Electrical Resistivity Based Empirical Model For Delineating Some Selected Soil Properties On Sandy-Loam Soil

Joshua, E. O, Mokuolu, A. O

Abstract: Electrical Resistivity (ER) survey was conducted on a Sandy-loam soil with a view to evaluate some selected soil properties. Electrical Resistivity was measured from the soil surface at 0 – 0.3 m (ER_{30}) and 0 – 0.9 m (ER_{90}) soil depths using multi-electrode Wenner array and Miller 400D resistance meter. Soil samples were collected to a depth 0.3 m at points where ER was measured, and analyzed for properties such as Organic Matter (OM), Cation Exchange Capacity (CEC), Soil Water Content (SWC), Sand, Silt and Clay contents using standard methods. The results indicated that lower ER areas exhibit higher content of soil properties than higher ER areas. The ER_{90} correlates insignificantly to the soil properties while ER_{30} correlates significantly to the soil properties, except clay (r = 0.63 - 0.75). The relationship between ER_{30} and soil properties were best fitted to multiple linear regression (R^2 = 0.90) and Boltzmann distribution (R^2 = 0.80 - 0.84). The study indicates the ability of ER to delineate some soil properties influencing yield on sandy-loam soil. This will help farmers take decisions that can improve yields.

Index Terms: electrical resistivity, sandy-loam soil, soil properties, Wenner array

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1 INTRODUCTION

The impact of soil properties in plant growth and yield cannot be under-estimated. This is because these properties e.g soil water, organic matter, etc influence plant growth and yield, and so must be treated with utmost importance. These soil properties which may be in form of physical, chemical and biological factors have the potential to effectively affect crop productivity and some ecological activities but cannot be measured directly. However, they can be evaluated indirectly using the electrical properties of the soil such as electrical resistivity (ER) – a parameter measured in-situ directly from the soil surface to certain depth beneath the soil. This is because these soil properties by nature are composed of electric charges or charged particles. Soil ER prospecting is one of the most attractive geophysical methods in agricultural fields application, offering a non – destructive tool for describing the subsurface properties over a large range of scales without digging as compared to classical soil science measurements and observations which perturb the soil by random or regular drilling and sampling [5], [8].

The soil resistivity measured by geophysical methods provide information about the volume density of mobile electric charges in soil [11] and is subject to great variation due to many soil properties such as soil water content, organic matter, salt, cation exchange capacity, soil texture (sand, silt and clay) and temperature [9]. Soil ER is increasingly used in near surface soil application because it is related to several soil properties and electrical survey information; it therefore represents a rapid and flexible tool to predict spatial soil variability at the field or local scale [13]. Resistivity mapping with limited depth resolution but good area cover is an emerging tool for mapping variations in physico–chemical soil parameters for precision agriculture [3], [2]. Electrical Resistivity techniques is inexpensive in terms of cost and time compared to direct pitting method, and supplies reliable subsurface information over depth ranges that are much greater than the depth ranges of direct pitting techniques [6]. Variations in ER of the earth materials when combined with other measurements can reveal information about the composition, extent of soil texture, structure, water content and salinity of the subsurface material [8]. Soil ER is affected by several soil physical and chemical properties such as soil water content, pore fluid composition, ionic solution, salinity, soil temperature, soil textural class, configuration of the survey electrodes, seasonal variation and current magnitude [14], [10], [7], [1], [4]. As proposed by [12], ER images could be used to guide sampling and other in-situ investigations of roots and root-related process. Soil ER measurements can be used not to monitor transport of water and solutes in the soil but also to indirectly study the development of plant roots systems [16]. Resistivity measurements have been identified as potentially useful for mapping soil compaction [15]. Soil ER is widely used in agricultural applications because of its calibration ease, its linear relationship with depth and relatively large volume of soil measurement compared to other methods. This study aims at determining the relationship between ER and soil properties on sandy-loam soil. It also intends to examine the possibility of using the ER to evaluate the status of some selected soil properties influencing yield on the soil.

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2 MATERIALS AND METHODS

2.1 Study area

This research study was conducted on a cassava farm field (7º 11′N, 3º 27′E, and 148 km altitude) located within the farm settlement area of Federal College of Education, Osiele, Odeda Local Government area, Abeokuta, Ogun State, Nigeria. The field has 5 m boarder spacing around it but the actual field space containing the cassava plants measures 40 m by 125 m in dimension, 0.7 Ha in size and is made up of sandy loam soil. The average temperature ranged between 16º C and 38º C. The field is made up of two parts: section 1 and section 2. Section 1 part of the field had been used for maize and cassava cultivation in the preceding years while section 2 had been uncultivated for some years.

2.2 Soil Electrical Resistivity Measurement

The Cassava field was divided into 147 grids measuring 6 m x 6 m each. Electrical resistivity measurements were conducted at the center of each grid from the soil surface at 0 – 0.3 m and 0 – 0.9 m soil depths using Miller 400D resistance meter. The resistance meter uses two pairs of electrodes connected via four insulated single-core copper wire cables and measures the average electrical resistance of the soil to a depth equal to the electrode spacing (a) using the principle of Wenner electrode array as shown in Fig. 1. One pair of electrodes serves as the current electrodes (C_1 and C_2) placed at the outer ends while the other pair of electrodes serves as the potential electrodes (P_1 and P_2) placed at the inner part of the arrangement, as in Fig. 1. The electrodes were equally spaced along a line (traverse) on the soil surface at a distance of 0.3 m between the electrodes for ER measurement at 0 – 0.3 m soil depth and distance 0.9 m between the electrodes for ER measurement at 0 – 0.9 m soil depth. Electrical current was introduced into the soil through the current electrodes at the soil surface and the potential difference (V) due to the current flow is then measured between the pair of potential electrodes. The meter processed the transmitted current and the received voltage, and then displays the result as average soil resistance (R). The actual point of resistance being measured in the soil is the midpoint between the potential electrodes. For Wenner array, the soil ER is calculated using:

$$\boxed{ER = \frac{2\pi a \Delta V}{I} = 2\pi a R} \tag{1}$$

Soil ER measured from 0 – 0.3 m soil depth is denoted by ER_{30} while ER measured from 0 – 0.9 m soil depth is denoted by ER_{90}. A total of 147 ER_{30} and 147 ER_{90} data were taken for the whole field.

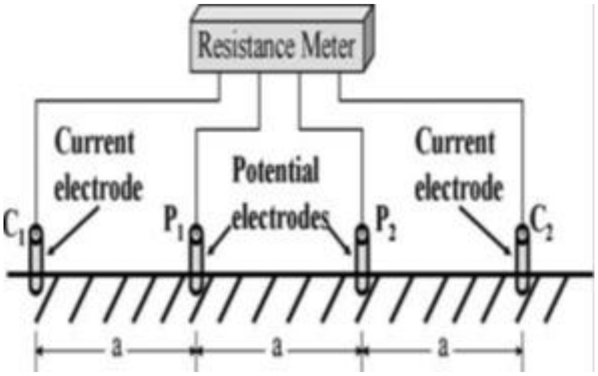

Fig. 1: *Wenner electrode configuration: C_1 and C_2 represent the current electrodes, P_1 and P_2 represents the potential electrodes, a represents the inter-electrode spacing. (Corwin and Lesch, 2005).*

2.3 Soil sampling and laboratory analysis

Soil samples were collected at the center of each grid (where soil ER was measured) from the soil surface to a depth of 0.3 m. Sixty-three (63) samples and eight-four (84) samples were collected from section 1 and section 2 respectively. The collected samples were packed into polythene nylon bags and taken to the laboratory. The samples were air dried for 3 days and passed through 5 mm sieve. The samples were then analyzed for particle size distribution (sand, silt and clay content) using pipette method; total organic matter OM, using dry combustion method; Cation Exchange Capacity CEC, using ammonium acetate method and soil water content SWC, was calculated as a percentage of the weight of dry soil using:

$$\boxed{\%\, SWC\ (\theta_m) = 100 \left[\frac{S_W - S_d}{S_d}\right]} \tag{2}$$

where S_W is the weight of wet soil (g) and S_g is the weight of dry soil (g).

2.4 Statistical Analysis

The distribution and variation of the collected data were analyzed using minimum, maximum, mean standard deviation and coefficient of variation. Correlation coefficient (r) analysis was used to investigate and analyze the nature and strength of the relationship between soil ER and the soil properties. Based on the value of the correlation coefficient, multiple linear regression (MLR) and curve estimation analyses were performed on soil ER and soil properties data to determine the relationship between them. The function with the best regression coefficient, R^2 was then used to develop an empirical relationship between soil ER and the soil properties. All the statistical analysis was implemented using OriginPro 8.1 software.

3 RESULTS AND DISCUSSION

3.1 Spatial distribution of Soil Electrical Resistivity, ER

Table 1a: *Statistical description of* ER_{30}

		ER_{30} (Ωm) (0 – 30 cm depth)			
S	**N**	**Min**	**Max**	**Mean**	**CV**
1	63	607.03	2,884.36	1,429.37	0.29
2	84	218.68	1,649.55	851.82	0.32

Table 1b: *Statistical description of* ER_{90}

ER_{90} (Ωm) (0 – 90 cm depth)				
S	**Min**	**Max**	**Mean**	**CV**
1	791.76	53,983.80	14,050.05	1.29
2	374.40	538,413.12	13,492.30	4.37

Table 1a, b shows the spatial distribution of soil electrical resistivity, ER across the field. According to the results, ER (ER_{30} and ER_{90}) had a comparatively higher value in section (S) 1 than in section (S) 2. There was a large difference between the mean ER of both sections. The variation in ER_{30} for both sections was generally low, but for ER_{90} it was relatively higher. This result generally indicates that section 1 is dominated by higher ER values compared to section 2. The lower ER values observed in section 2 compared to section 1 might be because the area had been uncultivated for some time, so electrical charges due to soil nutrients and properties (like OM, SWC, CEC etc) may have build up, thus leading to the observed lower ER values compared to section 1 which had been under continuous cultivation over years. Generally, ER (ER_{30} and ER_{90}) and its variation were observed to increase with increasing depth across the whole field. This is an indication of a decrease in the density of mobile charges and hence, a decrease in the quantity of the soil properties/nutrients (such as SWC, OM, CEC etc) as the soil depth increases.

3.2 Spatial distribution of soil properties

Table 2a: *Basic statistical description of the soil properties (SP) in section 1*

	Section 1 (N = 63)			
SP	Min	Max	Mean	S.D
OM (%)	0.72	2.28	1.56	0.30
CEC (Cmol/Kg)	5.28	6.85	6.02	0.26
SWC (%)	7.30	11.62	9.04	0.81
Clay (%)	6.40	9.20	8.56	0.59
Sand (%)	78.80	83.23	81.96	0.82
Silt (%)	8.40	13.00	9.49	0.89

Table 2b: *Basic statistical description of the soil properties (SP) in section 2*

	Section 2 (N = 84)			
SP	Min	Max	Mean	S.D
OM (%)	1.22	5.00	2.19	0.72
CEC (Cmol/Kg)	5.27	9.98	6.67	0.68
SWC (%)	7.53	21.39	11.06	2.04
Clay (%)	7.14	13.20	8.89	0.73
Sand (%)	70.80	82.80	80.23	2.05
Silt (%)	8.30	22.01	10.88	2.08

Table 2a, b shows the result of soil properties collected in both sections of the study field. The soil properties examined are higher in section 2 than in section 1 except for Sand which is slightly higher in section 1 (78.80 %) than in section 2 (70.80 %). The variation in soil properties was also higher in section 2 than in section 1. This may have indicated a higher and stronger distribution of soil properties across section 2.

3.3 Relationship between Soil Resistivity and Soil Properties.

Table 3a: *Correlation (r) of ER and Soil properties*

Soil Property	ER_{30} (r)	ER_{90} (r)
SWC	- 0.75**	0.16*
OM	- 0.73**	0.30*
CEC	- 0.74**	0.14*
Sand	0.73**	- 0.14*
Silt	- 0.63**	0.20**
Clay	- 0.30**	- 0.15*

*** Correlation is significant at 0.01 level*
** Correlation is significant at 0.05 level*

From table 3a, ER_{30} correlated more significantly to the soil properties than ER_{90}. This implies a strong relationship between ER_{30} and soil properties, and a weak relationship between ER_{90} and soil properties. In addition, the correlations of ER_{30} to the soil properties are all negative except for Sand which is positive. This implies that as the ER_{30} decreases, the Sand content decreases while SWC, OM, CEC, Silt and Clay content increases. The very weak correlation value (r = - 0.30 and - 0.17) of clay to ER may have implies that Clay had the least contribution to ER compared to other soil properties. This may likely be because the field is largely dominated by higher content of Sand and Silt.

Table 3b: *MLR analysis result for* ER_{30} *and Soil properties*

	Dependent variable: In (ER_{30}) Correl. Coeff., r = 0.95, R^2 = 0.90
Predictors	Coefficients
constant	59.58
In SWC	- 0.63
In OM	- 0.55
In CEC	- 0.54
In Sand	- 9.28
In Silt	- 2.15
In Clay	- 1.91

Table 3b shows the results of multiple linear regression analysis conducted. The results showed a correlation coefficient, r value of 0.95 and R^2 value of 0.90 between ER_{30} and soil properties. This indicates that a strong relationship exist between them. Therefore, from MLR analysis the relationship between ER_{30} and the soil properties is given by:

$$\boxed{In(ER_{30}) = -[0.63\, In\, SWC + 0.55\, In\, OM + 0.54\, In\, CEC + 9.28\, In\, Sand + 2.15\, In\, Silt + 1.91\, In\, Clay - 59.58\,]} \qquad (3)$$

Table 3c: *Curve estimation analysis for ER_{30} and Soil properties*

Independ. variable: ER_{30}	SWC	OM	CEC
Fitted functions	R^2	R^2	R^2
Lorentz	0.71	0.66	0.68
Gauss	0.71	0.66	- 0.02
*Boltzmann	0.83	0.81	0.80
*Exp (Decay)	0.83	0.81	0.80
Quadratic	0.73	0.68	0.70
Cubic	0.80	0.79	0.77
Linear	0.57	0.53	0.54
Spherical	0.81	0.73	0.80
Power	0.79	0.77	0.75
Logarithm	0.76	0.71	0.73

Table 3d: *Curve estimation analysis for ER_{30} and Soil properties*

Independent variable: ER_{30}	Sand	Silt	Clay
Fitted functions	R^2	R^2	R^2
Lorentz	0.69	0.64	0.15
Gauss	0.70	0.65	0.27
*Boltzmann	0.83	0.84	0.15
*Exp (Decay)	0.83	0.84	- 0.55
Quadratic	0.71	0.67	0.15
Cubic	0.79	0.79	0.17
Linear	0.54	0.40	0.09
Spherical	0.84	0.79	0.01
Power	0.72	0.66	0.04
Logarithm	0.73	0.63	0.04

Table 3c, d shows the curve estimation analysis performed on soil properties and ER_{30}. As shown on the table, each of the soil properties correlated to almost all the fitted curves except clay. It is an indication of the complex interactions among these soil properties within the soil. The non – significant correlation of clay to the fitted curves may be due to its relatively very small content in the study area, thus its contribution to ER of the study area is insignificant. The results further shows that all the soil properties (except clay) correlated strongly to Boltzmann distribution and exponential decay with $R^2 = 0.80 – 0.84$. But exponential decay is a direct component of Boltzmann distribution. Therefore, exponential decay can be ignored while Boltzmann distribution is taken for describing the relationship between soil ER_{30} and soil properties.

Table 3e: *Results of Boltzmann distribution (non-linear) curve fit*

Indep: ER_{30}	Boltzmann distribution Constants			
Dep.	A_1	A_2	x_0	dx
SWC	2,175.24	8.62	- 1,578.88	340.56
OM	383.27	1.43	- 1,249.41	319.32
CEC	578.87	5.88	- 1,537.76	345.53
Sand	-1,344.05	82.40	- 1,340.94	320.58
Silt	1,756.71	9.21	- 1,029.42	251.40

Table 3e shows the results of the Boltzmann distribution curve estimation analysis conducted for ER_{30} (independent variable) and soil properties (dependent variable). The Boltzmann distribution function is given by;

$$\boxed{y = A_2 + (A_1 - A_2)\left[1 + exp\left(\frac{x - x_0}{dx}\right)\right]^{-1}} \quad (4)$$

Where y represents the soil properties (SWC, OM, CEC, Sand and Silt) and x represents the soil ER_{30}. A_1, A_2, x_0, and dx are constants of the function given in table 3e. But,

$$\mathrm{ER}_{30} = (2\pi a)\,\mathrm{R}_{30} = 2\pi(0.3)\,\mathrm{R}_{30} \quad (5a)$$

$$\mathrm{ER}_{30} = (1.8858)\,\mathrm{R}_{30} \quad (5b)$$

$$\mathrm{R}_{30} = \frac{\mathrm{V}_{30}}{\mathrm{I}_{30}} \quad (6)$$

Where a in "(5a)" represents the soil depth (0.3m) at which the soil resistivity is measured; R_{30}, V_{30} and I_{30} represents the average soil resistance, potential difference and electric current at 0 – 0.3 m soil depth respectively. Therefore, using the results in Table 3e and "(4)" – "(6)", the relationship between soil properties and ER_{30} can be described by the following "(7)" – "(11)" derived from Boltzmann distribution function:

$$\boxed{SWC = 8.62 + (2166.62)\left[1 + exp\left(\frac{ER_{30}}{340.56} - \frac{1578.88}{340.56}\right)\right]^{-1}} \quad (7a)$$

$$\boxed{SWC = 8.62 + (2166.62)[1 + exp(0.00294\,ER_{30} + 4.64)]^{-1}} \quad (7b)$$

$$\boxed{SWC = 8.62 + (2166.62)[1 + exp(0.00554\,R_{30} + 4.64)]^{-1}} \quad (7c)$$

$$\boxed{SWC = 8.62 + (2166.62)\left[1 + exp\left(\frac{0.00554\,V_{30}}{I_{30}} + 4.64\right)\right]^{-1}} \quad (7d)$$

$$\boxed{OM = 1.43 + (381.84)[1 + exp(0.00313\,ER_{30} + 3.91)]^{-1}} \quad (8a)$$

$$\boxed{OM = 1.43 + (381.84)[1 + exp(0.00590\,R_{30} + 3.91)]^{-1}} \quad (8b)$$

$$\boxed{OM = 1.43 + (381.84)\left[1 + exp\left(\frac{0.00590\,V_{30}}{I_{30}} + 3.91\right)\right]^{-1}} \quad (8c)$$

$$\boxed{CEC = 5.88 + (572.99)[1 + exp(0.00289\,ER_{30} + 4.45)]^{-1}} \quad (9a)$$

$$\boxed{CEC = 5.88 + (572.99)[1 + exp(0.00545\,R_{30} + 4.45)]^{-1}} \quad (9b)$$

$$\boxed{CEC = 5.88 + (572.99)\left[1 + exp\left(\frac{0.00545\,V_{30}}{I_{30}} + 4.45\right)\right]^{-1}} \quad (9c)$$

$$\boxed{Sand = 82.40 - (1426.45)[1 + exp(0.00312\,ER_{30} + 4.18)]^{-1}} \quad (10a)$$

$$\boxed{Sand = 82.40 - (1426.45)[1 + exp(0.00588\, R_{30} + 4.18)]^{-1}} \quad (10b)$$

$$\boxed{Sand = 82.40 - (1426.45)\left[1 + exp\left(\frac{0.00588\, V_{30}}{I_{30}} + 4.18\right)\right]^{-1}} \quad (10c)$$

$$\boxed{Silt = 9.21 + (1747.50)[1\ + exp(0.00398\, ER_{30} + 4.10)]^{-1}} \quad (11a)$$

$$\boxed{Silt = 9.21 + (1747.50)[1 + exp(0.00751\, R_{30} + 4.10)]^{-1}} \quad (11b)$$

$$\boxed{Silt = 9.21 + (1747.50)\left[1 + exp\left(\frac{0.00751\, V_{30}}{I_{30}} + 4.10\right)\right]^{-1}} \quad (11c)$$

With the series of equations stated above, each of the soil properties influencing ER of soil can be estimated. The graphs of the relationship between the ER_{30} and each of the soil properties are also given by Figs. 2 - 6.

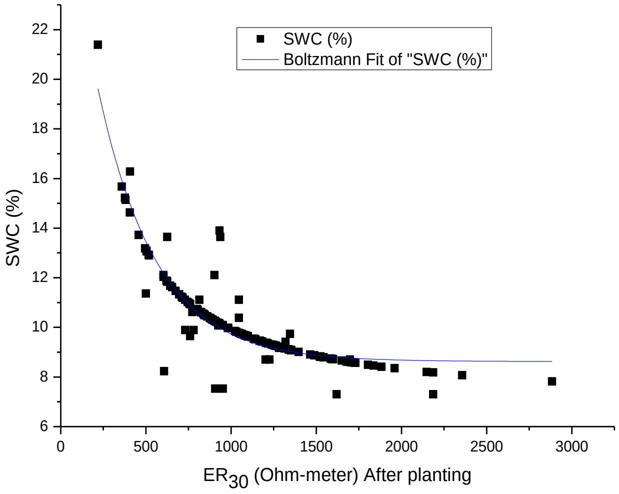

Fig. 2: *Graph of SWC against ER_{30} at shallow depth 0 – 0.3 m.*

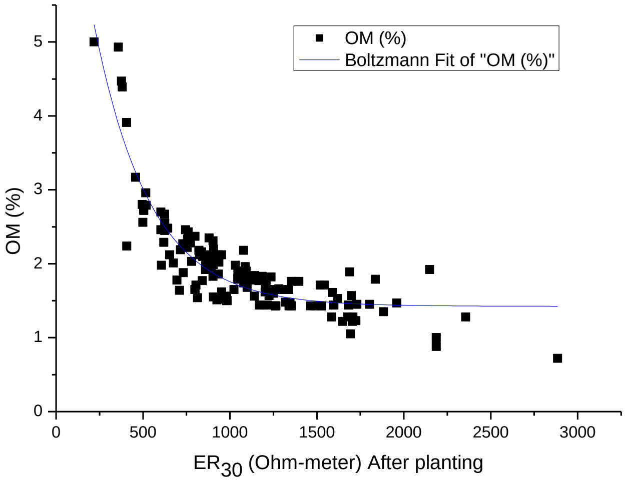

Fig. 3: *Graph of OM against ER_{30} at shallow depth 0 – 0.3 m.*

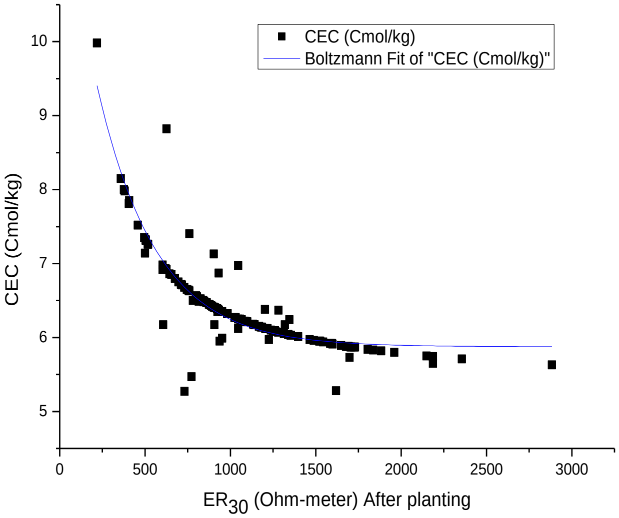

Fig. 4: *Graph of CEC against ER_{30} at shallow depth 0 – 0.3 m.*

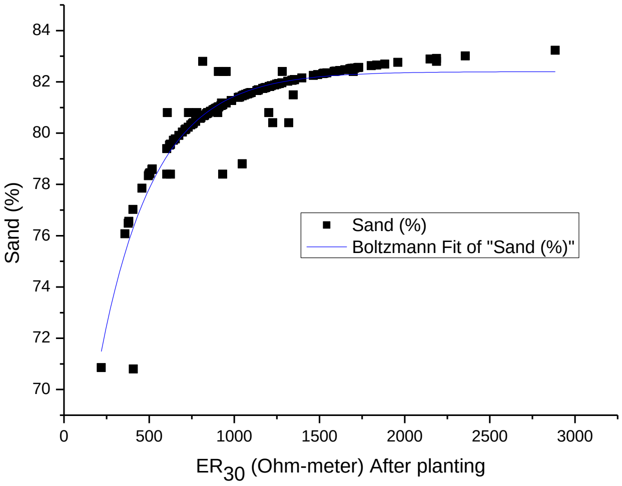

Fig. 5: *Graph of Sand content against ER_{30} at depth 0 – 0.3 m.*

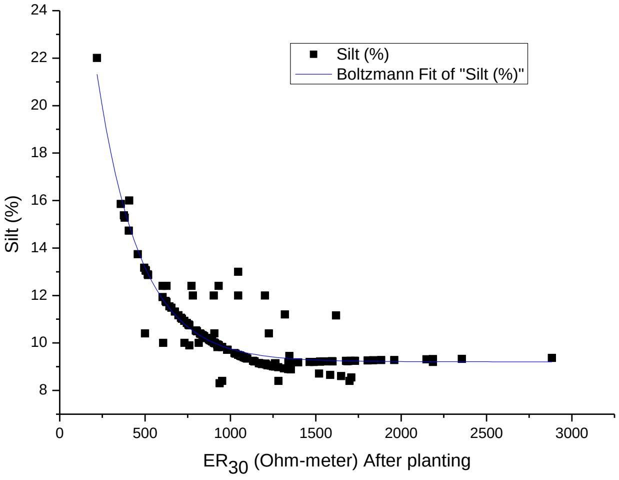

Fig. 6: *Graph of Silt content against ER_{30} at depth 0 – 0.3 m.*

A closer examination of the graphs above showed that soil ER_{30} decreases rapidly with increasing SWC, OM, Silt and CEC except for graph of sand where low soil ER_{30} also showed low sand content. The physical interpretation of the graphs' behavior is that as the soil properties/nutrients increases (except sand), the density of mobile electrical charges also increases thus reducing the soil ER_{30} of the soil. In essence, soils with high density of mobile charges (due to high plant nutrients) possess low soil ER_{30} and potential.

4 CONCLUSIONS

1) This study showed the ability of soil ER as a form of rapid soil information acquisition for effective delineation of soil properties, characterization and its heterogeneities on sandy loam soil. Based on the results of this study, the following conclusions were made;
2) Field areas with lower ER were observed to exhibit higher content of soil properties than areas with higher ER.
3) Soil ER was also observed to generally increase with increasing depth across the whole field. This indicates a decrease in the density of mobile charges and hence, a decrease in the content and quantity of the soil properties/nutrients (such as SWC, OM, CEC etc) as the soil depth increases.
4) Soil ER_{90} showed non-significant correlation (r = 0.14 – 0.30) with the soil properties.
5) Soil ER_{30} was observed to correlate significantly to soil properties (except clay): SWC (r = - 0.75), OM (r = - 0.73), CEC (r = - 0.74), Sand (r = - 0.73) and Silt (r = - 0.63).
6) By MLR analysis, ER_{30} correlates significantly to the soil properties with r = 0.95.
7) The relationship between Soil ER_{30} and soil properties were best fitted to MLR analysis (R^2 = 0.90) and Boltzmann distribution: SWC (R^2 = 0.83), OM (R^2 = 0.81), CEC (R^2 = 0.80), Sand (R^2 = 0.83) and Silt (R^2 = 0.84).

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