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Electrical Geophysical method and GIS in Agricultural Crop Productivity in a Typical Sedimentary Environment

K.O. Ozegin and S.O. Salufu

Department of Physics, Ambrose Alli University, Ekpoma Edo, Nigeria

ABSTRACT
Accurate information about soil properties is required in plant growth and yield. Hence, the rising knowledge in the preservation of favourable soil properties is basically driven by its vital role in agricultural crop productivity. Electrical Resistivity Tomography (ERT) and GIS were used for site selection, soil suitability for agricultural use and topographical effect on soil properties distribution in Ambrose Alli University. Twelve traverses were conducted across the study area using Wenner array configuration. The least-square inversion method was adopted for the inversion model using RES2Dinver. Seven soil samples were collected from the selected site for soil test and grain analysis using IS standard in order to validate the ERT results. The results of the ERT gave resistivity signatures in the form of colour variations that depict the organic matter and mineral constituents of the soil. Soil in the valley side of the study area showed low resistivity signatures < 100 Ωm, slopy portion ranged from 100 to 600 Ωm, and soil at the top of the slope has resistivity values > 600 Ωm. GIS results generally classified spatial distribution of soil parameters across the area. Soil with low resistivity values < 100 Ωm has Organic Matter (OM): 4.27–4.80 %, Phosphorus (P): 50.23–54.22 mg/kg, Potassium (K): 290.0–340.0 cmol/kg, Total Nitrogen (TN): 62.20–65.11%, and pH: 6.8 to 6.9. Soil with resistivity values ranging from 100 to 600 Ωm has OM: 2.21–2.75%, P: 30.14–34.00 mg/kg, K: 100.2–107.2 cmol/kg, TN: 54.00–59.20%, and pH: 6.7–6.8. Soil with resistivity values > 600 Ωm showed lowest value ranges for OM: 0.51–0.61%, P: 10.20–15.20 cmol/kg, K: 37.20–40.20 mg/kg, TN: 10.20–15.20 %, and pH: 7.0 – 7.2. This study has shown that the study area with resistivity values < 100 Ωm would be most appropriate for high agricultural productivity as well as soil management.

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Electrical resistivity; soil samples; spatial distribution; soil properties; topography effect

1. Introduction

Agriculture is an intrinsically geographical practice that plays a major role in every nation's financial system. The growing demand for food security and sufficiency requires an immediate and quicker scientific technique(s) to investigate the properties of topsoil with the intention of influencing agricultural crop productivity with or without disturbing the soil structure for soil samples collection. In the study of Allred et al. (2008), it was opined that agricultural geophysics is an aspect of geophysics that is exclusively centred on agricultural applications. Agricultural crop productivity is governed by soil properties such as organic composition, mineral composition, soil water and salinity. According to Joshua and Mokuolu (2016), these properties are capable of influencing plant growth and yield; consequently, it should be handled with the utmost importance.

The applications of geophysical methods such as electrical methods have progressively and systematically made its way to the top within a wide range of agricultural geophysics. Geophysical methods have the ability to characterise the properties of soil that influence the flow and storage of soil water, making such methods relevant for plant-related application (Jayawickreme et al. 2014; Shanahan et al. 2015; Whalley et al. 2017; Zhao et al. 2019; Cimpoiaşu et al. 2020). Hence, the significance of soil properties on agricultural yield cannot be overstated in precision agriculture. The goal of precision agriculture is to enhance or optimise crop production while minimising harmful environmental consequences. In soil investigations using geophysical method(s), attention is regularly centred on a distance from the soil surface to a depth of two metres. Evidently, this is because, according to Allred et al. (2008), this interval of depth in general contains the entire soil profile, as well as the crop root precinct.

Geographic Information System (GIS) is a computer oriented system that is used to capture, store, analyse, manage, model and display spatially referenced data and is used to provide solutions to a wide range of problems in numerous fields of endeavour such as agriculture, geography, aviation, engineering, geology, environment, astronomy, archaeology and architecture (Abbas and Amanabo 2017). In order to identify the potential land for any particular crop, GIS is the best technique as it brings all the data on a single platform for the analysis. The ability of GIS to study and envisage agricultural environments and workflows has proved to be favourable to those involved in the farming industry (Acharya 2018).

CONTACT K.O. Ozegin ozeginkess@yahoo.com Department of Physics, Ambrose Alli University, Ekpoma Edo, Nigeria

The organic composition that is defined as the summation of plant and animal residues at various stages of decomposition, of cells and tissues of soil organisms, and well-decomposed substances (Brady and Weil 1999) provides a significant lasting supply of nutrients. This means that organic composition exemplifies a reservoir of nutrients and water in the soil, serves in reducing compaction and surface crusting, and enhances water infiltration into the soil. This represents roughly 35–50% of the entire soil organic composition. Humus contributes greatly to soil's capacity to maintain organic matter on substitute sites (Prasad and Power 1997). Organic chemicals that are dissolved act as a "sealant" in order to join soil particles, thus improving agglomeration and boosting in general soil aeration, water penetration and preservation (McCauley et al. 2009), which in turn affects the resistivity of the upper geologic strata in which they exist.

The mineral composition forms the greater percentage of the volume of soil, and it consists of gravels, stones, sand, silt and clay. Soils high in clay, shale, and silt cause decomposition rate to slow, resulting in less rapid release of nutrients, while sandy soils as a consequence improved breakdown in addition to fast discharge of organic matter to the soil (McCauley et al. 2009). Soils high in clay, shale, and silt will subsequently lead to a corresponding decrease in the resistivity values of the topsoil in the area so affected.

Soil water is characteristically obtained from rain or irrigation and is typically found in the soil within the pore spaces. The ability of soil to hold on to water accessible to plants is defined as soil water availability. When the soil is wet, plant roots can easily extract the soil water, while in dry soils, the soil water is strongly bound to the matrix and is less readily available to the crop. Its significance changes with the frequency of wetting and the duration of the dry periods (Verdoodt and Ranst 2003). It aids the absorption of essential nutrients from the soil by the plants in its photosynthesis process. The amount of soil water in a formation affects the resistivity of the formation (Telford et al. 1990; Lowrie 1997; Sharma 1997; Garg 2007).

Most crops are highly sensitive to salinity caused by the concentration of salts in the soils. Salinity is often linked with water-logging occurring from high water table conditions, where there is upward movement of salts at least some of the time due to evaporation (Tanji 1990; San Joaquin Valley Drainage Program 1990); and hydrologic imbalance from disturbing the natural vegetation that occurs when pasture lands that have been overgrazed cause an imbalance between precipitation and evapotranspiration (Holmes and Talsma 1981; Halvorson 1990). Low soil salinity is usually characterised by relatively high resistivity values (>100 Ωm), as indicated by Roberge (2000) and Ozegin et al. (2011).

Before planting, soil investigation could engage the conventional method of perturbing the soil in order to remove soil samples and then proceed to analyse it in the laboratory. This can also be carried out using the non-invasive geophysical method such as electrical resistivity investigation, which permits quick measurement of soil electrical properties directly from the soil surface to a required depth without soil disturbance (Omar 2012), and this is also true for GIS. Swinton and Lowenberg-deboer (1998) noted that if soil samples are collected with the intensiveness suitable for significant precision agriculture management, the sampling costs would exceed any potential benefits from the site-specific approach. An understanding of the spatial and temporal variability in the properties of soil (precision farming) using the electrical geophysical method and GIS will enhance the agricultural produce as well as soil management. Therefore, it is desirable to investigate the subsurface soil properties in the study area with a view to ascertaining the soil condition in order to select the most suitable site for agricultural use and, where possible, the degree of occurrence of these properties using deductions from the integration of electrical resistivity tomography survey and geographic information system.

1.1. Site description and geological setting

The study area is located within the main campus of Ambrose Alli University, Ekpoma, Edo State, Nigeria (Figure 1). The university campus is situated on the northwestern flank of Ekpoma, which is the headquarters of Esan west local government Edo State, Nigeria. The University, which occupies an area of about 7.3 km^2, lies within the tropical region between latitudes 6° 4′ 00" N and 6° 7′ 03" N and longitudes 6° 1′41" E and 6° 11′55" E (Figure 1). The area is accessible through Benin-Auchi thruway. The study area is interconnected with a network of roads and foot paths (Figure 1). The landscape of the area is generally characterised by high topography that ranges from 1020.00 to 1030.00 ft forming a plateau. The plateau has been subjected to seasonal erosional activities that have modified the topography to slightly slopy landscape from the eastern part of the study area towards the western part as shown by the cross section of the area in Figure 1.

The study area falls within the Edo State arm of Anambra Basin. The Anambra Basin is located west of the Lower Benue Trough. The basin was formed as a result of Santonian tectonic event that affected the floor of the basin. Anambra Basin derives its sediments from the erosion of the Abakaliki Anticlinorium, which had become the major site of deposition in Late Cretaceous–Eocene time (Airewele et al. 2020). The study area is majorly underlain by Bende-Ameki Formation, which comprises two major facies; lateritic sandstone facies and organic silty sandstone facies (Figure 2)

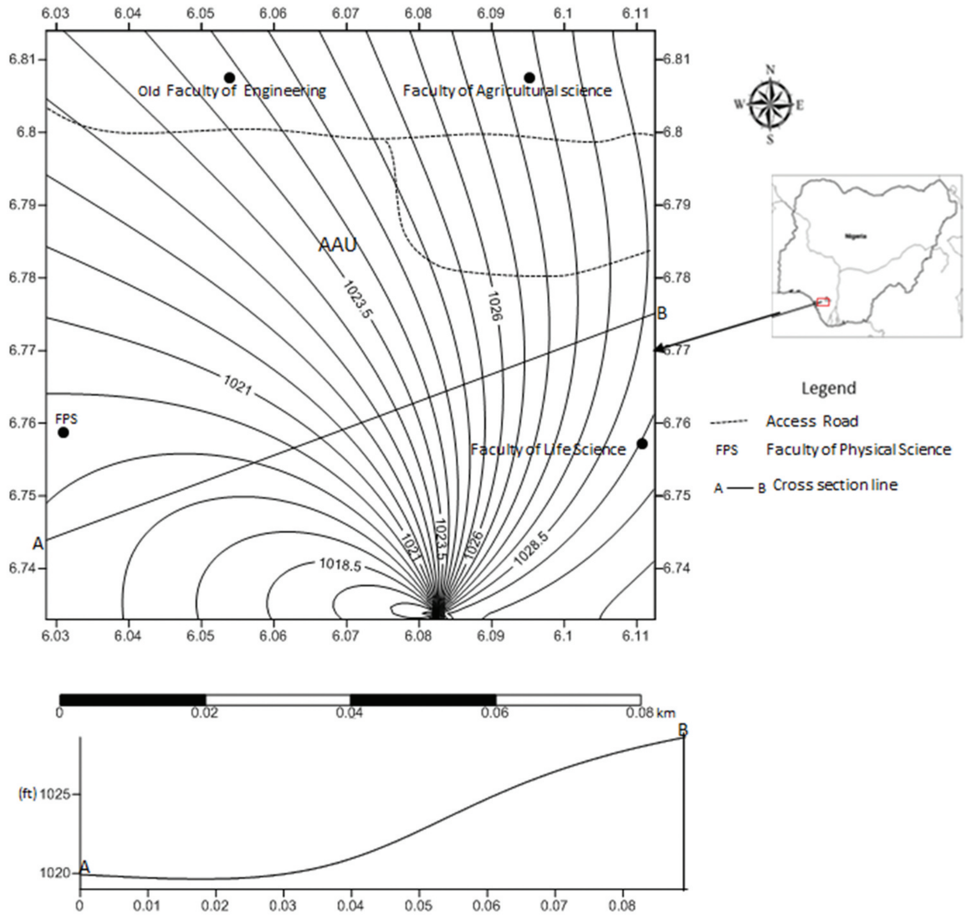

Figure 1. Location and accessibility map of the study area.

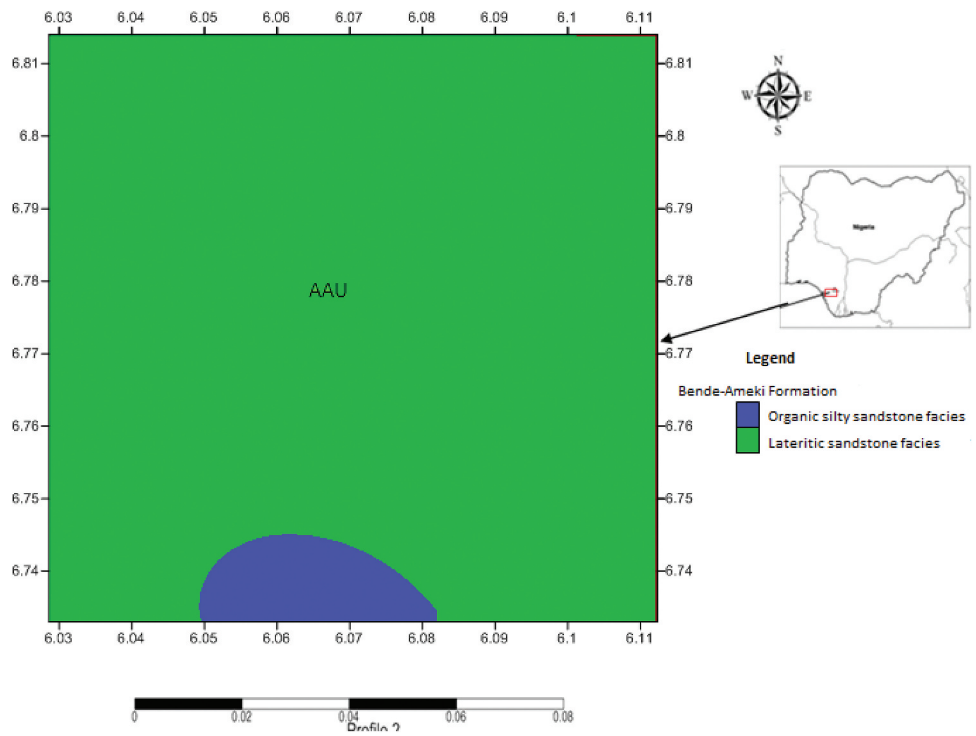

Figure 2. Geological map of the study area.

2. Materials and methods

Geophysical investigation was carried out using ERT to ascertain the soil mineral and nutrient compositions in the study area. The wenner array configuration was adopted in this study because it has better depth resolution, less susceptibility to acquisition noise and higher signal strength, and it requires fewer measurement points for the same line coverage than the dipole–dipole array. Also, the apparent resistivity of the Wenner array is easily calculated in the field. It is a co-linear array in which all four electrodes are arranged in a straight line, while current was passed through the earth by means of a pair of current electrodes C_1 and C_2 while measuring the potential difference by the potential electrodes P_1 and P_2, which were placed at an equal distance or interval "a" along or across the line of electrode, as shown in Figure 3 (Telford et al. 1990; Reynolds 2011; Ozegin and Oseghale 2012). Twelve traverses were mapped out in the study area along which the ERT data was acquired using SAS 1000 ABEM and geo-referenced. The electrode cables were oriented in the *x*-direction, which is approximately north to west for the first ten traverses, while measurements using a *y*-spacing of 2 m were carried out simultaneously; hence, the total area of investigation was 30 m x 18 m plot of farmable land for the first ten traverses. Conversely, traverses 11 and 12 were oriented approximately south to west for the same measurement (Figure 4). The Wenner array was employed with 2 m, 4 m and 6 m electrode spacing, which gave a data set of 30 data points for each traverse line. The inversion model was carried out using RES2DINVER. The least-squares inversion method was used to carry out the inversion model.

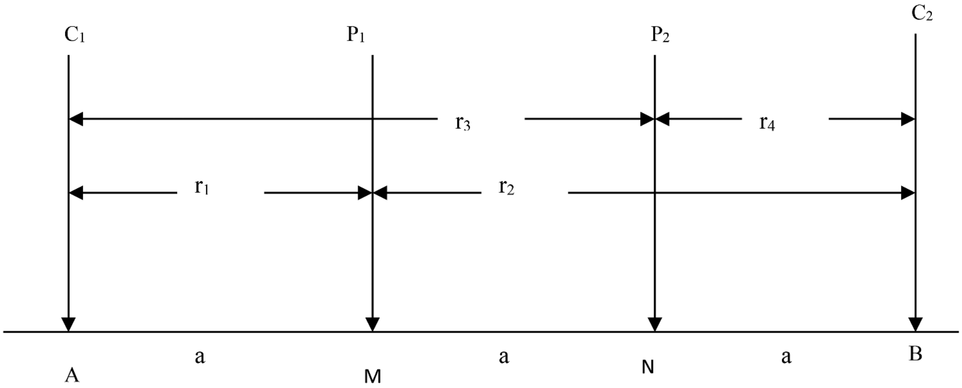

Figure 3. A typical Wenner configuration.

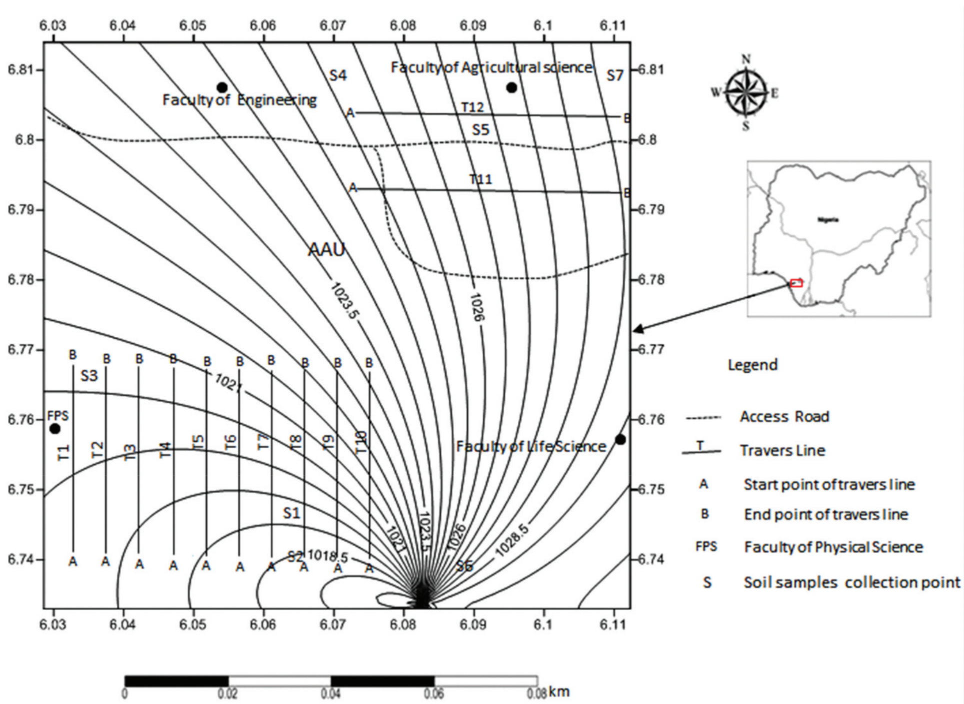

Figure 4. Data acquisition map.

Soil test [for pH, organic matter (OM), phosphorus (P), potassium (K), and total nitrogen (TN)] and textural analysis for sand, silt and clay were done using seven soil samples in the study area (Figure 4). The soil test was done using the international standard method, and particle size analysis (textural analysis) was done using an international standard sieve. Correlation of ERT signatures with soil samples analysis was carried out to delineate the effect of soil parameters on the soil's resistivity in the study area.

Recall from the generalised apparent resistivity (ρ_a) equation that

$$\rho_a = 2\pi R\left(\frac{1}{r_1} - \frac{1}{r_2} - \frac{1}{r_3} + \frac{1}{r_4}\right)^{-1} \quad (1)$$

However, for apparent resistivity for the Wenner array (ρ_{wa}), we have

r $_1$ = a, $r_2 = 2ar_3 = 2a, r_4 = a$

$$\rho_{wa} = 2\pi R\left(\frac{1}{a} - \frac{1}{2a} - \frac{1}{2a} + \frac{1}{a}\right)^{-1} \quad (2)$$

$$\rho_{wa} = 2\pi R\left(\frac{2-1-1+2}{2a}\right)^{-1} \quad (3)$$

$$\rho_{wa} = 2\pi R\left(\frac{1}{a}\right)^{-1} \quad (4)$$

$$\rho_{wa} = 2\pi R\, a \quad (5)$$

where R is the resistance and π (22/7) is a constant.

The theoretical depth of penetration (d) for the Wenner array is approximately 0.115 AB (Telford et al. 1990), where AB is the total current electrode spread length.

A GIS is a thematic mapping system. This means that one can generate maps based on themes such as soils or hydrology. GIS combines location data with both quantitative and qualitative information about the location, allowing you to visualise, analyse, and report information through maps and charts. Spatial analysis is the vital part of GIS. In this study, GIS was used to generate spatial distribution of soil types.

3. Results and discussion

The results of the inversion model for the twelve traverses gave six layers each and model blocks that ranged from 134 to 141 with root-mean-square error ranged from 1.61% to 9.9%, as shown in the inversion model results (Figures 5–16). The soil resistivity signatures were also displayed in colour variation and resistivity values according to mineral constituents of the soil.

Resistivity signatures with values less than 100 Ωm in the ERT results suggest that the soil in such portion of the area studied is rich in organic matter akin to the observation made by Blanco-Canqui and Lal (2007) and Ulrike et al. (2009). It should be noted that the presence of organic matter within the soil indicates that the soil is very fine-grained (silt and clay) that must have given way for partial decay of plants and animals that formed the organic matter. This observation is similar to that of Lowrie (2007). These soil types have

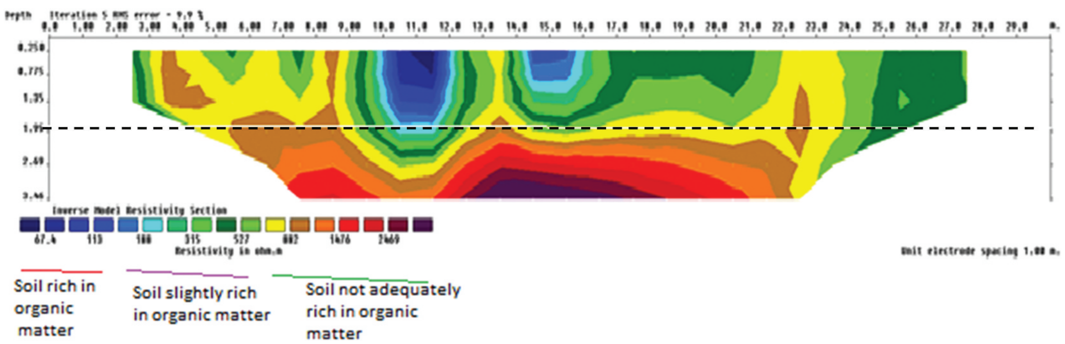

Figure 5. 2D inversion model for traverse 1.

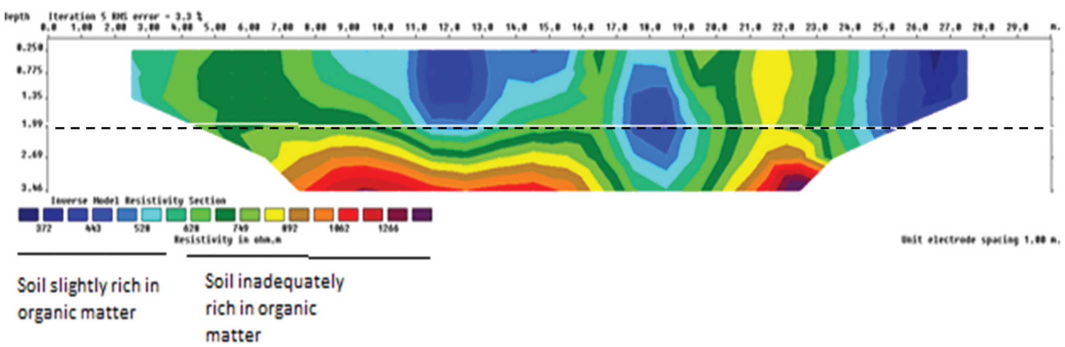

Figure 6. 2D inversion model for traverse 2.

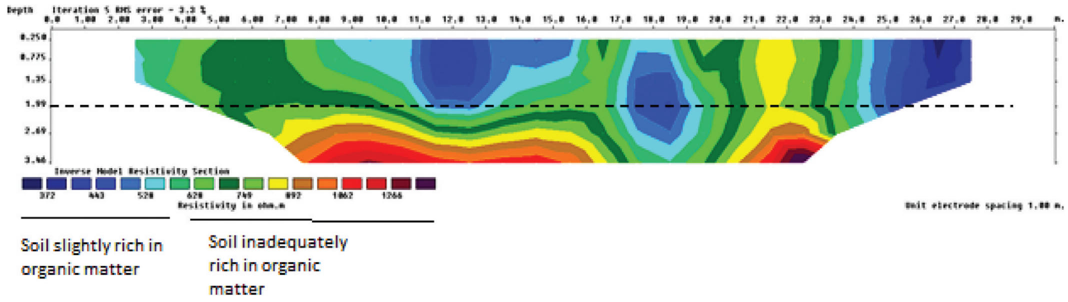

Figure 7. 2D inversion model for traverse 3.

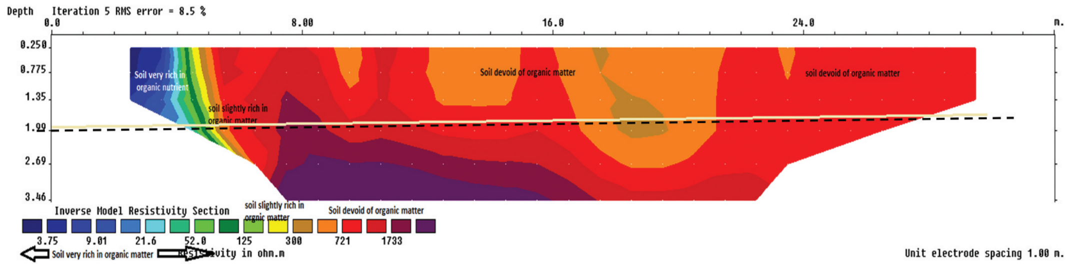

Figure 8. 2D inversion model for traverse 4.

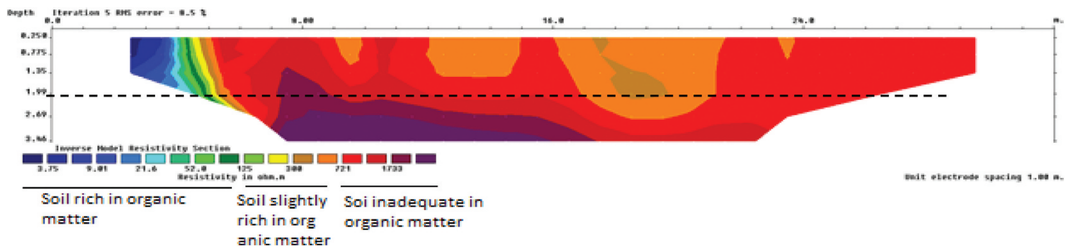

Figure 9. 2D inversion model for traverse 5.

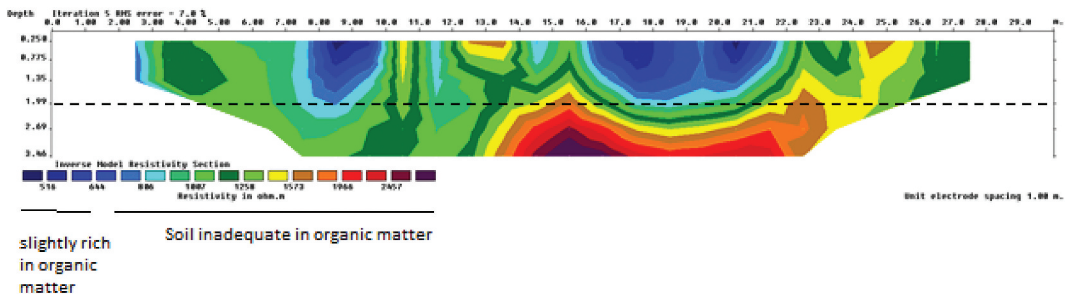

Figure 10. 2D inversion model for traverse 6.

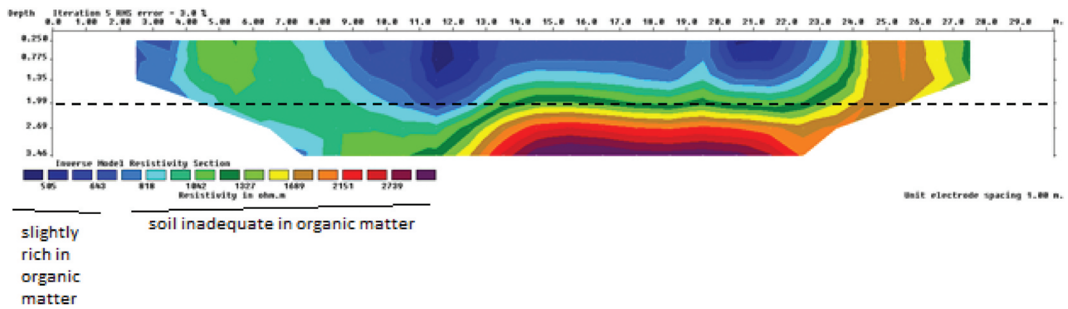

Figure 11. 2D inversion model for traverse 7.

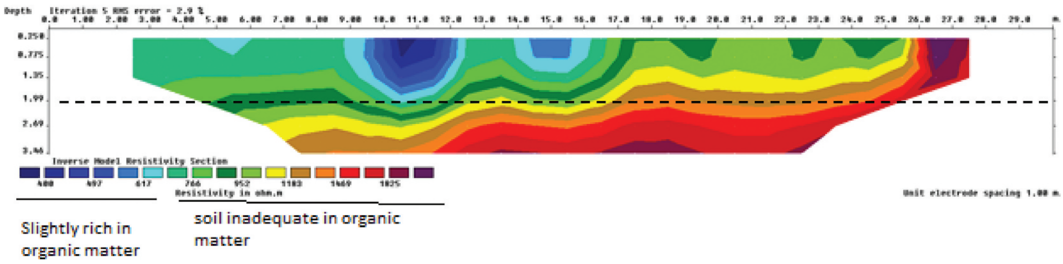

Figure 12. 2D inversion model for traverse 8.

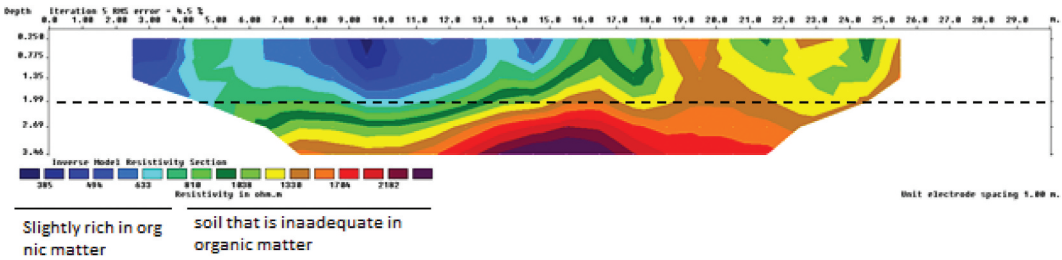

Figure 13. 2D inversion model for traverse 9.

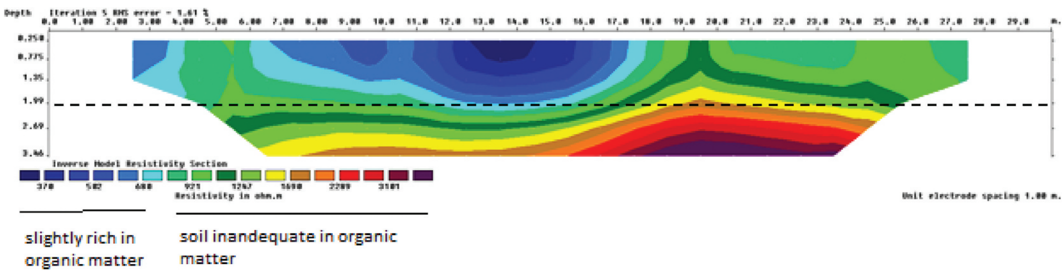

Figure 14. 2D inversion model for traverse 10.

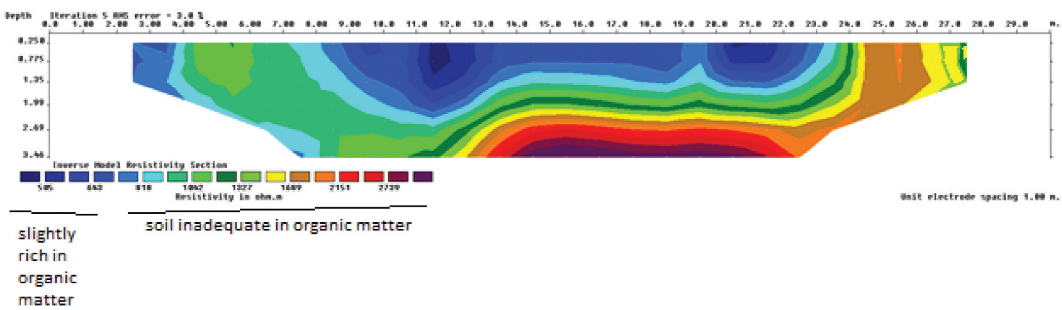

Figure 15. 2D inversion model for traverse 11.

little or no stoniness that limits the effective rooting depth and highly porous with a high water retention capacity that is very suitable for both tuber crops and stem plants. In dry conditions, its soil water is strongly bound to the soil matrix and less readily available to the plants; they are highly saline as indicated in the studies of Roberge (2000) and Ozegin et al. (2011).

The resistivity signature of ERT results in the study area with resistivity values ranged from 100 to 600 Ωm indicates soil that is slightly or moderately rich in organic matter. This observation suggests that the soil is partially rich in both very fine-grained and sand, which must have given room for both oxidation (aerobic) condition and reduced (anaerobic) environment. These soil types have a medium degree of stoniness, which aids effective rooting depth similar to the observation made by Verdoodt and Ranst (2003) and Pitman and Läuchli (2002). Such environment has been observed by Roberge (2000) in his earlier work to have adequate water retention capacity with no anaerobic effect, and such area has general characteristic of low to no salinity as indicated, thus making the study area relatively saline with their pH

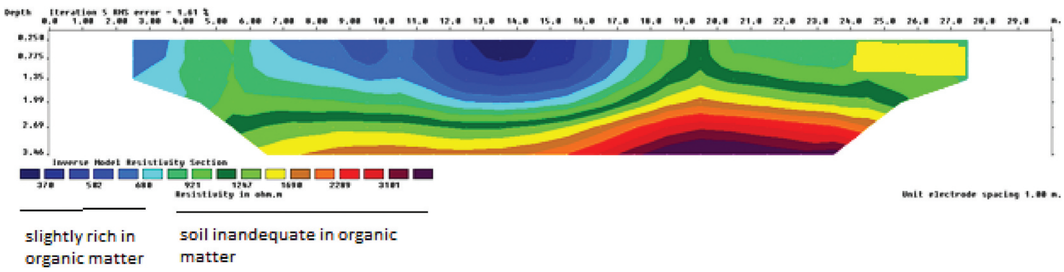

Figure 16. 2D inversion model for traverse 12.

values close to 7; and increases decomposition rates accompanied by a speedy discharge of nutrients to the soil (McCauley et al. 2009) since it is rich in microorganisms involved in decomposition.

Resistivity values of the ERT greater than 600 Ωm reflects soil that is inadequate or deficient in organic matter as indicated in the study of Ulrike et al. (2009). The soil is high in laterite, that is, it is lateritic in nature. These soils indicate high level of stoniness making certain crops (e.g. Sorghum) disadvantaged, since high stoniness strongly reduces the effective rooting depth but does not abruptly end the root development when a threshold of stoniness is exceeded as indicated in Verdoodt and Ranst (2003); are semi-permeable/non-permeable /non-porous; highly drained since they retain little or no water for plant use due to their highly coarse texture; are practically non-saline (Roberge 2000) with their pH values being ±7 as indicated in (McCauley et al. 2009); and contain little or no organic matter since they cannot provide the amount of water needed to house microorganisms due to their degree of stoniness. The aforementioned is summarised in Table 1.

3.1. Correlation of soil analysis results with soil resistivity results

The results of the soil test (for pH, organic matter, phosphorus, potassium, and total nitrogen) and the textural analysis (for sand, silt and clay) were used to validate the resistivity signatures of the soil in the study area. The values of soil pH, organic matter, phosphorus, potassium and total nitrogen for soil resistivity values less than 100 Ωm in the study area are 6.8–6.9, 4.27–4.80 %, 50.23–54.22 mg/kg, 290.0–340.0 cmol/kg, 62.20–65.11%, respectively (Table 2). This indicates the soil in such portion of the area is rich in organic matter and mineral nutrients as opined in Islam et al. (2017) and slightly acidic for the desired high crop productivity (Tomlin et al. 1995). For the values of the soil pH, organic matter, phosphorus, potassium and total nitrogen for soil with resistivity values ranged from 100–600 Ωm in the study area are 6.7–6.8, 2.21–2.75%, 30.14–34.00 mg/kg, 100.2–107.2 cmol/kg, and 54.00–59.20%, respectively (Table 2). This observation suggests that the soil with the resistivity values ranged from 100 to 600 Ωm is moderately rich in organic matter and mineral nutrients needed for crop growth (Islam et al. 2017) in the study area and slightly acidic. Furthermore, the values of soil pH, organic matter, phosphorus, potassium and total nitrogen for the soil with resistivity values greater than 600 Ωm in the study area are 7.0–7.2, 0.51–0.61%, 7.02–9.02 mg/kg, 37.2–40.2 cmol/kg, and 10.20–15.20 %, (Table 2), respectively. This correlation has shown that soil with high resistivity signatures in the study area is deficient of organic matter and mineral constituents needed for high crop yield. The grain size across the study area in each soil texture has a uniform proportion of grain distributions. This showed that they are categorised as silty loam using the triangular plot (Figure 17). The sand grain size distribution ranged from 5.5 to 10.4%, silt ranged from 77.4 to 81.2%, and clay ranged from 13.0 to 14.2% (Table 2). The soil grain analysis (textural) indicates silt as the dominant grain size distribution followed by clay, and sand has the least grain percentage (Table 2).

SS – Soil Sample

GIS in general was used to generate spatial information on the soil organic matter distribution, which shows that the study area comprises three major soil forms, viz. soil rich in organic matter and mineral

Table 1. Data distribution of resistivity values.

Resistivity value range (Ωm)	Soil classification
Less than 100	Soil rich in organic matter
100–600	Partially or moderately rich in organic matter
Greater than 600	Inadequately rich in organic matter

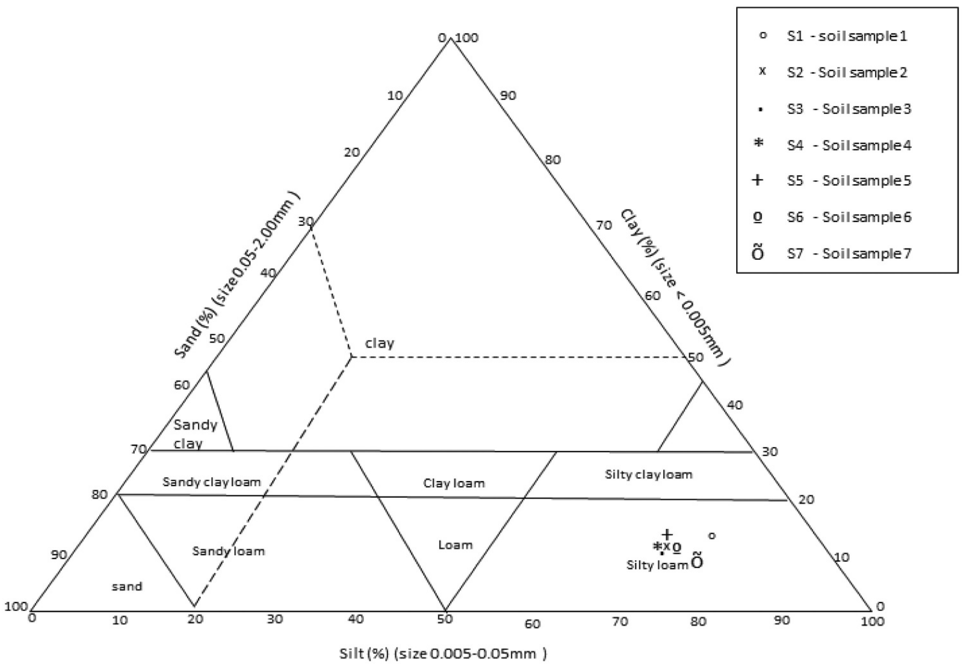

Figure 17. Soil textural classification triangle for the seven soil samples collected from the study area.

nutrients, soil slightly rich in organic matter and mineral nutrients and soil with inadequate organic matter and mineral nutrients (Figure 18).

3.2. Effects of topography on soil nutrient distributions

For the purpose of delineating the topography effect on soil nutrients and minerals distribution in the study area, a cross section of the spatial distribution of ERT results depicting the soil organic matter contents (soil nutrients) was carried out with special attention to the topography effect and the soil within each unit. The results showed that the study area has three categories of topography units where soil occurs, namely, valley soil, slopy soil and soil at the top of slope, as shown in Figure 19. The ERT results showed that the soil at the valley region of the study area is very rich in organic matter and mineral nutrients; soil at the slopy region of the study area is partially rich in organic matter and mineral nutrients, while soil at the top of the slope is inadequate of organic matter and mineral nutrients.

This variation in spatial organic matter and mineral nutrients distribution in the study area indicates that the soil nutrients were washed down from the top of the topography to the valley ultimately.

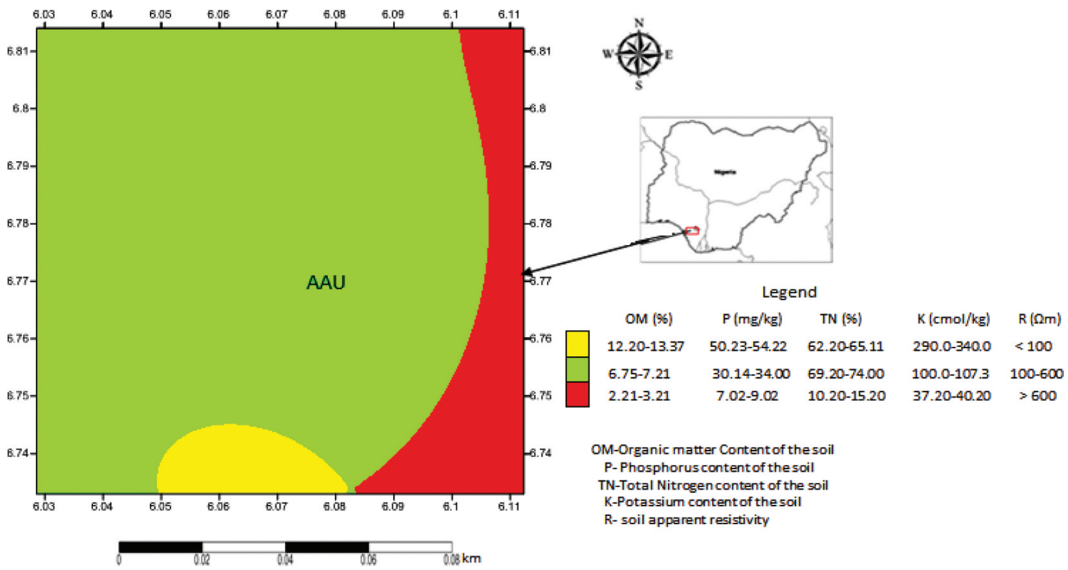

Figure 18. Spatial distribution of soil forms in the study area.

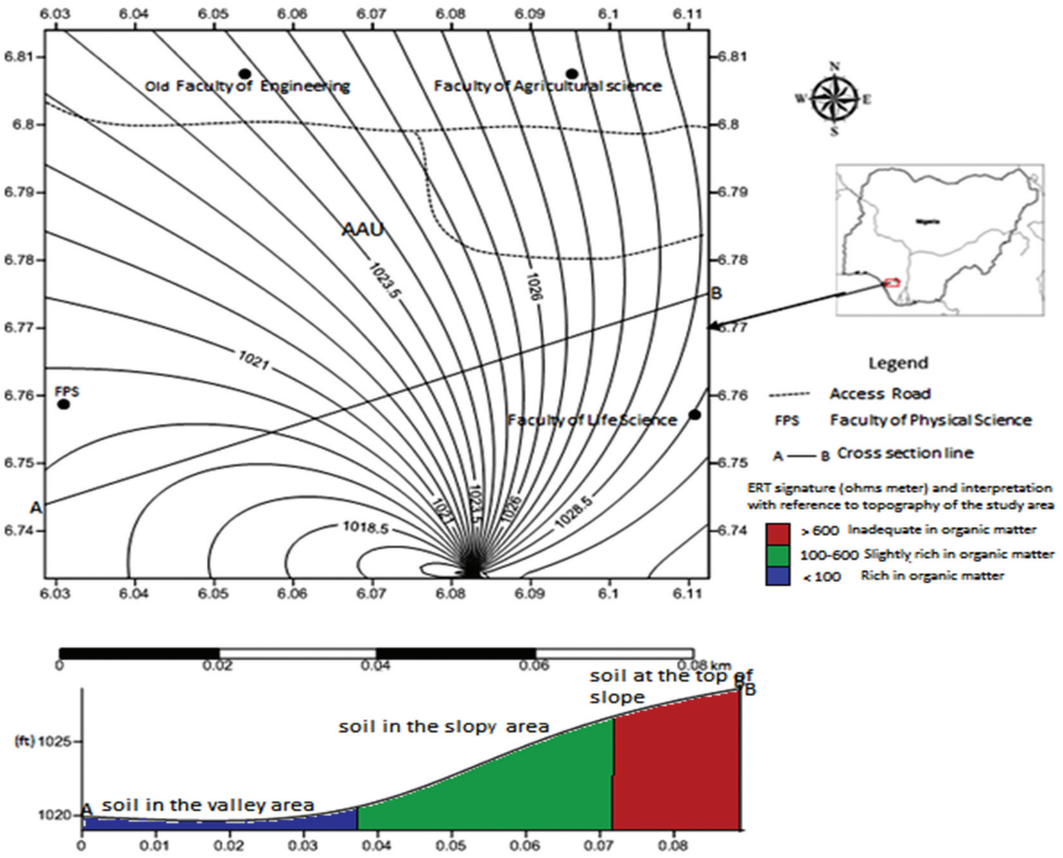

Figure 19. Topography effect on soil nutrient distributions in the study area.

This is the reason the valley has the highest concentration of soil nutrients, while the slope's top is inadequate of soil nutrients. However, the slopy region of the study area is partially rich in organic matter and mineral nutrients because along a slope water run-off as a result of rainfall does not carry the entire nutrients in the soil.

4. Conclusion

The study has effectively shown that the electrical geophysical method and Geographic Information System (GIS) could be conveniently used to determine soil properties and spatial distribution of soil properties for the purpose of suitable site selection for agricultural productivity. Generally, the study has demonstrated that there is significant correlation between the soil resistivity and the soil nutrients. Soil resistivity values from locations less than 100 Ωm in the study area were very rich in soil nutrients; locations with soil resistivity values that ranged from 100 to 600 Ωm were slightly rich in basic soil nutrients, while locations with soil resistivity greater than 600 Ωm were noticed to be inadequate in soil nutrients. Nevertheless, spatial distribution of soil nutrients in the study area was observed to have been generally controlled by the topography of the area. Low topography (valley) area was noticed to have soil nutrients with highest concentration; slopy area was associated with soil nutrients that were slightly concentrated, while area with the highest topography has soil nutrients with inadequate concentration. The aforesaid shows that topography form has major effect on soil nutrients and mineral distribution.

Table 2. Soil analysis results with the soil resistivity results in the study area.

SS	pH	OM (%)	TN (%)	P (mg/kg)	K(cmol/kg)	Sand (%)	Silt (%)	Clay (%)	Resistivity (Ωm)
SS 1	6.8	4.80	62.20	54.22	290.0	5.5	81.2	13.3	< 100
SS 2	6.9	4.27	65.11	50.23	340.0	10.4	79.3	13.1	< 100
SS 3	6.7	2.75	59.10	30.14	101.3	9.3	77.4	13.3	100–600
SS 4	6.8	2.16	54.00	34.00	107.2	7.7	79.2	13.1	100–600
SS 5	6.7	2.21	59.20	32.02	100.2	6.6	79.1	13.3	100–600
SS 6	7.2	0.51	10.20	9.02	37.2	8.7	78.3	13.0	>600
SS 7	7.0	0.61	15.20	7.02	40.2	5.7	80.1	14.2	>600

The benefits of rapidly acquiring widespread data on the horizontal and vertical distributions of electrical properties in soil profiles with no recourse to soil perturbation and to determine spatial distribution of soil forms in order to select the most suitable site for agricultural purpose should be used in precision agriculture and also in soil research more frequently.

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Disclosure statement

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ORCID

K.O. Ozegin http://orcid.org/0000-0001-5788-1142

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