (clay+silt) and EC_a indicates a moderate positive coefficient (0.562) occurring between these parameters (Figure 17).

EC_a data acquired during the dry season were also related with the soil particle size to access their relationship. By relating EC_a with the clay content (Figure 18), it was generated a weak positive correlation coefficient (0.326), indicating that an increase in clay content leads to a rise in the EC_a value measured on the cacao plot (Heil and Schmidhalter, 2017). A weak positive coefficient (0.318) is noted from the interaction of EC_a with silt content in Figure 19, suggesting that soils with increasing silt fractions tend to have high EC_a value. Evaluating the relationship between EC_a and sand fraction in Figure 20, an increase in sand fraction is noted with a decrease in the EC_a value measured in the farm, presenting a correlation coefficient equals to -0.427 (Korsaeth, 2005). The correlation coefficient determined from the interaction of EC_a with the fine fraction (Figure 21) was a moderate positive correlation (+0.427). By relating the EC_a with the soil particles, it was shown that, in the wet season, a better correlation was established with these variables than in the dry season. This is due to the presence of higher soil moisture in the wet season than in the dry period, thus promoting the mobility of ions in solution, as extracted from the soil particle, and aiding the conductivity.

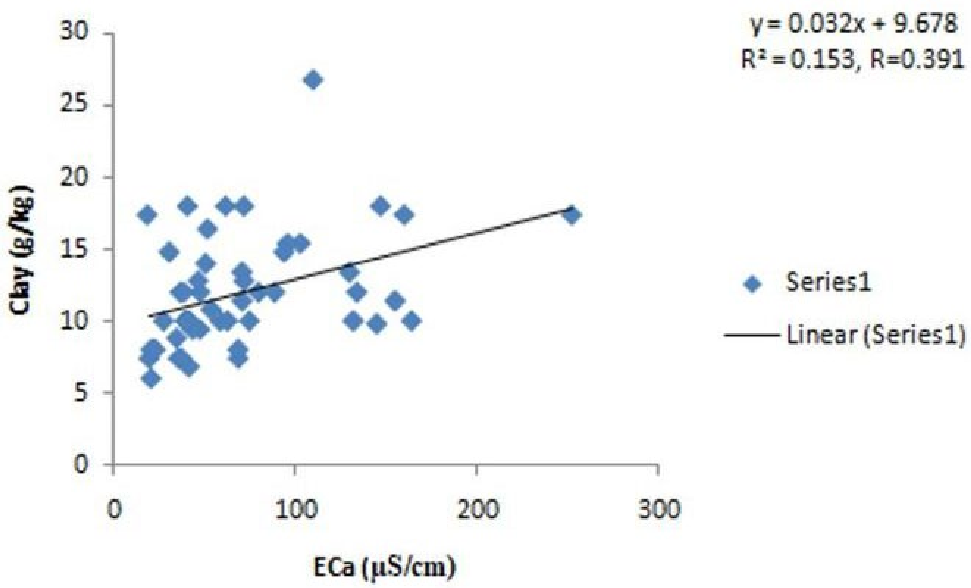


Figure 14: Plot of EC_a versus clay fraction in the cacao farm during the wet season.

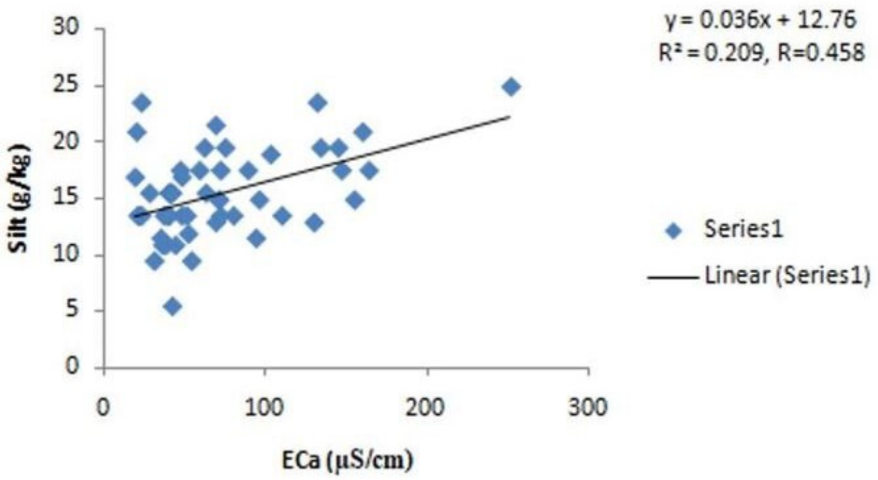


Figure 15: Plot of EC_a versus silt fraction in the cacao farm during the wet season.

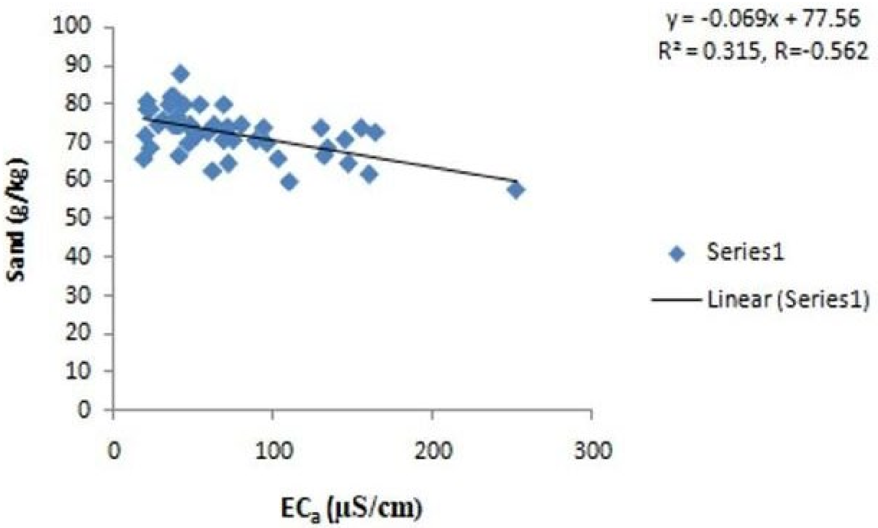


Figure 16: Plot of EC_a versus sand fraction in the cacao farm during the wet season.

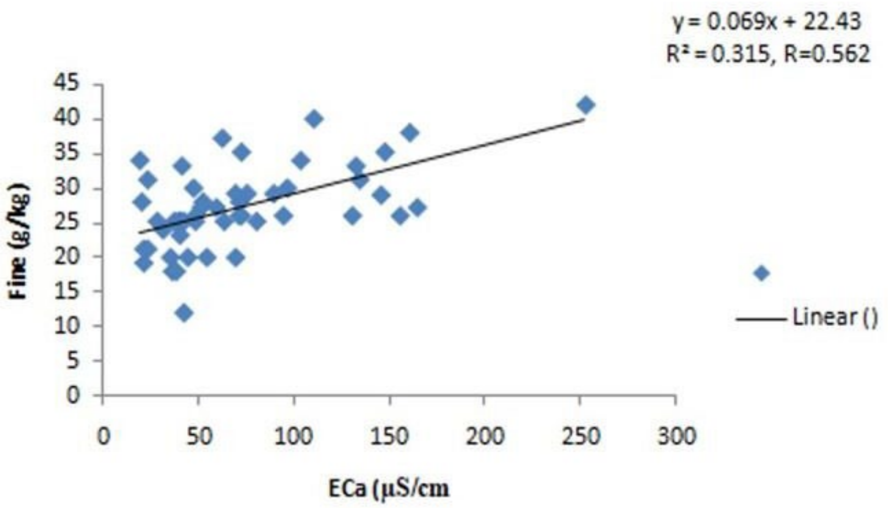


Figure 17: Plot of EC_a versus fine fraction in the cacao farm during the wet season.

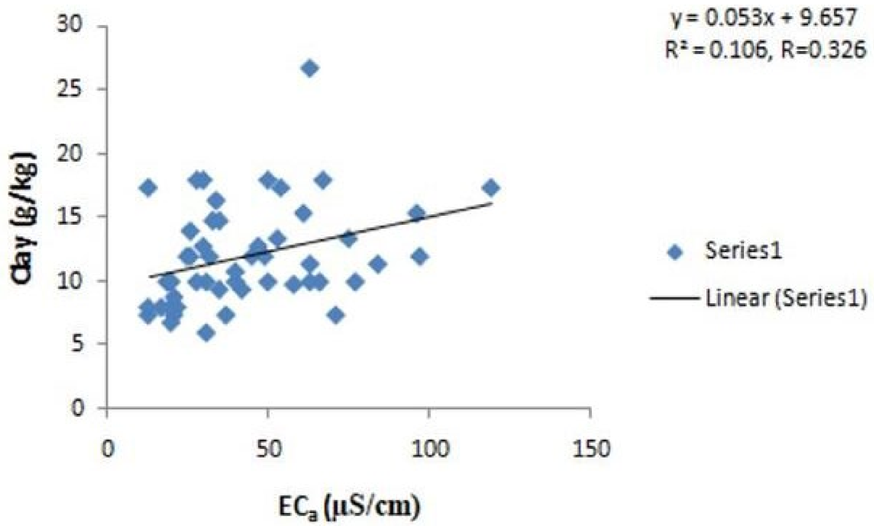


Figure 18: Plot of EC_a versus clay fraction in the cacao farm during the dry season.

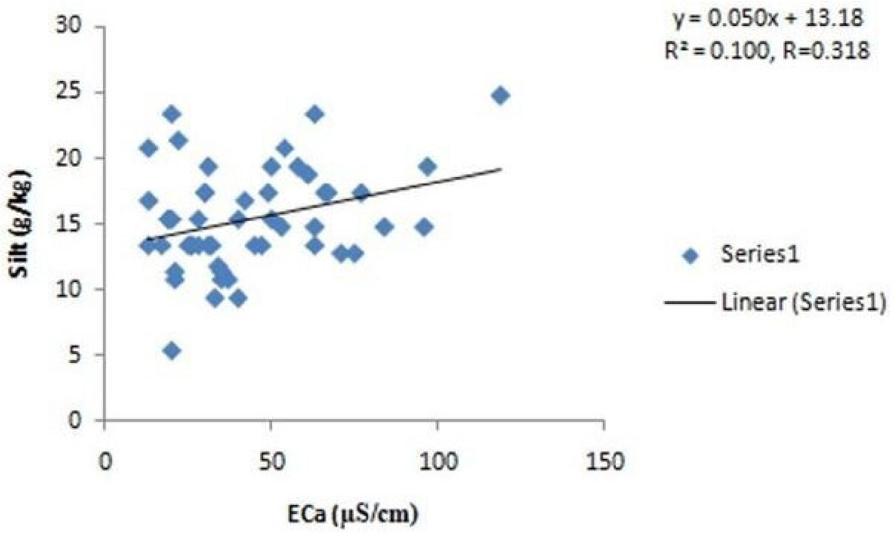


Figure 19: Plot of EC_a versus silt fraction in the cacao farm during the dry season.

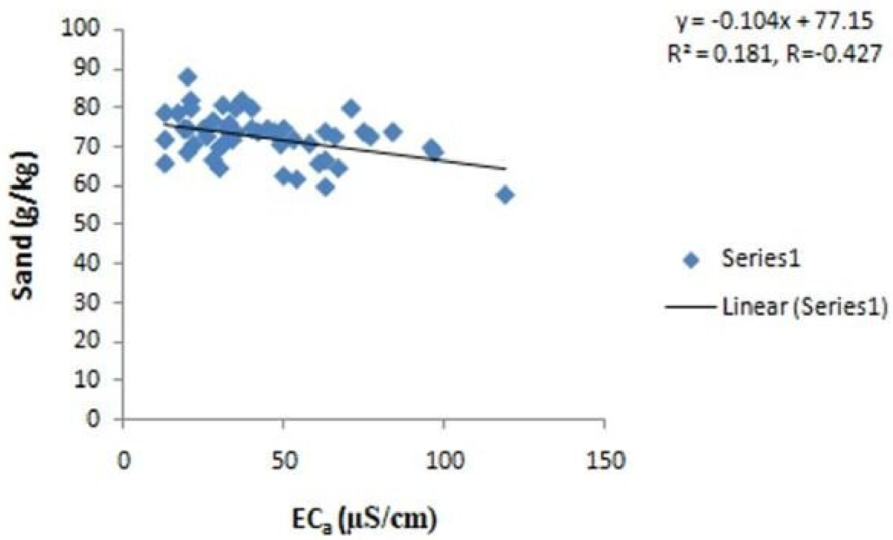


Figure 20: Plot of EC_a versus sand fraction in the cacao farm during the dry season.

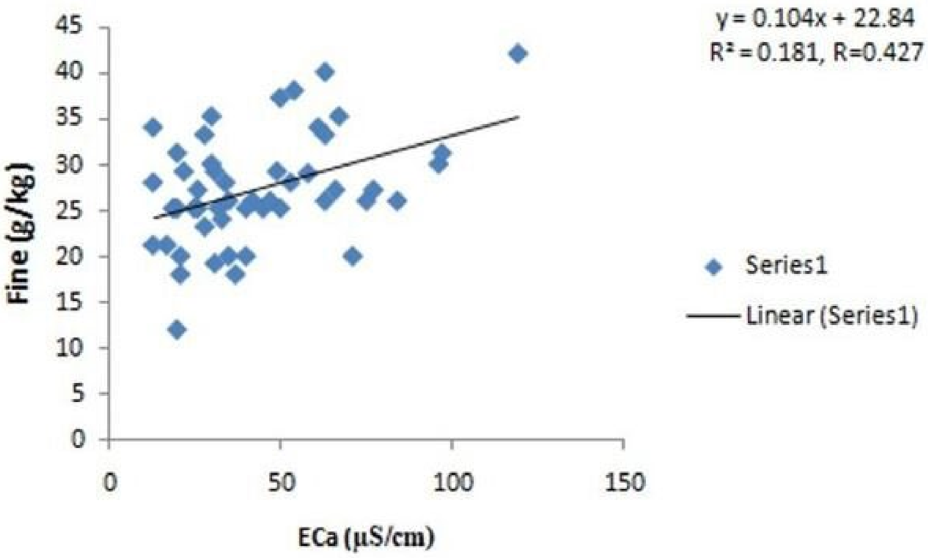


Figure 21: Plot of EC_a versus fine fraction in the cacao farm during the dry season.

Evaluating the productivity of the soil from its textural classes in the regions of low, moderate and high EC_a (Figures 22, 23 and 24) with respect to the result of the electrical conductivity assessment of the soil has helped to delineate sections classified to be productive, partly productive and non-productive. The EC_a analysis was corroborated with the soil textural variation within the cacao plot. The dominant soil texture class across the entire farm is sandy loam as determined from the USDA soil texture triangle.

The region of low EC_a was characterized with low proportion of clay and silt contents and high proportion of sand fraction whereas the moderate EC_a segment has more content of clay and silt, and less of sand particles than the low EC_a portion. High EC_a areas were noted with a greater proportion of clay and silt and far less of sand compared to the low and moderate EC_a regions. Soils in high EC_a regions have higher proportion of fine particles (clay and silt) than soils in other regions; they have the ability to retain more water, soil nutrient and are less prone to nutrient leaching due to the presence of small pores (Sharu et al., 2013; Amos-Tautua et al., 2014). The relationship between the EC_a data measured in the wet and dry seasons and the soil particle has shown that EC_a values increase in soil with high proportion of clay and silt and low sand fraction and vice versa.

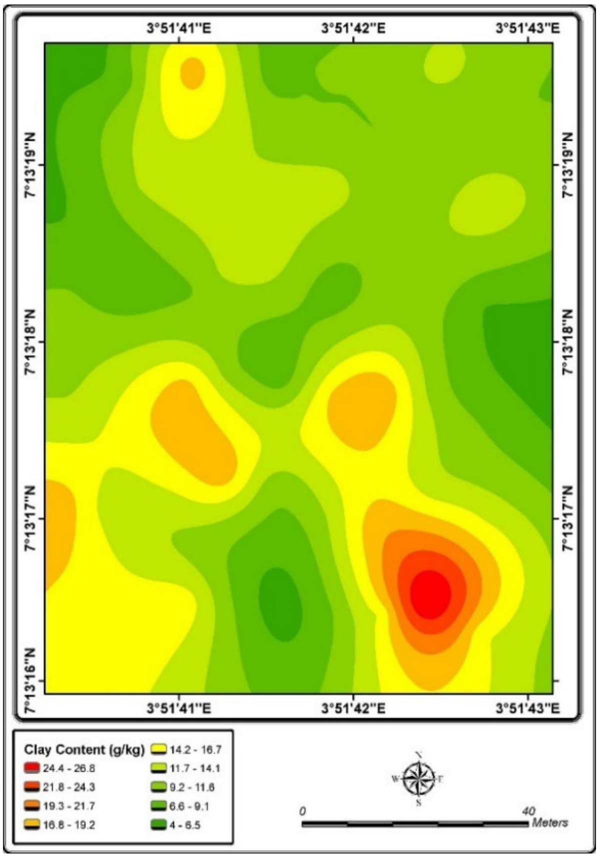


Figure 22: The spatial variation of the clay content in the cacao farm.

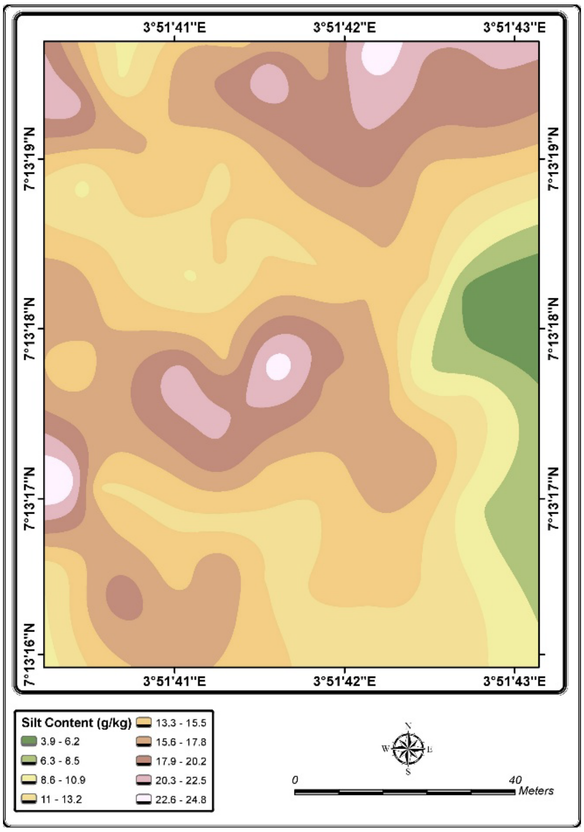


Figure 23: The spatial variation of the silt content in the cacao farm.

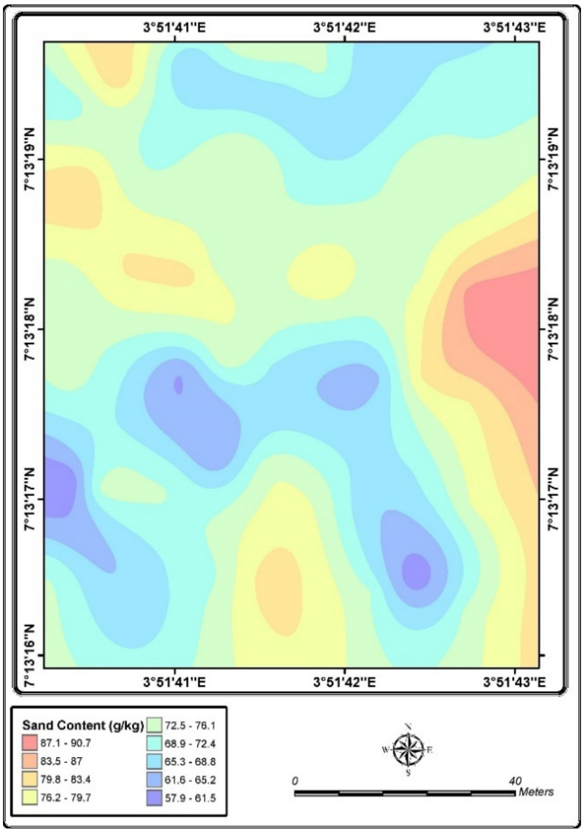


Figure 22: The spatial variation of the clay content in the cacao farm.

Falling Head Permeability Assessment of Soils in the Cacao Farm

Table A2 shows the computation of the falling head hydraulic conductivity performed on selected soil samples from the farm. Table A3 shows a typical breakdown of hydraulic conductivity of soils already established. Soils from the high electrical conductivity section are characterized with a permeability coefficient ranging between 4.110x10^{-5} cm/sec and 6.570x10^{-4} cm/sec. They were classified to be silty sand (Terzaghi and Peck, 1967) with relative permeability, signifying low hydraulic conductivity. The soil with a 6.540x10^{-4} cm/sec coefficient of permeability (moderate EC_a) was categorized to be silty sand and its relative permeability was low. Soils (low EC_a) of high permeability (1.870x10^{-4}-6.660x10^{-4} cm/sec) have their permeability classes to be low and soils within this category were regarded as silty sands. Comparing the numerical coefficients, the permeability coefficients in soils of high EC_a were lower, in contrast to the moderate and low EC_a segments.

Soil Permeability and Infiltration Rate in the Cacao Plot

The permeability coefficients were used in classifing the soil permeability based on its infiltration rate (Table A4). The high EC_a section has the permeability ranging from 4.110x10^{-5} cm/sec to 6.570x10^{-4} cm/sec and it can be categorized as very slow to moderately slow. Permeability of 6.540x10^{-4} cm/sec was obtained in the moderate electrical conductivity segment designated as moderate infiltration. The soils (1.870x10^{-4}-6.660x10^{-4} cm/sec) in electrically less conductive section were classified as moderate slow to moderately rapid infiltration. The technique classified soils of the high EC_a section to be silt and silty sand, while soils in the medium EC_a segment were classified as silty sand. Values obtained from soils in the low EC_a section indicate textural composition of fine sand to silty sand content.

CONCLUSION

The distribution of EC_a varies significantly with the volumetric water content such that the area of high EC_a corresponds to high VWC and vice versa. EC_a is useful in predicting water content in soils due to the strong correlation coefficients generated with these variables. Loamy sand, sandy loam and sandy clayey loam were three soil textural classes identified in the farm. Soils in the region of high EC_a have high clay and silt fractions and a few sand constituents. Soil with high clay fraction favours nutrient retention as well as the ability to retain soil water and vice versa. Areas of large quantity of clay and silt contents have high EC_a value and low permeability resulting in higher water-holding capability and nutrient retention capacity in comparison to the moderate and low EC_a parts that are characterized with quick water drain, which leads to leaching of soil nutrient. Fine fractions have a large surface area whereas the coarse fragment has less surface area, thereby resulting in a large catchment/retention area for water and soil nutrients in solution. Low permeable soil has high nutrient retention and high water holding capacity, thereby preventing leaching of soil nutrients. Highly permeable soils in low EC_a areas permit low nutrient withholding as water is easily drained through, which is responsible for the less cacao pod production.

The electrical conductivity technique can be used to map out areas of water, texture and permeability variations. This study showed that the use of physical parameters is relevant and efficient in delineating agricultural soil nutrient unpredictability. It should be adapted into agricultural farming practices as a rapid tool in assessing the management soil zones.

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APPENDIX

Table 1: Particle size distribution with EC_a values for soils in the cacao farm.

S/N	I.D	Clay g/kg	Silt g/kg	Sand g/kg	EC_a (Wet) µS/cm	EC_a (Dry) µS/cm
1	CL 1 at 0m	7.4	20.8	71.8	20	13
2	CL 1 at 18m	7.4	10.8	81.8	36	21
3	CL 1 at 36m	9.4	16.8	73.8	48	42
4	CL 1 at 54m	11.4	14.8	73.8	155	84
5	CL 1 at 72m	17.4	24.8	57.8	252	119
6	CL 1 at 90m	16.4	11.8	71.8	52	34
7	CL 4 at 0m	7.4	10.8	81.8	38	37
8	CL 4 at 18m	11.4	14.8	73.8	71	63
9	CL 4 at 36m	7.4	12.8	79.8	69	71
10	CL 4 at 72m	13.4	12.8	73.8	130	75
11	CL 4 at 90m	15.4	18.8	65.8	103	61
12	CL 7 at 0m	17.4	16.8	65.8	19	13
13	CL 7 at 36m	9.4	10.8	79.8	44	35
14	CL 7 at 54m	17.4	20.8	61.8	160	54
15	CL 7 at 72m	13.4	14.8	71.8	71	53
16	CL 7 at 90m	15.4	14.8	69.8	96	96
17	CL 10 at 0m	10	15.4	74.6	40	19
18	CL 10 at 18m	12	13.4	74.6	37	32
19	CL 10 at 36m	12	13.4	74.6	39	25
20	CL 10 at 54m	10	15.4	74.6	28	19
21	CL 10 at 72m	18	19.4	62.6	62	50
22	CL 10 at 90m	10	17.4	72.6	59	66

continue

Table 1 (cont.): Particle size distribution with EC_a values for soils in the cacao farm.

S/N	I.D	Clay g/kg	Silt g/kg	Sand g/kg	EC_a (Wet) µS/cm	EC_a (Dry) µS/cm
23	CL 13 at 0m	8	21.4	70.6	69	22
24	CL 13 at 36m	12	13.4	74.6	80	45
25	CL 13 at 54m	8	23.4	68.6	23	20
26	CL 13 at 72m	10	15.4	74.6	40	40
27	CL 13 at 90m	6	13.4	80.6	21	31
28	CL 16 at 0m	10	17.4	72.6	164	77
29	CL 16 at 18m	12	17.4	70.6	89	49
30	CL 16 at 36m	8	13.4	78.6	21	13
31	CL 16 at 54m	18	17.4	64.6	72	30
32	CL 16 at 72m	12	13.4	74.6	48	26
33	CL 16 at 90m	8	13.4	78.6	23	17
34	CL 19 at 0m	10	23.4	66.6	132	63
35	CL 19 at 18m	10	19.4	70.6	75	31
36	CL 19 at 36m	10	15.4	74.6	63	50
37	CL 19 at 54m	18	17.4	64.6	147	67
38	CL 19 at 72m	18	15.4	66.6	41	28
39	CL 19 at 90m	14	13.4	72.6	51	26
40	CL 22 at 0m	12	19.4	68.6	134	97
41	CL 22 at 18m	10	15.4	74.6	42	20
42	CL 22 at 36m	10	13.4	76.6	40	28
43	CL 22 at 54m	10.8	9.4	79.8	54	40
44	CL 22 at 72m	12.8	17.4	69.8	47	30
45	CL 22 at 90m	26.8	13.4	59.8	110	63
46	CL 25 at 0m	9.8	19.4	70.8	145	58
47	CL 25 at 18m	12.8	13.4	73.8	72	47
48	CL 25 at 36m	6.8	5.4	87.8	42	20
49	CL 25 at 54m	8.8	11.4	79.8	35	21
50	CL 25 at 72m	14.8	9.4	75.8	31	33
51	CL 25 at 90m	14.8	11.4	73.8	94	35
	Mean	12	15	73	71	44
	Std. Dev.	4	4	6	47	24
	CV%	35	27	9	66	56

Table 2: Falling head permeability (k) coefficients of some selected soils from the cacao farm.

S/N	Coordinate	EC_a region	a (cm^2)	L (cm)	A (cm^2)	Δt (sec)	H_1 (cm)	H_2 (cm)	k (cm/sec)
1	7⁰13′18.5″N 3⁰51′40.6″E	High	0.159	7	38.49	176	143	26	$2.800x10^{-4}$
2	7⁰13′16.8″N 3⁰51′40.6″E	High	0.159	7	38.49	1200	143	26	$4.110x10^{-5}$
3	7⁰13′16.2″N 3⁰51′41.1″E	High	0.159	7	38.49	384	143	26	$1.280x10^{-4}$
4	7⁰13′17.7″N 3⁰51′41.6″E	Low	0.159	7	38.49	74	143	26	$6.660x10^{-4}$
5	7⁰13′19.3″N 3⁰51′41.4″E	Low	0.159	7	38.49	263	143	26	$1.870x10^{-4}$
6	7⁰13′16.6″N 3⁰51′42.9″E	Medium	0.159	6.5	38.49	70	143	26	$6.540x10^{-4}$
7	7⁰13′17.8″N 3⁰51′42.3″E	High	0.159	7	38.49	75	143	26	$6.570x10^{-4}$
8	7⁰13′17.9″N 3⁰51′41.9″E	Low	0.159	6.8	38.49	112	143	26	$4.280x10^{-4}$
9	7⁰13′19.0″N 3⁰51′43.0″E	High	0.159	7	38.49	450	143	26	$1.100x10^{-4}$

Table 3: Classification of soils according to their coefficients of permeability (after Terzaghi and Peck, 1967).

S/N	Relative Permeability	Typical Soil	Value of *k* (cm/s)
1	High	Coarse gravel	$> 10^{-1}$
2	Medium	Sand, fine sand	10^{-1} to 10^{-3}
3	Low	Silty sand, dirty sand	10^{-3} to 10^{-5}
4	Very Low	Silt, fine sandstone	10^{-5} to 10^{-7}
5	Practically impermeable	Clay	$<10^{-7}$

Table 4: Classification of soil moisture infiltration rate (modified after Scherer et al., 2013).

S/N	Classification	Infiltration Rate (inches/hour)	Infiltration Rate (cm/s)
1	Very slow	less than $6.000x10^{-2}$	$< 4.233x10^{-5}$
2	Slow	$6.000x10^{-2}$ to $2.000x10^{-1}$	$4.233x10^{-5}$ to $1.411x10^{-4}$
3	Moderately slow	$2.000x10^{-1}$ to $6.000x10^{-1}$	$1.411x10^{-4}$ to $4.233x10^{-4}$
4	Moderate	$6.000x10^{-1}$ to $2.000x10^{0}$	$4.233x10^{-4}$ to $1.411x10^{-3}$
5	Moderately rapid	$2.000x10^{0}$ to $6.000x10^{0}$	$1.411x10^{-3}$ to $4.233x10^{-3}$
6	Rapid	$6.000x10^{0}$ to $2.000x10^{1}$	$4.233x10^{-3}$ to $1.411x10^{-2}$
7	Very rapid	greater than $2.000x10^{1}$	$> 1.411x10^{-2}$

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