2-D ELECTRICAL RESISTIVITY TOMOGRAPHY MONITORING OF SOIL MOISTURE DISTRIBUTION IN A RAIN-FED MAIZE PLOT

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Abstract: This study presents the 2-D Electrical Resistivity Tomography (ERT) monitoring of soil moisture distribution on a small maize plot. It was aimed to investigate how soil moisture distribution affects maize plants (*Zea Mays*) growth and development in rain-fed agriculture. Gravimetric and textural analyses were carried out on the soil samples from the plot. Results of both textural and gravimetric analyses revealed a gradual increase in clay content and soil moisture from east-west across the study area. It was observed that area with low clay content of about 4.8% and moisture content of about 17% has high resistivity value of about 1068 ohms metre (Ωm) where as higher clay content of about 12.7% and moisture content of 20% has low resistivity of about 33 Ωm. High soil resistivity in the eastern part of the field is composed of material texture with less clay content and higher infiltration while low soil resistivity in the western part has material texture with more clay content and lower infiltration. Maize planted on moderate infiltration and low resistivity soil retained moisture with luxuriant growth during shortage of rainfall where as higher infiltration and high resistivity soil was affected by wilting and stunted growth with poor yield.

Keywords: Electrical resistivity tomography, gravimetric analyses, texture, rain-fed agriculture

Introduction

Inadequate rainfall in recent years in Sub-Sahara Africa has resulted in high prevalent of food scarcity across the region (Makurira, 2010). This insufficient rainfall has caused wide spread ravaging diseases and pestilence in the region. In Nigeria, shortage of rainfall is one of the factors responsible for the low yield and turnout of agricultural produce couple with the fact that a larger percentage of the farmer's population engaged in small scale farming using orthodox method of farming. Moreover, the continuing increase in population in Nigeria has also resulted in scarcity and increase in the price of food crop because the available produce cannot carter for the populace.

In Agriculture, irrigation and rainfall are two very important ways soil can be watered since crop plants need soil with adequate moisture for plant growth during the planting season. Low rainfall is responsible for poor soil moisture distribution in the vadose zone which will lead to wilting and ultimately poor crop growth and yield. Soils derived from pre-existing rocks consist of sand, clay, silt, moisture, minerals and air in a heterogeneous form. Percentage composition of these soil constituents (sand, silt and clay) defined its texture. Soil texture and moisture distribution are two major factors influencing crop growth and development. These two factors are related because texture of a soil influences the movement of water (moisture) through the soil. The soil moisture and air usually filled the pore spaces (texture) in the soil and plants taps their nutrients directly from it with the aid of their root system. After rain or irrigation, the pore spaces in soil are filled up with water and gravity slowly drains away excess water through the soil to accumulate below the water table. As the water drains away air (oxygen) is pulled into the pore spaces, creating a good environment for plant roots to enhance growth and development of the plant (MEA, 2017).

Poor understanding of the soil from which plants derived its nutrients is a major reason for poor growth and development of crop because a good understanding of the soil water content (SWC) distribution at the field scale is essentials to improve the management of water, soil and crops (Beff *et al.*, 2013), since, soil moisture and nutrients balances are essential ingredients for good crop yields (Makurira, 2010). Gravimetric measurements can determine soil moisture content from soil cores (Sharp and Davies, 1985). They are known to determine correctly the soil water content but they can only give local measurement and are usually destructive (Beff *et al.*, 2013). Since, soil texture affects the movement and availability of air, nutrient and water in a soil, it is important to determine soil texture before farmers embark on planting to know the soil retention capacity which is a function of crop growth and development. This can be determine in the field based on the length of ribbon the soil can be formed without breaking and a table of field characteristic of different texture can be found in Mc Donald *et al.* (1998).

Electrical resistivity is influence by soil moisture distribution. Therefore, electrical resistivity is a very useful method to study soil moisture distribution because it is responsive to fluid. Electrical resistivity method involves the passage of electric current into the subsurface through two electrodes and subsequently measuring the potential difference on separate electrodes. The soil moisture content is a property of the soil and the presence of water in the soil will make the soil to be more electrically conductive (Sheets and Hendrickx, 1995). Electrical resistivity tomography is an appropriate tool to monitor the impact of plant competition for soil moisture because it has been found promising in spatially measuring of soil water variations and distribution in a field scale (Garre *et al.*, 2013). It has been adopted by several researchers to investigate soil moisture variations and distribution in the vadose zone. It was used to monitor: water use of agricultural crops (Michot *et al*., 2003; Amato *et al.*, 2009; Garre *et al.*, 2011), soil water content distribution in a maize field (Beff *et al.*, 2013), soil moisture dynamics in two different cropping systems (Garre *et al.*, 2012), plant and soil water relationships (Brillante *et al*., 2015) and soil water relationship in heterogeneous soil system (Michot *et al.*, 2015). Resistivity imaging has also been used to map the spatial and temporal changes in moisture content in response to sustained drought and rainfall (Gunn *et al.*, 2014). These researchers show how ERT has been used to investigate soil water distribution in a field scale but studies on monitoring of effect of soil texture on soil moisture distribution are rare to the best of my knowledge. This paper focuses on the use of ERT in monitoring the soil moisture distribution in two slightly different soil textures in a maize plot.

Materials and Methods

Study site location, topography and climate

This study was conducted between 27 April 2016 and 27 May 2016 in a small maize farm, located within the premises of Federal University Oye-Ekiti. The site is relatively flat (Fig. 1). The climate condition is hot characterized by dry and wet seasons. The dry season occurs between November and March. The wet season lasts between April and October, with July and September recording the highest rainfall. The average annual rainfall is about 1334.2 mm. The maize crop is planted in rows running from East to West. A profile X-Y of about 4.5 m was chosen in the middle of the plot for ERT data and sample collection.

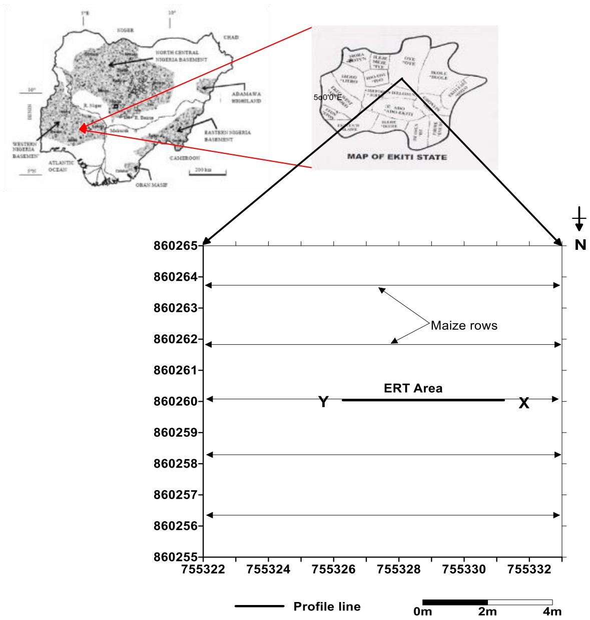

Fig. 1: Location map showing the study site

Resistivity of rock and soil

The relationship between resistivity in sands and gravels and other various factors was first established by Archie's Equation [1] (Archie, 1942). It shows that conduction (current flows) in the near surface rocks and soil is majorly electrolytic, which takes place in connected pores spaces around non-conducting grain boundaries. Therefore, ground resistivity is dependent on the composite soil or rock, which is controlled by the amount of moisture stored within the pore spaces and the ionic distribution about grain surfaces (Gunn et al., 2014).

$$\rho = a\rho_w \varphi^{-m} S_w^{-n} \quad (1)$$

Where: a = compaction factor, S = saturation (0<S<1), φ = porosity, m = cementation factor, n = saturation factor.

Whereas, clay soils are typically characterise by electrically conductive minerals and exhibits the lower resistivity values because clay particle acts as a separate conducting path in addition to the electrolyte path. The abnormally high clay conductivity lies in the double layer of exchange cations. The effect of cations exchange capacity of clay minerals in soil increases the electrical conductivity of the soil and thereby lowering the resistivity of the medium. Waxman and Smits (1968) have developed a relationship (Equation [2]) between clay resistivity and moisture content which is controlled by both the conductive minerals and cations exchange capacity.

$$\rho = \frac{a\rho_w \varphi^{-m} S^{(1-n)}}{(S+\rho_w BQ)} \quad (2)$$

Where: B = conductance of cations in double layer, Q = cations exchange capacity per unit pore volume.

The commonly occurring rocks and soils resistivity ranges are shown in the Fig. 2. It is apparent that there is a considerable overlap between different rock types and, consequently, identification of a rock type is not possible solely on the basis of resistivity data (Kareay *et al*., 2002).

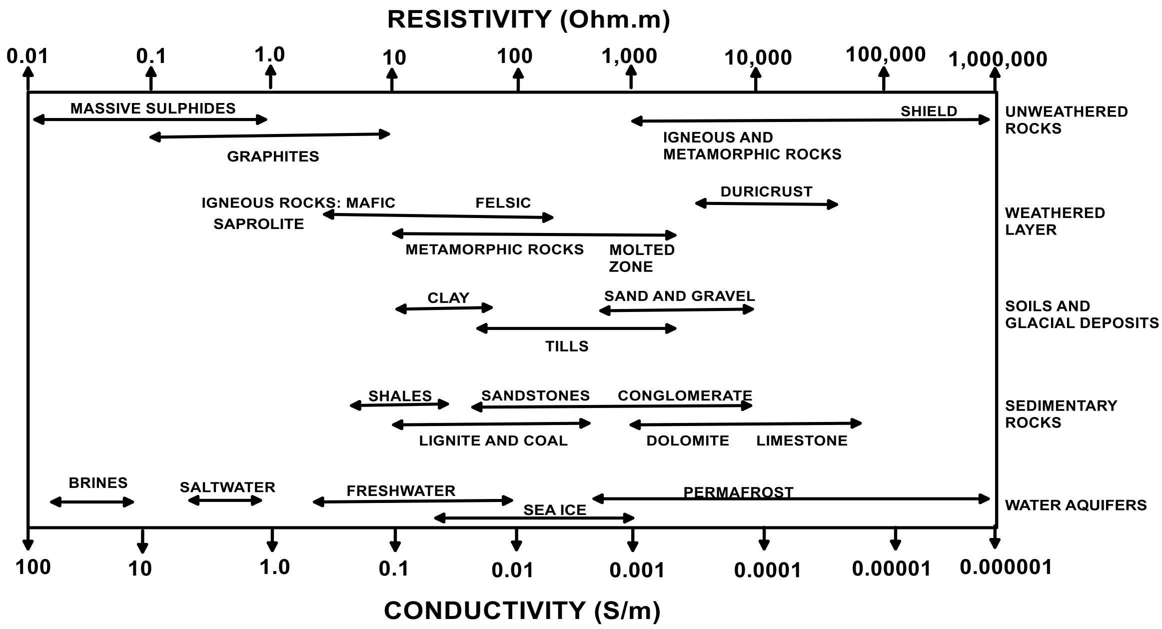

Fig. 2: Resistivities range for soils, water, rocks and minerals

The resistivity of a material can be defined as the resistance between two opposing faces of a unit cube of the material. If we consider a current flow, I in a cylinder of length, L the resistance, R of the material is directly proportional to the length of the resistive material and inversely proportional to the cross sectional area, A (Reynolds, 1997).

$$R \propto \frac{L}{A} \quad (3)$$

Then,

$$R = \rho \frac{L}{A} \quad (4)$$

Where ρ is the constant of proportionality, resistivity and R = $\frac{V}{I}$ ohm's law, V is the potential difference.

Therefore equation (4) can be given as,

$$\rho = \frac{V}{I} X \frac{A}{L} \quad (5)$$

Electrical Resistivity is measured in the field using four co-linear electrode inserted into the ground consisting of two current electrodes and two potential electrodes. The depth of investigation is a function of the type of array used.

Materials and Method

Geophysical investigation

Wenner array was used for data acquisition, because it allowed the greatest number of measurements for the number of electrodes present, which was advantageous for data inversion. The depth of investigation for Wenner array is related to the common spacing, a, between the current and potential electrode pair as shown in the Fig. 3.

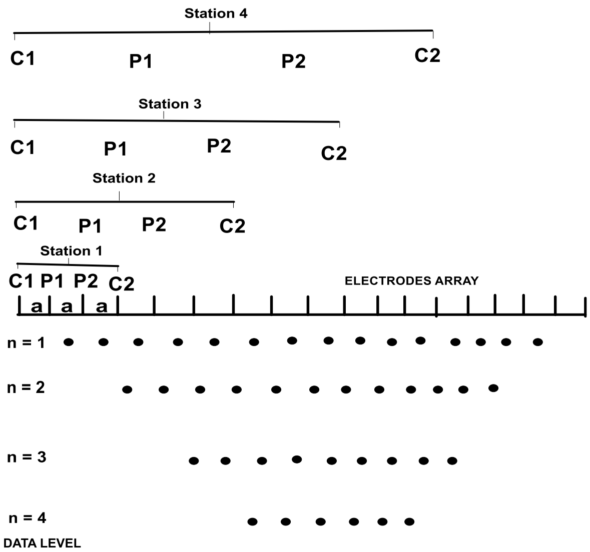

Fig. 3: The measurement sequence for building a pseudosection and an array of electrodes for Wenner configuration

Moreover, the Wenner electrode arrangement is sensitive to lateral changes in resistivity. Ten (10) ERT measurements were performed between 27 April 2016 and 27 May 2016 in the maize plot with the Soil tester R-50 resistivity meter. The accuracy of the instrument is 0.3% which agrees with the measured data. The readings were taken along the profile X-Y at the middle of the maize plot. The four electrodes were lined up in a graduated constructed wooden box with a lever to insert it into the ground for measurement. Four data sets were taken in each day of data acquisition as shown in Figure 3. The first measurement was taken at an electrode spacing, a = 0.25 m, followed by 0.5 m, 0.75 m and lastly 1 m electrode spacing. The surveyed length is 4.5 m long. Resistivity data were collected to generate 2-D resistivity structure of the subsurface (pseudosection) (Fig. 3).

The gravimetric and soil textural analysis

Gravimetric and soil textural analysis was carried out to validate the geophysical investigation.

Gravimetric analysis

Four soil samples were collected for gravimetric analysis from the composite soil in the plot along the profile X-Y (Fig. 1) and were weighed and then oven dried at 75°C for 24 h. The samples were measured at regular interval to know the amount of water loose with respect to the time of drying in order to determine the actual time it will dry completely. After it was completely dried, the samples were reweighed. The amount of weight loss is the amount of moisture present in each soil sample.

Moisture is expressed by the formula:

% soil moisture (θ) = ((mass of fresh sample – mass of dry sample/mass of dry sample) * 100

Soil textural analysis

Field or hand texturing was conducted on two samples using ribbon test before planting was done. The first sample was collected at the eastern part of the plot and the other at the west along the profile X-Y (Fig. 1). The ribbon test was carried out by moistening the samples with a little water and threading a small handful of the soil into a ball (bolus) for 2 min after removing its gravel content (Fig 4a). The bolus was placed between the thumb and forefinger and pressed out to form a ribbon (Fig. 4b). The length of the ribbon produced was measured. The length produced before it breaks characterise the field texture.

Fig. 4: Field soil textural analysis (a) threading of soil into bolus (b) bolus pressed out to form a ribbon

Results and Discussion

Soil texture analysis

Figure 4 shows field textural analysis performed on the different samples taken along the profile. Sample A was taken 1.0 m away from the X while sample B was taken 3.0 m away from Y. Sample A is 7.8 mm ribbon length and sample B is 16.7 mm ribbon length. Using the table of field characteristic of different textures from Mc Donald *et al*. (1998); sample A is clayey sand while sample B is sandy loam. The result shows that the soil samples vary between clayey sand in the eastern X end of the profile to sandy loam at the western Y end. The eastern part could not retain moisture after rain because the soil texture allows high infiltration as a result of less clay compare to the western part with moderate infiltration with higher clay content. This is evident in the sudden wilting experienced by the crop in the eastern part while the western part is mild as shown in Plate 3a&b.

Gravimetric estimation analysis

Table 1 show the result of the four samples collected at 0.25 m depth from the plot along the profile from east to west on 27/04/16. Soil moisture content was estimated for Sample 1 to be 14% at 0.25 m away from the eastern end of the profile. Sample 2 was taken at 1.25 m and the soil moisture content estimated at this point was 14% which is the same with Sample 1. Sample 3 was collected at 3.25 m along the same profile and the soil moisture content estimated at this point was 17%. Sample 4 was collected at 4.50 m and the soil moisture content of 20% was obtained for this point.

Table 2 shows the result of second experiment that was performed on 06-05-16, eight (8) days after the first rain. The two soil samples were collected at about 0.5 m depth. Sample 5 was taken at 0.5 m depth and at the eastern end of the plot along the same profile line; the moisture content was estimated to be 12.8 % at this point. Sample 6 was collected at 0.5 m depth and at 3.25 m along the traverse; the moisture content was estimated to be 17.4%, indicating higher moisture content compare to sample 5. The results show that moisture content increase from east to west along the profile in the study site. This is correlated with the result obtained from the textural analysis section 4.1 because the soil texture obtained for sample A in the eastern part supported higher infiltration than that of sample B in the western end.

Table 1: Shows the result of soil moisture estimated from gravimetric method at 0.25 m depth on 27-04-2017

Samples nos	Mass of empty dish(g)	Mass of wet soil + dish(g)	Mass of wet soil(g)	Oven dry after 1 h	Oven dry after 2 h	Oven dry after 7 h	Oven dry after 11h	Oven dry after 16h	Dried soil + Dish (g) after 24h	Dried soil(g)	Soil moisture %
1	147	906	759	837	832	813	812	812	812	665	14
2	170	824	654	767	762	747	745	745	745	575	14
3	172	902	730	831	826	801	798	799	799	626	17
4	151	842	691	766	760	729	726	726	726	575	20

Table 2: Shows the result of soil moisture estimated from gravimetric method at 0.5 m depth

Samples nos	Mass of empty dish(g)	Mass of wet soil + dish(g)	Mass of wet soil(g)	Oven dry after 1 h	Oven dry after 2 h	Oven dry after 7 h	Oven dry after 11h	Oven dry after 16h	Dried soil + Dish (g) after 24h	Dried soil(g)	Soil moisture %
5	170	593	423	561	546	545	545	545	545	375	12.8
6	173	490	317	459	443	443	443	443	443	270	17.4

Pseudosection

Figure 5 shows the 2-D resistivity distribution within 0.75 m depth of the subsurface in the East-West direction. Since the average depth of maize root in the field is about 0.20 m, the interested depth of investigation is shallow between 0 – 0.5 m. The 2-D resistivity structure shows the variation in resistivity distribution within the vadose zone. High resistivity values ranging from 150 to 468 Ωm were observed within the root zone of the maize plant (0.0 - 0.25 m) and down to 0.75 m depth in the Eastern (X) part of the plot during the second day of the first rainfall, where as in the central towards the western part lower resistivity values ranging from 150 to 42 Ωm were observed. The maize responded well to the increase moisture in the subsurface as shown in Plate 1.

Plate 1: Maize plant respond to rainfall after a prolong shortage

27-04-16

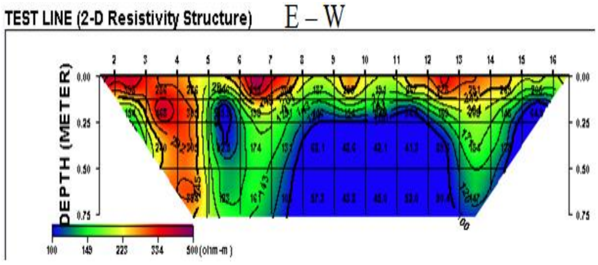

Fig. 5: Shows the soil 2-D resistivity distribution of the subsurface after rainfall

06-05-16

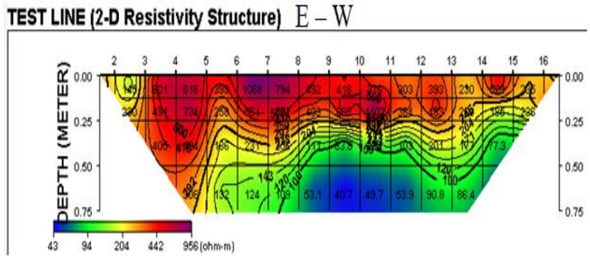

Fig. 6: Shows 2D resistivity distribution of the subsurface after a delayed rainfall

Plate 2a: Maize plant in the western part with fresh leaves

Plate 2b: Maize plant in the eastern part with wilted leaves

Figure 6 shows the resistivity distribution within 0.75 m depth in the subsurface in East West direction, high resistivity values were recorded in the first 0.0 - 0.25 m depth and 1 m away from the Eastern (X) part of the plot. The eastern part of the plot recorded higher resistivity values between 340 – 1068 Ωm compared to lower resistivity values between 180 - 430 Ωm which were recorded towards the western part of the plot at the same depth. It was observed that the resistivity of soil has increased significantly due to shortage of rainfall for a peroid of eight days, during this period the soil moisture within the root zone of the maize plant has reduced due to infiltration. The inadequate rainfall has resulted in the higher resistivity values of the soil because the soil moisture in the topsoil has drained downward.

Plates 3a&b show the impact of the reduced soil moisture on the maize plant during the short period of inadequate rainfall, thereby subjecting the maize to wilting. Maize plants behave differently in each half of the plot. Maize plants at the western part (Plate 2a) was more luxuriant than those at the eastern part because of the adequate soil miosture content available in the western part as a result of higher retention capacity of the soil in that area. The maize plants at eastern part (Plate 2b) has lame stem because of the reduced soil water content which was resulted in high resistivity recorded in Fig. 6.

13-05-2016

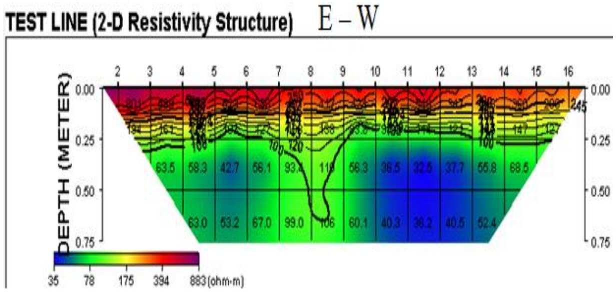

Figure 7: The soil 2-D resistivity distribution during a sufficient rainfall period.

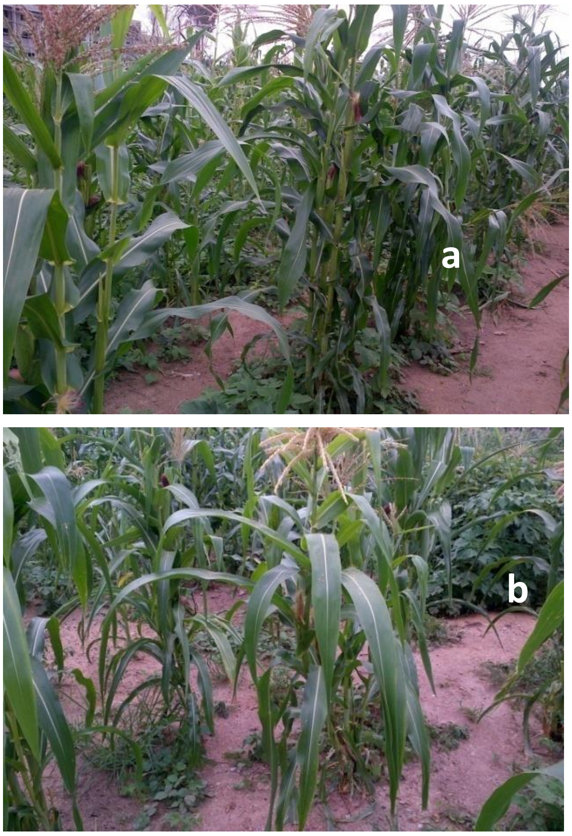

Plate 3: Maize response to prolonge rainfall in different soil texture (a) sandy loam soil (b) clayey sand soil

Fig. 7 shows the resistivity distribution within 0.75 m depth in the subsurface in the direction of east to west.

Low resistivity value of approximately 100 Ωm were observed across the length of the profile at about 0.25 m which falls approximately within the root zone of maize but lower resistivity value of about 33 Ωm were also observed between 0.25 and 0.50 m depth. The area has recorded a sufficient rainfall during this period and the soil moisture has increased as shown in the 2-D resistivity structure. The 2-D structure shows that the subsurface probably has abundant soil moisture even within the root zone of the maize because of the low resistivity recorded across the profile. It can be concluded that between 27th April and 6th May there was decrease in the amount of water within the vadose zone, as a result of insufficient rainfall as observed in Fig. 6 but between 11th May and 13th May it is obvious that the effect of the wilting has disappear as shown in Plate 3 above. However, the maize crop plant in eastern end of the profile had stunted growth compare to the better growth of maize plant observed at the western end of the profile as shown in Plate 3.

Summary and Conclusion

2-D Electrical Resistivity Tomography was used to monitor the soil moisture distribution in a small plot of maize crops located within the premises of Federal University Oye-Ekiti, Ekiti State. The 2-D resistivity structure shows the variation in electrical resistivity distribution within the vadose zone in a maize plot during the 5 weeks of monitoring between 27th April 2016 and 27th May 2016. The 2-D resistivity structure was able to delineate areas with high and low resistivity values. The highest resistivity value observed in the study area was 1068 Ωm during eight days of delayed rainfall and the lowest was 43 Ωm at the same location during the period of abundant rainfall. High resistivity values ranging between 351 and 1068 Ωm were observed at 0.25 m depth, within the root zone of maize, in the eastern half of the profile X-Y while low resistivity values ranging between 33 and 430 Ωm were also observed towards the western half of the profile at the same depth. The maize crops in the eastern half of the plot had stunted growth compare to the maize at the western half which had good growth. It was evident from the result of the textural analysis that the eastern part is predominantly clayey sand which has higher infiltration with low to moderate water retention capacity as a result of less clay content while the western part is predominantly sandy loam which has lesser infiltration with moderate water retention capacity as a result of higher clay content.

The result of gravimetric analysis shows that the area with higher resistivity has low soil moisture content while area with low resistivity has higher soil moisture content. The result revealed the impact of uneven soil moisture distribution on the growth and development of the maize crop because of changes in soil texture in the study area. The estimated soil moisture content also validated this result because area with high resistivity values has low soil moisture content with poor growth while area with low resistivity values has high soil moisture content with good growth.

In conclusion, this study has demonstrated that 2-D ERT is capable of monitoring the effect of soil moisture distribution on a maize crop in different soil textures within the vadose zone. It has been shown that the amount of soil moisture present in a particular plot of land is a function of the soil texture and consequently a determinant of the growth of plant. The area in the study with high soil resistivity is composed of material texture with less clay content and higher infiltration while low soil resistivity has material texture with more clay content and moderate infiltration. The material texture with moderate infiltration and higher clay content supported better growth than material texture with higher infiltration and lesser clay content.

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References

Amato M, Bitella G, Rossi R, Gómez JA, Lovelli S & Gomes JJF 2009. Multi - electrode 3D resistivity imaging of alfalfa root zone. *Eur. J. Agron*., 31: 213–222.

Archie GE 1942. The electrical resistivity log as an aid in determining some reservoir characteristics. *Trans. American. Inst. Min. Metall. Pet. Eng*., 146: 54–67.

Beff L, Gunther T, Vandoorne B, Couvreur V & Javaux M 2013. Three-dimensional monitoring of soil water content in a maize field using electrical resistivity tomography. *Hydrology and Earth System Sciences*, 17: 595-609.

Brillante L, Mathieu O, Bois B, Leeuwen C & van Lévêque J 2015. The use of soil electrical resistivity to monitor plant and soil water relationships in vineyards. *Open Access SOIL*, 1: 273–286.

Garré S, Coteur I, Wongleecharoen C, Kongkaew T, Diels J & Vanderborght J 2013. Non-invasive monitoring of soil water dynamics in mixed cropping systems. A case study in Ratchaburi Province, Thailand. *Vadose Zone J*., 12: 1–12.

Garré S, Günther T, Diels J & Vanderborght J 2012. Evaluating experimental design of ERT for soil moisture monitoring in contour hedgerow intercropping systems. *Vadose Zone J*., 11: 14pages, doi:10.2136/vzj2011.0186.

Garré S, Javaux M, Vanderborght J, Pages L & Vereecken H 2011. Three dimensional electrical resistivity tomography to monitor root zone water dynamics. *Vadose Zone J*., 10: 412–424. doi:10.2136/vzj2010.0079.

Gunn DA, Chambers JE, Uhlemann S, Wilkinson PB, Meldrum PI, Dijkstra TA, Haslam E, Kirkham M, Wragg J, Holyoake S, Hughes PN, Hen-Jones R & Glendinning S 2015. Moisture monitoring in clay embankments using electrical resistivity tomography. *Construction and Building Materials*, 92: 82-94.

Kareay P, Brooks M & Hill I 2002. An Introduction to Geophysical Exploration. Third Edition. Blackwell Science Ltd.

Makurira H 2010. Water Productivity in Rainfed Agriculture: Redrawing the rainbow of water to achieve food security in rainfed smallholder systems, CRC Press/Balkema, Ph.D. Thesis, Delft University of Technology.

McDonald RC, Isbell RF, Speight JG, Walker J & Hopkins MS 1998. Australian Soil and Land Survey Field Handbook, Australian Collaborative Land Evaluation program: Canberra.

MEA 2017. Soil, Texture and Moisture, Measurement Engineering Australia, an online publication.

Michot D, Thomas Z & Adam I 2015. Non-stationarity of electrical resistivity and soil moisture relationship in heterogeneous soil system: A case study. *SOIL*. 2: 955-994.

Michot D, Benderitter Y, Dorigny A, Nicoullaud B, King D & Tabbagh A 2003. Spatial and temporal monitoring of soil water content with an irrigated corn crop cover using surface electrical resistivity tomography. *Water Resour. Res*., 39: 1138-1143.

Reynolds JM 1997. An Introduction to Applied and Environmental Geophysics. Wiley, Chichester.

Sharp RE & Davies WJ 1985. Root growth and water uptake by maize plants in drying soil. *J. Exp. Bot*., 36: 1441–1456.

Sheets KR & Hendrickx JMH 1995. Non-invasive soil water content measurement using electromagnetic induction, *Water Resources. Res.*, 31: 2401–2409.

Waxman MH & Smits LJM 1968. Electrical conductivities in oil-bearing shaly sands. *Soc. Pet. Eng. J*., 8: 107–122.