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Variability of Soil Thermal Properties of a Seasonally Cultivated Agricultural Teaching and Research Farm, University of Ibadan, South- Western Nigeria

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VARIABILITY OF SOIL THERMAL PROPERTIES OF A SEASONALLY CULTIVATED AGRICULTURAL TEACHING AND RESEARCH FARM, UNIVERSITY OF IBADAN, SOUTH- WESTERN NIGERIA

Variability of Soil Thermal Properties of a Seasonally Cultivated Agricultural Teaching and Research Farm, University of Ibadan, South-Western Nigeria

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Abstract - Knowledge of the thermal properties of the soil top layer is of great importance in agricultural meteorology where problems of heat exchange at the soil surface are encountered. The availability of these data is important because of the improvements in wider applications of soil heat and water transport models as well as seed germination and crop growth. This research work therefore intends to determine the variability of soil thermal properties of a seasonally cultivated Agricultural Teaching and Research Farm located within the University of Ibadan campus, South-western Nigeria with a view to have understanding of how different soils warm up in order to allow better planning of planting of crops and have knowledge for the control of thermal-moisture regime of soil in the field and greenhouse.

Forty-five points were located for the measurements of thermal properties in cultivated fields of maize, pineapple, cowpea, Okro and vegetables. A *KD-2 Pro* thermal analyzer was used for the measurements of these thermal properties such as thermal conductivity, thermal resistivity, volumetric specific heat and thermal diffusivity. Samples were collected at each location for the laboratory determination of soil moisture content and bulk density. The variability of soil thermal properties was analysed using classical statistics such as mean, range, standard deviation and coefficient of variation.

The results show that for the whole site, the thermal conductivity, volumetric specific heat, thermal diffusivity and temperature ranges from 1.103-2.151 W/mK, 1.247-2.936 mJ/m^{3}K, 0.486-1.000 mm^2/s and 23.83-34.49 °C with mean values of 1.672 W/mK, 1.831 mJ/m^{3}K, 0.785 mm^2/s and 27.71 °C respectively. Also soil moisture content and bulk density ranges from 0.146-0.223 m^{3}m^{-3} and 1.260-1.410 mg/m^3 with an average of 0.191 m^{3}m^{-3} and 1.340 mg/m^3 respectively.

It was found out that the thermal properties of agricultural soils within University of Ibadan vary from one point to the other and the variations are related to soil moisture content and bulk density which would have significant effects on plant germination and growth. This implies that knowledge of the thermal-moisture regime of soils is quite essential for better planning in agriculture.

Keywords : variability, thermal properties, moisture content, bulk density, agricultural farm, seed germination.

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I. Introduction

Soil thermal properties are required in many areas of engineering, agronomy, and soil science, and in recent years considerable effort has gone into developing techniques to determine these properties. The thermal properties of soil are one of the factors that determine mass and energy exchange that takes place in soil-plant-atmosphere system. The determination of these properties such as thermal conductivity, thermal diffusivity and volumetric heat capacity, and their variability is therefore a very important factor in understanding these processes at an individual scale of crop field and larger areas. The investigation of these thermal properties can have significant practical consequences such as evaluation of optimum conditions for plant growth and development and can also be utilized for the control of thermal-moisture regime of soil in the field (Usowicz, 1991). Seed germination, seedling emergence, and subsequent stand establishment are influenced by the microclimate. Thermal properties of soils play an important role in influencing microclimate (Ghuman and Lal, 1985). These properties influence how energy is partitioned in the soil profile. The ability to monitor soil thermal properties is an important tool in managing the soil temperature regime to affect seed germination and growth. While related to soil temperature, it is more accurately associated with the transfer of heat throughout the soil, by radiation, conduction and convection. Plants processes such as root growth or germination do not occur until the soil reaches certain temperature depending on the particular plant. Another plant process adversely affected by cold temperature is transport of nutrients and water. A better understanding of how different soils warm up would benefit agriculture by allowing for better planning of planting of crops.

The use of a thermal probe called KD 2 Pro has made it possible to measure the thermal properties of soil (in-situ) as well as its spatial variability. Thermal properties and physical properties of soil in cultivated fields are modified by different treatments and crops. Hence the variability of thermal properties may be

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different for an individual field with the growth of a specific crop compared with a group of fields with different crops.

For the agriculture farm within the premises of University of Ibadan, information on thermal properties has been lacking. These data are needed for constructing models to predict the thermal regime of soils. Such information assumes greater importance with increasing attention paid to developing the agricultural industry in University of Ibadan and its environs. Since the early growth and development of a crop may be determined to a large extent by microclimate, the practical significance of knowing the thermal properties of soils under a given set of conditions is most important.

This study therefore aims at determining the thermal properties of agricultural farm with different crops within University of Ibadan campus in order to establish the variability of thermal conductivity, thermal diffusivity and volumetric specific heat of soil as well as to investigate the distribution of soil water content and bulk density and its consequences on the variability of a particular thermal properties.

II. Site Description

The study area is a Teaching and Research Farm for undergraduate and postgraduate students of Faculty of Agriculture and Forestry located within the University of Ibadan campus between longitudes 07° 26' 00" to 07 ° 27' 30" and latitudes 03 ° 53' 00" to 03° 54' 30". (Figure 1). Different plants such as maize, pineapple, cowpea, okro and vegetables are cultivated on each farm land. The farm land has been in use for the past twenty years.

III. Method of Study

The thermal properties of soils in Teaching and Research Farm were determined using KD2 Pro (Plate 1). The KD2 Pro is a fully portable field and laboratory thermal properties analyzer. It uses the transient line heat source method to measure the thermal diffusivity, specific heat (heat capacity), thermal conductivity, and thermal resistivity. Sophisticated data analysis is based on over thirty years of research experience on heat and mass transfer in soils and other porous materials.

To measure the thermal resistivity, thermal sensor with one single needle (TR-1) (Plate 2) was employed. A small dual-needle sensor (SH-1) (Plate 3) was used to measure the thermal diffusivity and volumetric specific heat. These kind of sensors use the heat pulse methodology and yields reliable soil thermal resistivity (*R*) and the inverse thermal conductivity (λ), thermal diffusivity and volumetric specific heat estimations by a nonlinear least squares procedure during both processes.

The SH-1 is the only sensor that measures thermal diffusivity and specific heat. It is 30mm long, 1.28mm in diameter with 6mm spacing. TR-1 is a 10cm Sensor that measures thermal conductivity and thermal resistivity and conforms to IEEE Standard 442-1981 and ASTM Standard D5334-00. It is 100mm long and 2.4mm diameter

IV. Field Procedures

The first step to develop a protocol to measure the thermal properties begins with the field sampling design. The measurements include scooping of the top surface of the ground and verification and preparation of the thermal sensor (calibration) using standard glycerol in order to check whether it was functioning properly (Rao and Singh, 1999; Krishnaiah, 2003). The thermal sensor to be used was then selected. The needle was positioned with respect to the scooped ground. Thermal diffusivity and volumetric specific heat were then measured by using the thermal sensor SH-1 while thermal resistivity and its inverse were measured with TR-1. To take measurements with the KD2 Pro; appropriate sensor was attached and the KD2 Pro was turned on; sensor was properly inserted into the material to be measured (for the dual needle sensor, the needles must remain parallel to each other during insertion); when the KD2 Pro turns on, one should be in the Main Menu, press enter to begin the measurement. Then the instrument was allowed to rest for about fifteen minutes before taking the next readings.

Forty-five sample points (Figure 2) were tested for various thermal properties while samples were collected at these points to determined the moisture content and soil bulk density in the laboratory. The samples were kept in polythene bags and stored in a cool dry place before the necessary tests were carried out on them. The variabilities of these soil thermal properties were analyzed using classical statistics such as mean and extreme values, standard deviation and coefficient of variability.

V. Laboratory Procedures

a) Moisture Content

The standard reference used for the determination of moisture content was AASTHO T 265. A representative test specimen of about 300g was selected. The tare mass of a clean, dry container and lid, was determined and recorded as WC. Moist specimen was placed in the container and the lid was secured onto the container. The mass of the container, lid, and moist specimen was determined and recorded as W_1. The lid was then removed and the container was placed with the sample in the drying over for about 17 hours for the material to be dried to a constant mass. The container was then removed from the oven and the lid was replaced firmly. The material and container was allowed to cool to room temperature. The mass of the container, lid, and dried specimen was measured and recorded as W_2.

The calculations are as follow:

Mass of the Water:

$Ww = W_1 - W_2$

Mass of the Solid Particle:

$Ws = W_2 - Wc$

Moisture Content (%):

$M_C = 100(Ww/Ws)$

Where:

Wc = mass of container and lid, g

W_1 = mass of container, lid, and moist specimen, g

W_2 = mass of container, lid, and oven-dried specimen, g.

b) Bulk Density

i. *Procedure*

a. The weight of a 25 mL graduated cylinder was determined. (Note: 1 mL = 1 cm^3)
b. the 25 mL was filled to the mark, by adding ~5 mL additions of soil and tapping lightly to pack the soil. (Vt for soil = 25 cm^3)
c. the weight of the graduated cylinder + soil and by difference the weight of the soil were determined. The soil's weight was corrected for moisture content.
d. A 100 mL graduated cylinder with tap water was filled to the 50 mL mark. The soil was quantitatively transferred from the 25 mL graduated cylinder to the water and was stirred to expel the air. It was allowed to stand for ~ 5 minutes.
e. The change in volume resulting from the addition of the soil was noted (Vs = volume change i.e volume after adding soil and stirring - 50 mL)

Calculations

Bulk density

ρ_b = OD wt/Vt

Vt = 25 cm^3

OD = Oven-dry weight OD wt = air-dry weight/(1 + water content)

Volume of solids (Vs) = (volume of soil + water) - (volume of water)

VI. Results and Discussion

a) Thermal Properties

i. *Thermal Conductivity*

For the whole site, the values of thermal conductivity range from 1.103 - 2.151 W/mK (Table 1) with a mean of 1.488 W/mK. Figure 3 shows the variation of thermal conductivity within the whole study site that comprises maize, pineapple, cowpea, okro and vegetable fields. It could be observed from the figure that there are much variations in thermal conductivity from one point to the other. Figures 4 and 5 also show the variation of soil moisture content and soil bulk density from one point to the other. The variation of thermal conductivity from one point to another may be as a result of variation in soil moisture content and bulk density [(Oladunjoye and Sanuade, 2012a; Rubio et al. (2009) and Singh and Devid (2000)]. However the plots of thermal conductivity against moisture content and soil bulk density shows a positive correlation with moisture content having the highest value of correlation coefficient (R = 0.4) (Figure 6A and 6B).

Considering individual fields, the thermal conductivity values of maize, pineapple, cowpea and okro+vegetable fields ranged from 1.103 - 2.015 W/mK, 1.777 - 2.151 W/mK, 1.183 - 1.873 W/mK and 1.354 - 1.920 W/mK with average values of 1.581 W/mK, 2.021 W/mK, 1.494 W/mK and 1.620 W/mK respectively (Tables 2, 3, 4, and 5). However, these variations from one field to another may be as a result of variations in soil moisture content [(Figure 8A -D) and soil bulk density (Figure 9A-D)]. From Figure 8A-D, it could be observed that there are strong positive correlations between soil moisture content and thermal conductivity in all fields with R = 0.98, 0.91, 0.92 and 0.83 for maize, pineapple, cowpea and okro+vegetable fields respectively (Ghuman and Lal, 1985; Brandon and Mitchell, 1989; Salomone et al, 1984; Salomone and Marlowe, 1989; Salomone and Kovacs, 1984; IEEE, 1998; Adjepong, 1997; Rubio et al, 2009; Singh and Devid, 2000; Oladunjoye and Sanuade, 2012a). Also there are positive correlations between thermal conductivity and soil bulk density (Zhang and Liu, 2006) with values of R^2 being smaller than that of soil moisture content (Figure 9A-D). This therefore means that the distribution of thermal conductivity in all fields was determined mainly by soil moisture content and partly by soil bulk density. High thermal conductivity ensures movement of heat into the ground. Interestingly, soils with lower thermal conductivity retain more heat than those with higher thermal conductivity once the sun goes down. Therefore, a balance neither too high nor too low is necessary to ensure proper conditions for seed germination and emergence (Alex Tan, 2013). From the thermal conductivity values of all the fields, it could be observed that the values are moderate which range from 1.103 – 2.151 W/mK. (Standard *Range of measurement is 0.02 – 4 W/mK*).

ii. *Thermal Diffusivity*

For the whole study sites, the values of thermal diffusivity ranges from 0.439 - 1.000 mm^2/s (Table 1, Fig. 10) with an average of 0.785 mm^2/s. There are variations in thermal diffusivity values from one point to another. However, the plots of thermal diffusivity against soil moisture content and bulk density show positive correlations with R^2= 0.81 and 0.79 respectively (Figs. 11 & 12). This could mean that both soil moisture content and bulk density are contributing to the variation of thermal diffusivity in the whole study site. For the individual fields, the thermal diffusivity of maize, pineapple, cowpea and okro+vegetable fields have range of values from 0.605 - 0.925 mm^2/s, 0.740 - 1.000 mm^2/s, 0.486-0.740 mm^2/s and 0.820 - 0.990 mm^2/s with mean values of 0.768 mm^2/s, 0.868 mm^2/s, 0.578 mm^2/s and 0.878 mm^2/s respectively (Tables 2, 3, 4, and 5). Plots of soil moisture content against thermal diffusivity in all the fields (Figure 13A-D) show a moderate positive correlations except in cowpea field with relatively high positive correlation (Ghuman and Lal, 1985; Adjepong, 1997; Verhoef et al,1996 and Rubio et al, 2009.

As shown in Figure 14 A-D, there are positive correlations between soil bulk density and thermal diffusivity in all the fields (Oladunjoye and Sanuade, 2012b). It could be observed that R^2 values in the relationship between thermal diffusivity and soil moisture content and bulk density are relatively high. This suggests that the distribution of thermal diffusivity in all the fields were controlled by both soil moisture and soil bulk density. High thermal diffusivity in soils favour root growth (Rodrigo et al., 2009). High thermal diffusivity will allow proper transport of nutrients and water. From the above results, it could be noted that the thermal diffusivity for all the fields ranged from moderate to high with fields that contained pineapple and okro+vegetable being the fields with the highest thermal diffusivity. This means that soils that contained pineapple and okro+vegetable will favour root growth than those that contained maize and cowpea.

iii. *Volumetric Specific Heat*

For the whole study site, volumetric specific heat ranges from 1.247 - 2.936 J/m^3K (Table 1) with a mean of 1.831 J/m^3K. From Figure 15, it could be observed that there are variations in the volumetric specific heat in the whole study site from one point to the other. These variations could be as a result of soil moisture content or bulk density (Oladunjoye and Sanuade, 2012b). From both Figures 16 and 17, weak positive correlation exists between volumetric specific heat and soil moisture content and bulk density. Considering individual fields, volumetric specific heat values ranged from 1.605 - 1.980 J/m^3K, 1.522 - 1.822 J/m^3K, 1.247 - 1.645 J/m^3K and 1.887 - 2.936 J/m^3K with average values of 1.727 J/m^3K, 1.684 J/m^3K, 1.515 J/m^3K and 2.208 J/m^3K for maize, pineapple, cowpea and okro + vegetable fields respectively (Tables 2, 3, 4, and 5). The variation of volumetric specific heat with soil moisture contents and bulk density were determined.

From Figures 18A-D and 19A-D , it could be observed that the relationships between soil moisture content and volumetric specific heat are relatively higher than that of soil bulk density and volumetric specific heat. This suggests that the distribution of volumetric specific heat in all the fields were controlled by soil moisture content. Volumetric specific heat affects soil temperature to a greater extent. All things being equal, a soil with a high volumetric specific heat exhibits lesser temperature change than those having a low volumetric heat capacity (Ghuman and Jalota, 2005). From the results above, it was observed that the volumetric specific heat in all the fields could be classified as moderate with ranges from 1.247 – 2.936 J/m^3K (Standard *Range of measurement is 0.5 – 4 J/m^3K).* Therefore, the volumetric specific heat of the soils in all the field are good for planting of crops as the temperature will not be much affected.

iv. *Temperature*

For the whole site, temperature ranges from 23.21 – 34.49 °C (Table 1) with a mean of 27.71°C with lowest and highest values found in the field planted with okro and vegetables. Considering individual fields, temperature values range from 27.88 – 30.89 °C, 25.88 – 28.54 °C, 27.61 – 29.82 °C and 23.21 – 34.49 °C with mean values of 29.03 °C, 27.29 °C, 28.93 °C and 26.30 °C (Tables 2, 3, 4, and 5) in the fields that contain maize, pineapple, cowpea and okro+vegetable respectively. Figures 20 and 21 A-D show the variation of temperature in the whole site and in individual fields. However, Decagon Devices Inc. 2010 stated that for a soil in place, the temperature typically varies over a small enough range to have only a small effect on thermal properties unless the soil freezes. Minimum temperature or specific zero which is that temperature below which plants cease to grow and generally remain dormant is 6 °C for most plants while the maximum temperature is 55 °C beyond which most plants cannot live without water (Chima et al., 2011). From the above results, it could be seen that the temperature values in all the fields ranged from 23.21 – 34.49 °C which means that these values do not reach the maximum. At these temperatures, most and if not all plants can live and grow well, if other conditions for plant growth are met.

VII. Statistical Analysis

a) Mean

In the whole study site, the mean values of thermal conductivity, thermal diffusivity and volumetric specific heat are 1.672 W/mK, 0.785 mm^2/s and 1.831 J/m^3K respectively.

In the individual fields, the lowest mean values of thermal conductivity, thermal diffusivity and volumetric specific heat were obtained in the field that contained cowpea while the highest mean values were seen in both pineapple and okro + vegetable fields (thermal conductivity highest in pineapple field, thermal diffusivity and volumetric specific heat highest in Okro+vegetable field). The differences between the mean values in these

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fields were calculated as 0.527 W/mK, 0.300 mm^2/s and 0.693 J/m^3K respectively for thermal conductivity, thermal diffusivity and volumetric specific heat. The mean temperature value for the whole site was calculated as 27.71 °C. Considering the individual fields, the lowest mean value of temperature was noticed in the field that contained both okro+vegetables while the highest was observed in the field that contained maize. The difference between the mean values of temperature in these fields was calculated as 2.73 °C.

b) Standard Deviation

i. Thermal Properties

Standard deviations were calculated as a measure of dispersion of the thermal properties. Considering the whole study site, the standard deviations of thermal conductivity, thermal diffusivity and volumetric specific heat were calculated as 0.342, 0.145 and 0.342 respectively. For the individual fields, the lowest standard deviation of thermal conductivity was seen in the field that has Pineapple while the highest was observed in the field that contained Maize. For thermal diffusivity, the field that has okro+vegetable has the lowest standard deviation while Maize field has the highest. Also for volumetric specific heat, the field that has Pineapple and Maize has the same and lowest standard deviation while the field with okro+vegetable has the highest standard deviation (Table 6).

c) Temperature

From Table 2, the standard deviation of the whole site was calculated as 2.299 which is very high. In the individual fields, the field that contained cowpea has the lowest standard deviation while okro+vegetable field has the highest standard deviation.

d) Coefficient of Variation

i. Thermal Properties

The coefficients of variation of particular thermal properties determined for the whole site vary from 18.5% to 23.0% with thermal diffusivity having the lowest CV while thermal conductivity has the highest. For the individual fields, the coefficients of variation range from 5.7 % to 21.1 % with the lowest and highest from thermal conductivity of the field that contained pineapple and maize respectively (Table 6). From the statistical analysis, the standard deviation values of all the thermal properties in the entire whole site and in individual fields, it could be said that all the properties are relatively uniform with thermal diffusivity more uniform. However, standard deviation alone is not particularly useful for this conclusion, hence coefficient of variation. From the coefficient of variation together with standard deviation, it could be said that the data are greatly uniform (coefficient of variation ranges from 5.7% to 23%). The higher the coefficient of variation, the greater the dispersion in the variable while the lower the coefficient of variation, the smaller the residuals relative to the predicted mean value (Bruin, 2006). Therefore lower values of coefficient of variation are suggestive of a good model fit.

VIII. Conclusions

The variability of thermal properties over cultivated fields is mainly determined by soil moisture content and bulk density values and their variation which is also modified by meteorological conditions, agricultural treatments and crops. Thermal properties of soils play an important role in influencing the microclimate. These properties influence how energy is partitioned in the soil profile. As regards soil temperature, it is more accurately associated with the transfer of heat throughout the soil, by radiation, conduction and convection. Plants processes such as root growth or germination do not occur until the soil reaches certain temperature depending on the particular plant. Another plant process adversely affected by cold temperature is transport of nutrients and water. A better understanding of how different soils warm up would benefit agriculture by allowing better planning of planting of crops.

Table 1 : Thermal properties of all the sampling points

Sample No	Thermal Diffusivity (mm^2/s)	Thermal Conductivity (W/mK)	Volumetric Specific Heat (J/m^3K)	Bulk Density (mg/m^3)	Moisture Content (m^3/m^3)	Temperature (°C)
1	0.651	1.379	1.605	1.350	0.174	28.80
2	0.874	1.630	1.891	1.360	0.187	27.88
3	0.605	1.220	1.671	1.300	0.171	30.89
4	0.746	1.899	1.682	1.330	0.192	28.33
5	0.770	1.695	1.786	1.350	0.188	29.26
6	0.751	1.103	1.650	1.340	0.169	28.64
7	0.910	1.777	1.980	1.370	0.191	30.89

8	0.759	1.974	1.681	1.340	0.194	27.88
9	0.693	1.116	1.620	1.350	0.170	29.50
10	0.925	2.015	1.700	1.380	0.198	28.24
11	0.900	2.151	1.742	1.340	0.223	25.88
12	0.800	2.000	1.729	1.330	0.211	26.71
13	1.000	2.145	1.765	1.410	0.226	26.30
14	0.950	2.062	1.800	1.380	0.218	25.97
15	0.884	1.979	1.525	1.370	0.209	27.67
16	0.952	2.105	1.822	1.400	0.216	27.40
17	0.850	1.876	1.524	1.370	0.199	28.38
18	0.757	1.777	1.522	1.350	0.194	28.54
19	0.740	2.001	1.624	1.330	0.210	27.87
20	0.850	2.112	1.784	1.360	0.213	28.13
21	0.712	1.696	1.625	1.300	0.162	29.73
22	0.645	1.183	1.608	1.310	0.159	29.82
23	0.584	1.443	1.468	1.290	0.155	29.36
24	0.500	1.529	1.597	1.270	0.155	27.61
25	0.486	1.409	1.446	1.290	0.151	29.61
26	0.462	1.873	1.456	1.280	0.152	29.06
27	0.439	1.525	1.247	1.260	0.146	28.35
28	0.614	1.350	1.420	1.310	0.152	29.00
29	0.600	1.412	1.640	1.290	0.163	28.46
30	0.740	1.520	1.645	1.320	0.168	28.30
31	0.850	1.600	2.016	1.350	0.203	23.82
32	0.864	1.883	2.936	1.360	0.210	24.26
33	0.990	1.920	2.748	1.380	0.212	25.00
34	0.845	1.416	1.983	1.360	0.198	24.69
35	0.835	1.775	2.547	1.340	0.209	25.76
36	0.843	1.595	1.990	1.350	0.201	29.17
37	0.820	1.354	1.887	1.300	0.198	32.30
38	0.846	1.426	2.018	1.340	0.203	24.45
39	0.900	1.526	2.223	1.360	0.206	25.01
40	0.830	1.400	1.998	1.320	0.199	24.91
41	0.850	1.456	2.000	1.350	0.202	26.24
42	0.940	1.800	2.334	1.370	0.209	24.01
43	0.982	1.875	2.116	1.380	0.210	23.21
44	0.930	1.690	2.335	1.360	0.208	34.49
45	0.838	1.580	1.990	1.330	0.200	27.12

Table 2 : Thermal and physical properties of soil in the maize field

Sample No	Thermal Conductivity (W/mK)	Thermal Diffusivity (mm^2/s)	Volumetric Specific Heat (J/m^3K)	Temperature (°C)	Moisture Content (m^3/m^3)	Bulk Density (mg/m^3)
1	1.379	0.651	1.605	28.80	0.174	1.350
2	1.630	0.874	1.891	27.88	0.187	1.360
3	1.220	0.605	1.671	30.89	0.171	1.300
4	1.899	0.746	1.682	28.33	0.192	1.330
5	1.695	0.770	1.786	29.26	0.188	1.350
6	1.103	0.751	1.650	28.64	0.169	1.340
7	1.777	0.910	1.980	30.89	0.191	1.370
8	1.974	0.759	1.681	27.88	0.194	1.340
9	1.116	0.693	1.620	29.50	0.170	1.350
10	2.015	0.925	1.700	28.24	0.198	1.380

Table 3 : Thermal and physical properties of soil in the pineapple field

Sample No	Thermal Conductivity (W/mK)	Thermal Diffusivity (mm^2/s)	Volumetric Specific Heat (J/m^3K)	Temperature (oC)	Moisture Content (m^3/m^3)	Bulk Density (mg/m^3)
1	2.151	0.900	1.742	25.88	0.223	1.340
2	2.000	0.800	1.729	26.71	0.211	1.330
3	2.145	1.000	1.765	26.30	0.226	1.410
4	2.062	0.950	1.800	25.97	0.218	1.380
5	1.979	0.884	1.525	27.67	0.209	1.370
6	2.105	0.952	1.822	27.40	0.216	1.400
7	1.876	0.850	1.524	28.38	0.199	1.370
8	1.777	0.757	1.522	28.54	0.194	1.350
9	2.001	0.740	1.624	27.87	0.210	1.330
10	2.112	0.850	1.784	28.13	0.213	1.360

Table 4 : Thermal and physical properties of soil in the cowpea field

Sample No	Thermal Conductivity (W/mK)	Thermal Diffusivity (mm2/s)	Volumetric Specific Heat (J/m3K)	Temperature (oC)	Moisture Content (m3/m3)	Bulk Density (mg/m3)
1	1.696	0.712	1.625	29.73	0.162	1.300
2	1.676	0.645	1.608	29.82	0.159	1.310
3	1.529	0.584	1.468	29.36	0.155	1.290
4	1.525	0.500	1.597	27.61	0.155	1.270
5	1.412	0.486	1.446	29.61	0.151	1.290
6	1.525	0.462	1.456	29.06	0.152	1.280
7	1.409	0.439	1.247	28.35	0.146	1.260
8	1.536	0.614	1.420	29.00	0.152	1.310
9	1.691	0.600	1.640	28.46	0.163	1.290
10	1.873	0.740	1.645	28.30	0.168	1.320

Table 5 : Thermal and physical properties of soil in the okro+vegetable field

Sample No	Thermal Conductivity (W/mK)	Thermal Diffusivity (mm^2/s)	Volumetric Specific Heat (J/m^3K)	Temperature (°C)	Moisture Content (m^3/m^3)	Bulk Density (mg/m^3)
1	1.600	0.850	2.016	23.82	0.203	1.350
2	1.883	0.864	2.936	24.26	0.210	1.360
3	1.920	0.990	2.748	25.00	0.212	1.380
4	1.416	0.845	1.983	24.69	0.198	1.360
5	1.775	0.835	2.547	25.76	0.209	1.340
6	1.595	0.843	1.990	29.17	0.201	1.350
7	1.354	0.820	1.887	32.30	0.198	1.300
8	1.426	0.846	2.018	24.45	0.203	1.340
9	1.526	0.900	2.223	25.01	0.206	1.360
10	1.400	0.830	1.998	24.91	0.199	1.320
11	1.456	0.850	2.000	26.24	0.202	1.350
12	1.800	0.940	2.334	24.01	0.209	1.370
13	1.875	0.982	2.116	23.21	0.210	1.380
14	1.690	0.930	2.335	34.49	0.208	1.360
15	1.580	0.838	1.990	27.12	0.200	1.330

Table 6 : Statistical summary of soil thermal properties, moisture content and bulk density on individual crop field

	Whole Site	Maize	Pineapple	Cowpea	Okro+vegetable
Thermal Conductivity					
SD	0.342	0.334	0.115	0.179	0.187
Mean	1.488	1.581	2.021	1.494	1.62
CV (%)	23	21.1	5.7	12	11.5
Volumetric Specific Heat					
SD	0.342	0.116	0.116	0.123	0.304
Mean	1.831	1.727	1.684	1.515	2.208
CV (%)	18.7	6.7	6.9	8.1	13.8
Thermal Diffusivity					
SD	0.145	0.1	0.082	0.099	0.055
Mean	0.785	0.768	0.868	0.578	0.878
CV (%)	18.5	13	9.4	17.1	6.3
Moisture Content					
SD	0.022	0.011	0.00936	0.0063	0.0047
Mean	0.191	0.183	0.212	0.156	0.205
CV (%)	11.5	6	4.4	4	2.3
Bulk Density					
SD	0.011	0.021	0.026	0.018	0.021
Mean	1.34	1.347	1.364	1.292	1.35
CV (%)	0.8	1.6	1.9	1.4	1.6

Plate 1 : KD 2 Pro

Plate 2 : TR-1 Sensor

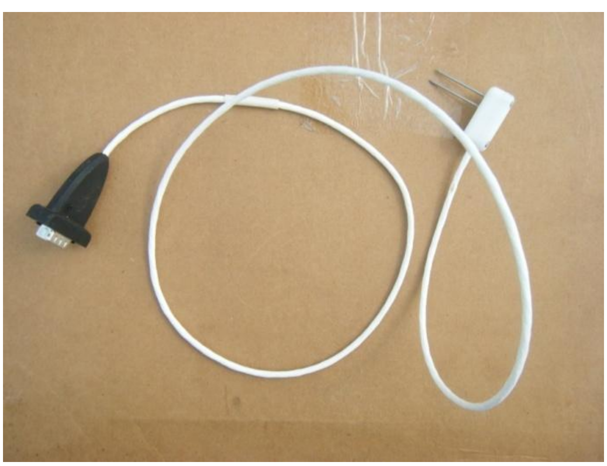


Plate 3 : SH-1 30mm Dual Sensor

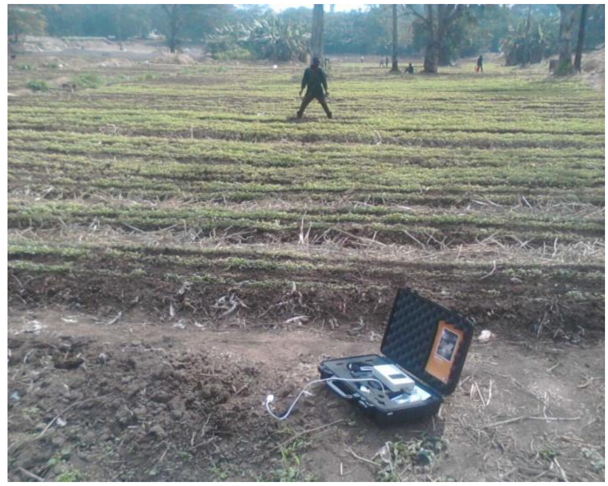


Plate 4 : KD 2 Pro Meter during measurement

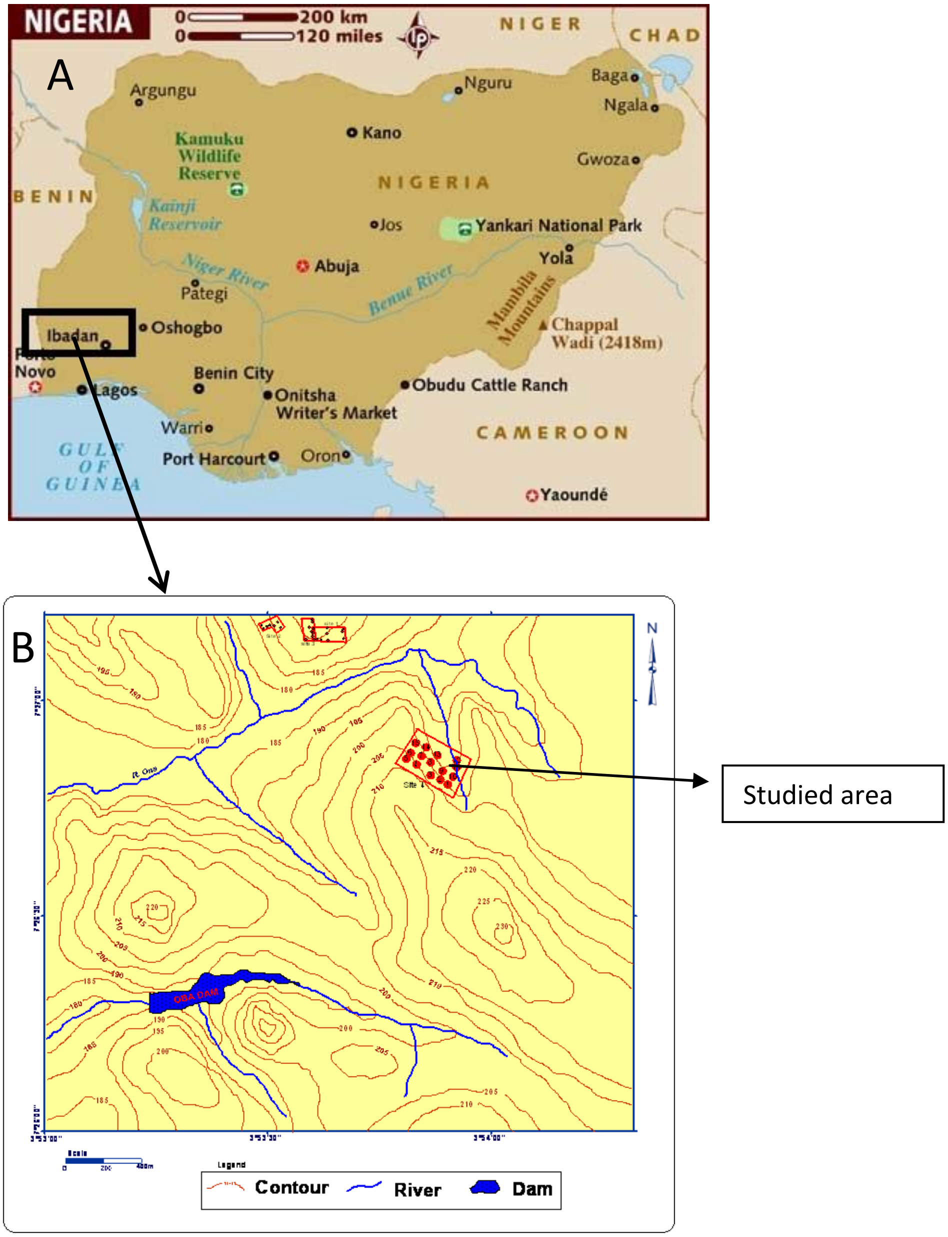


Figure 1 : (A) Topographical map of Nigeria showing Ibadan
(B) Topographical map of University of Ibadan showing studied area

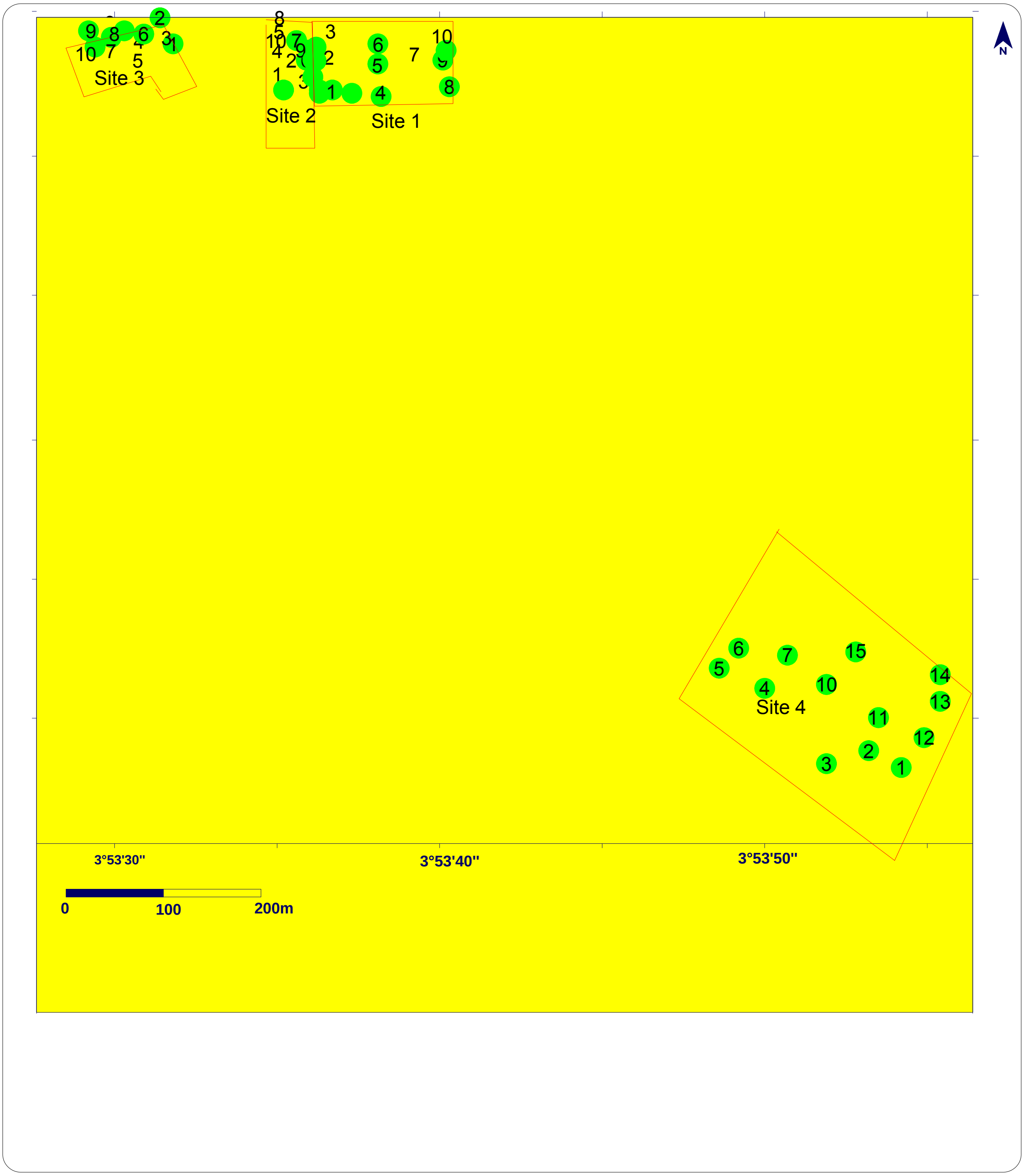


Figure 2 : Location map of the study area showing sites

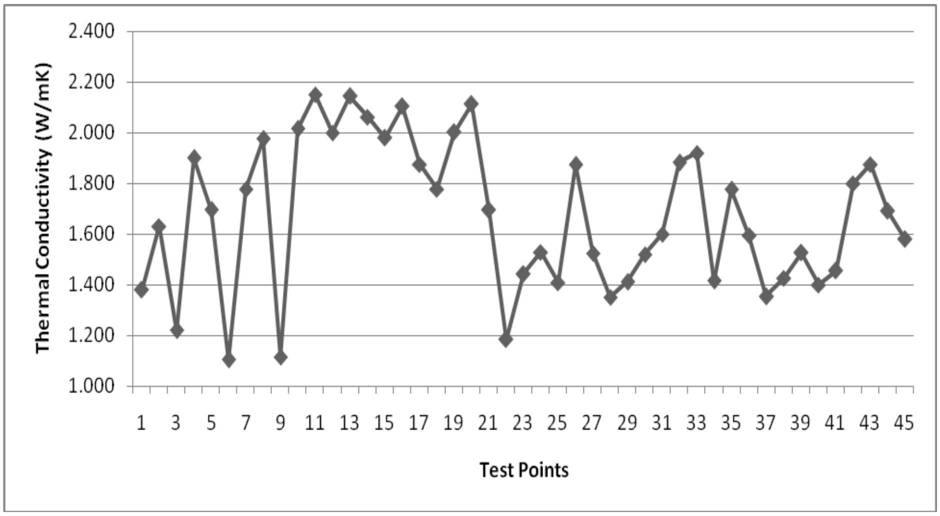


Figure 3 : Variation of Thermal Conductivity within the whole study site

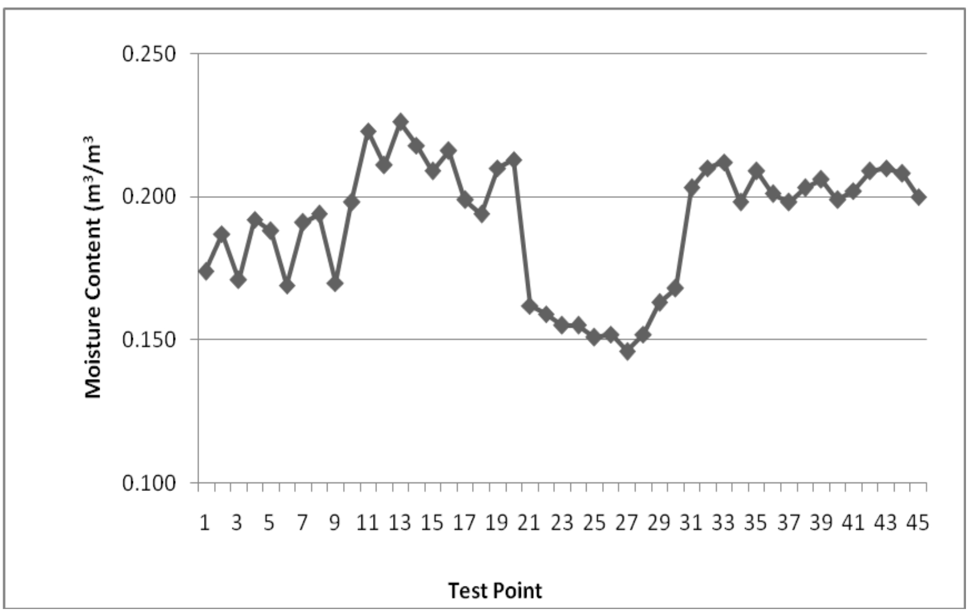


Figure 4 : Variation of Moisture content in the study site

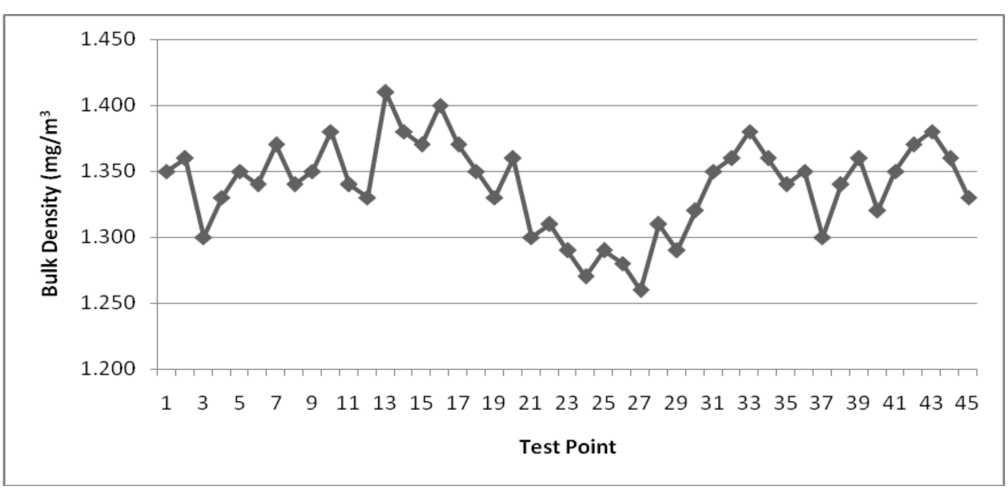


Figure 5 : Variation of Bulk density in the whole study site

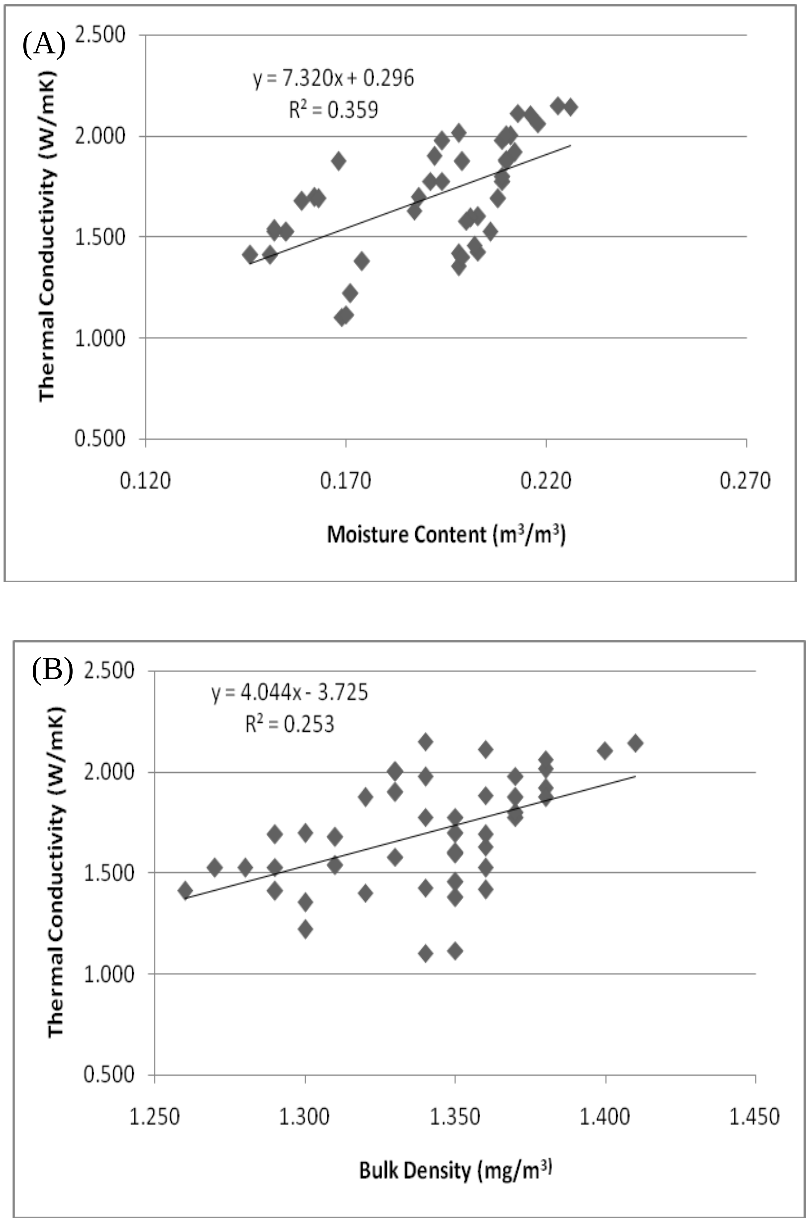
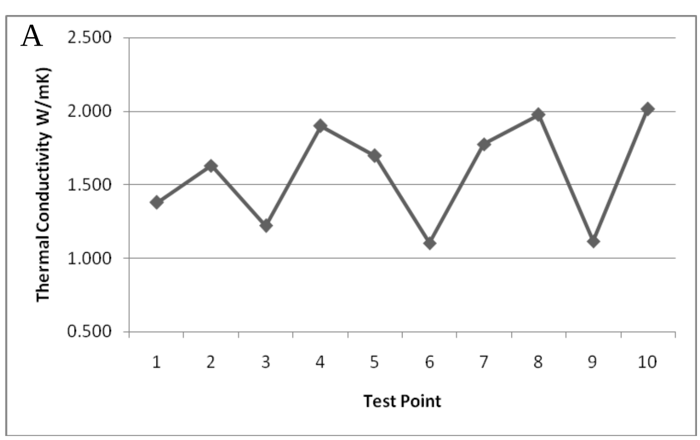


Figure 6 : Variation of thermal conductivity with (A) Moisture content (B) Bulk density



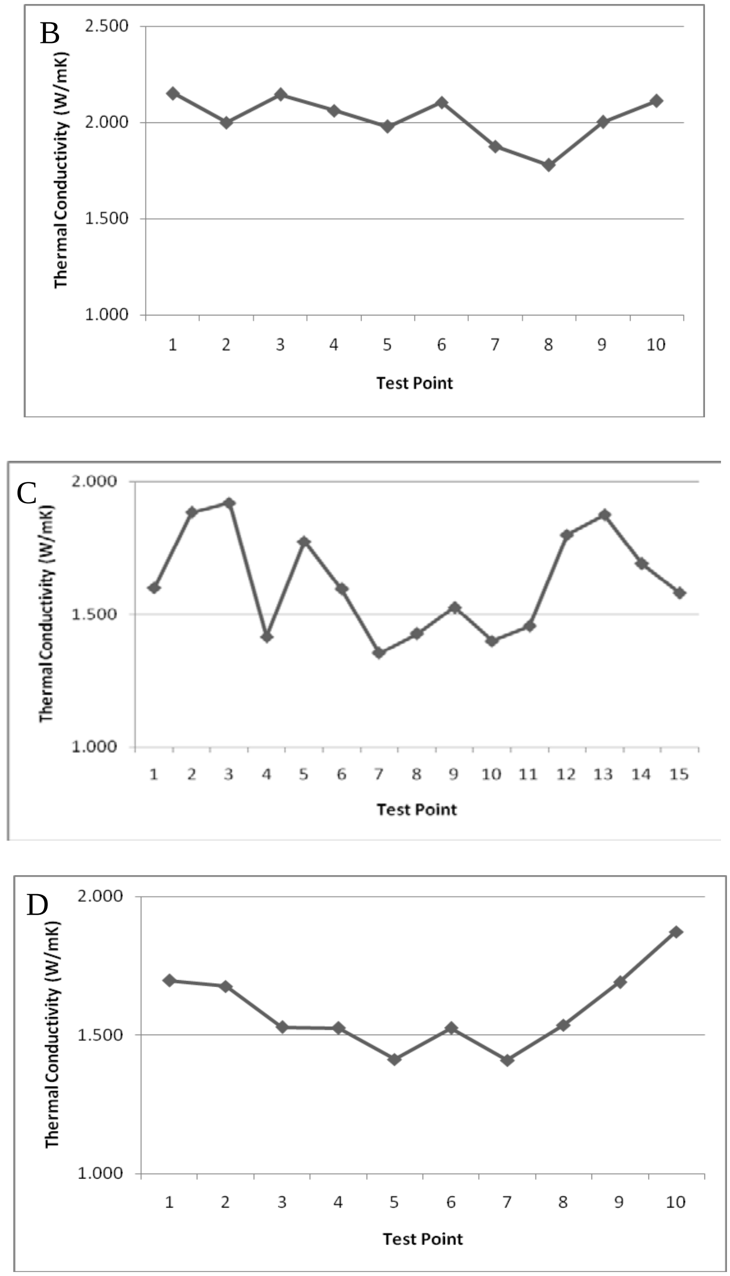
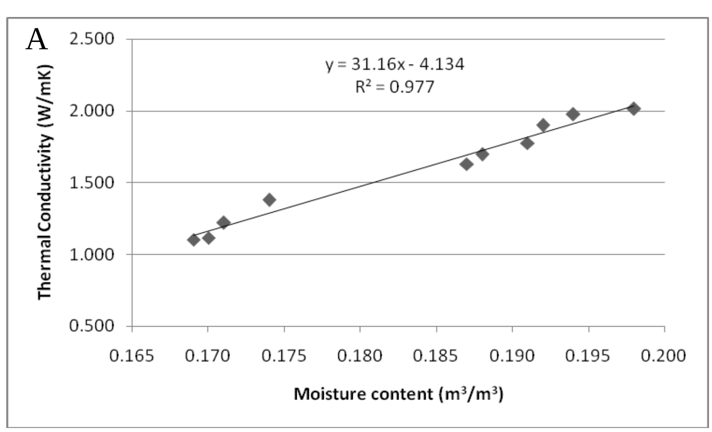


Figure 7 : Variation of thermal conductivity in all the fields (A) maize (B) Pineapple (C) cowpea and (D) Okro+vegetables



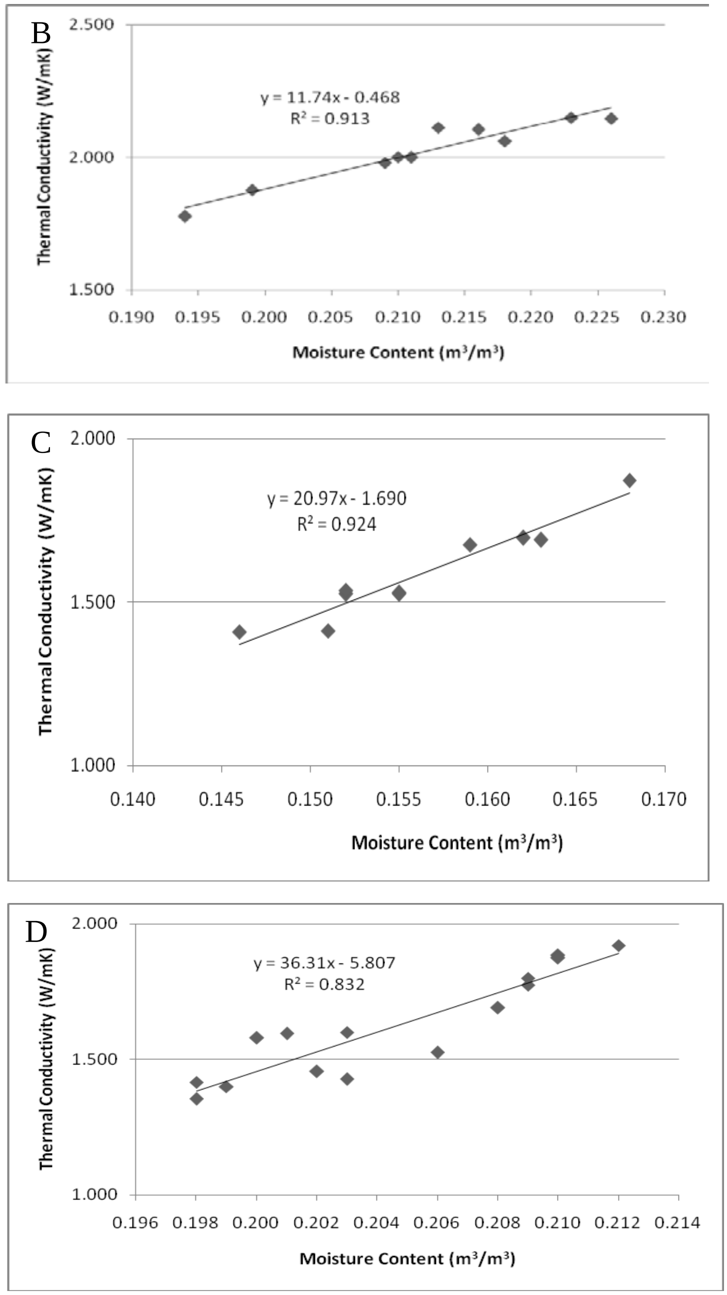
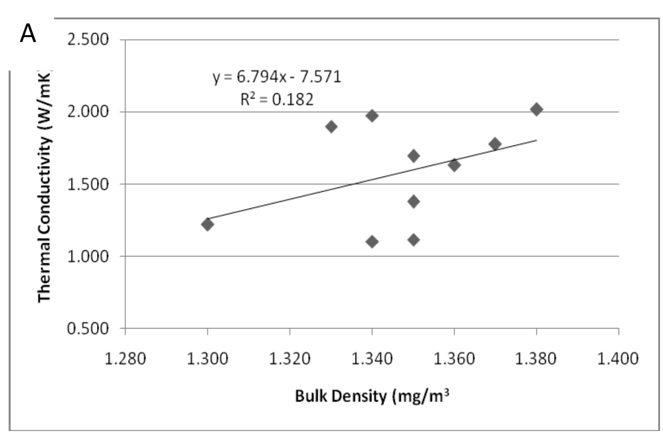


Figure 8 : Variation of thermal conductivity with moisture content in (A) maize (B) pineapple (C) cowpea and (D) okro +vegetable fields



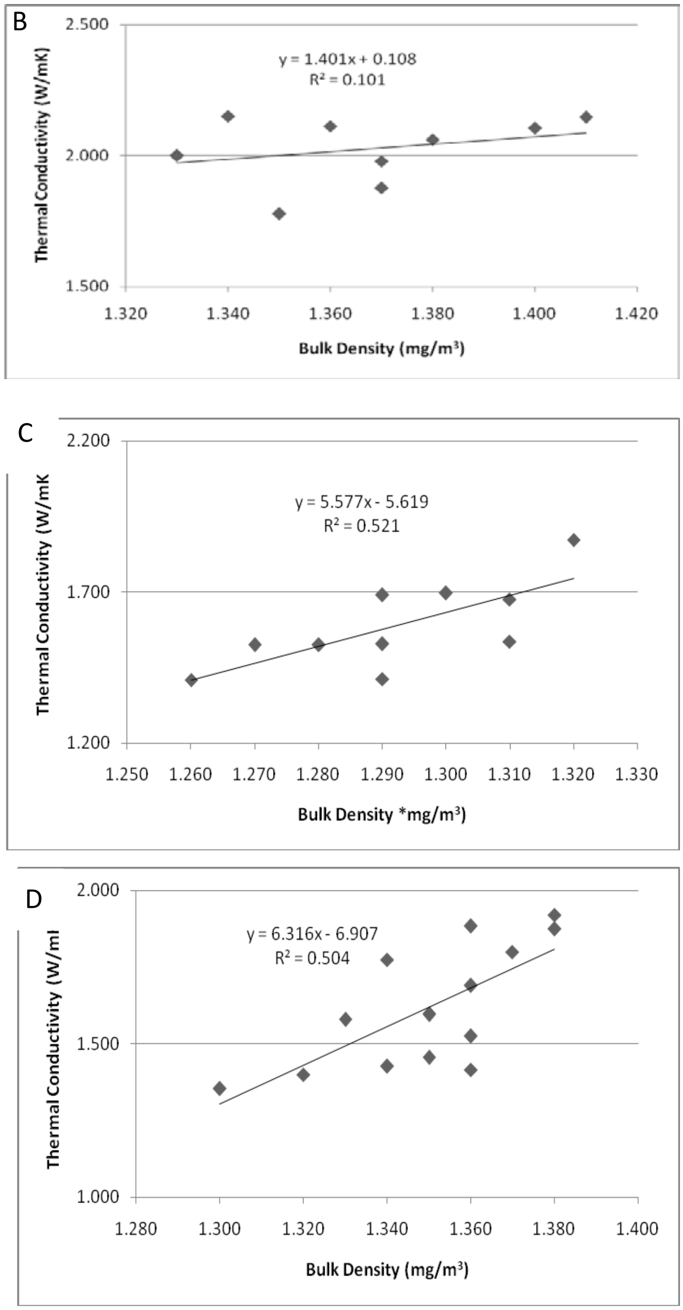


Figure 9 : Variation of thermal conductivity with Bulk density in (A) maize (B) pineapple (C) cowpea and (D) okro +vegetable fields

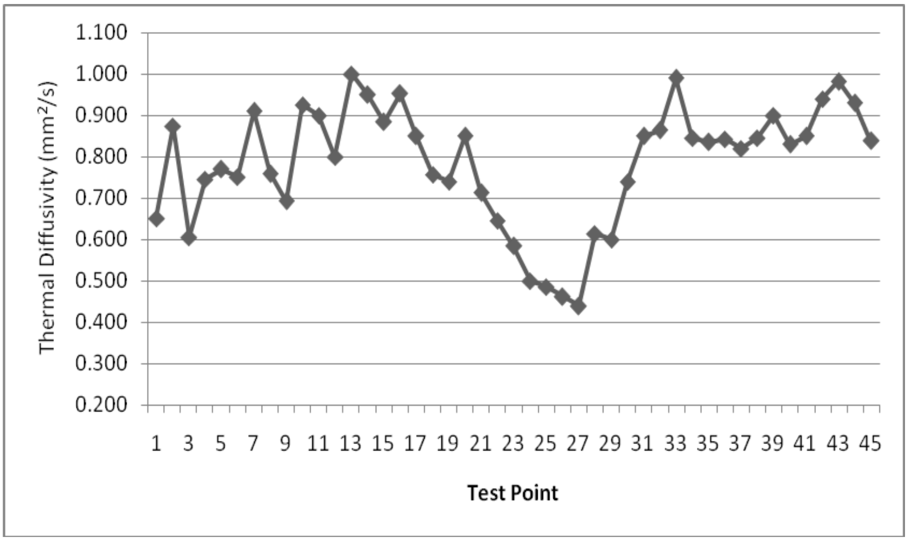


Figure 10 : Variation of thermal diffusivity in the whole study site

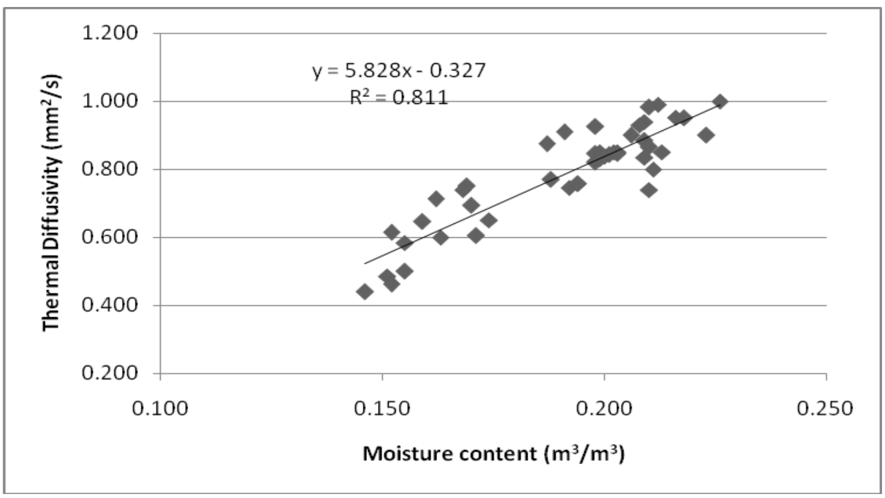


Figure 11 : Influence of Moisture content on thermal diffusivity in the whole study site

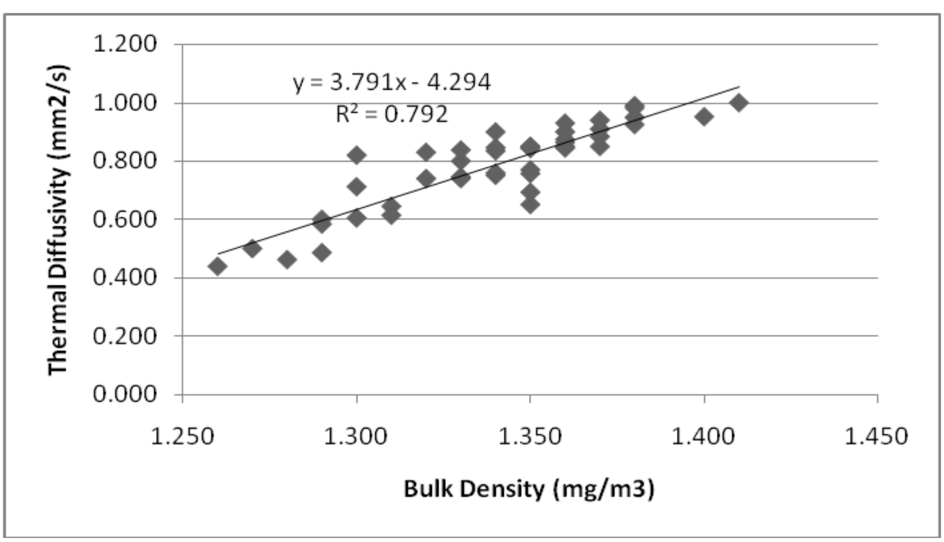


Figure 12 : Influence of Bulk Density on thermal diffusivity in the whole study site

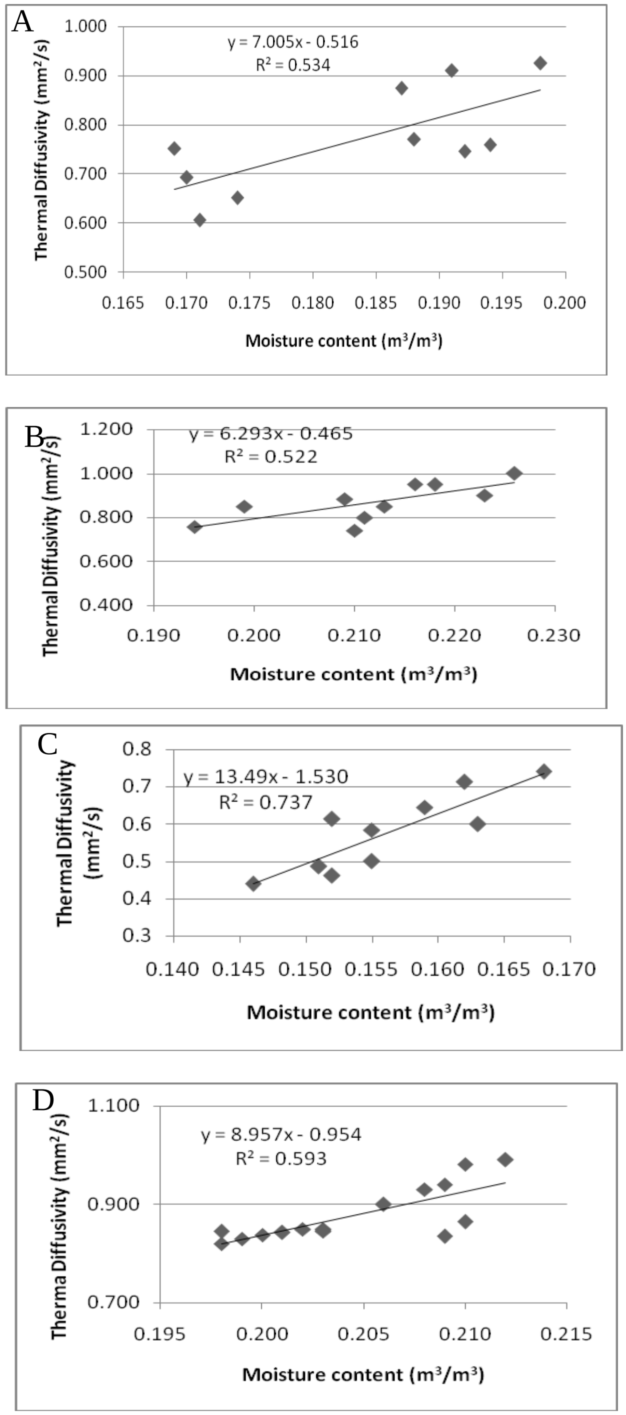


Figure 13 : Influence of moisture content on thermal diffusivity in (A) maize (B) pineapple (C) cowpea and (D) Okro+vegetable fields

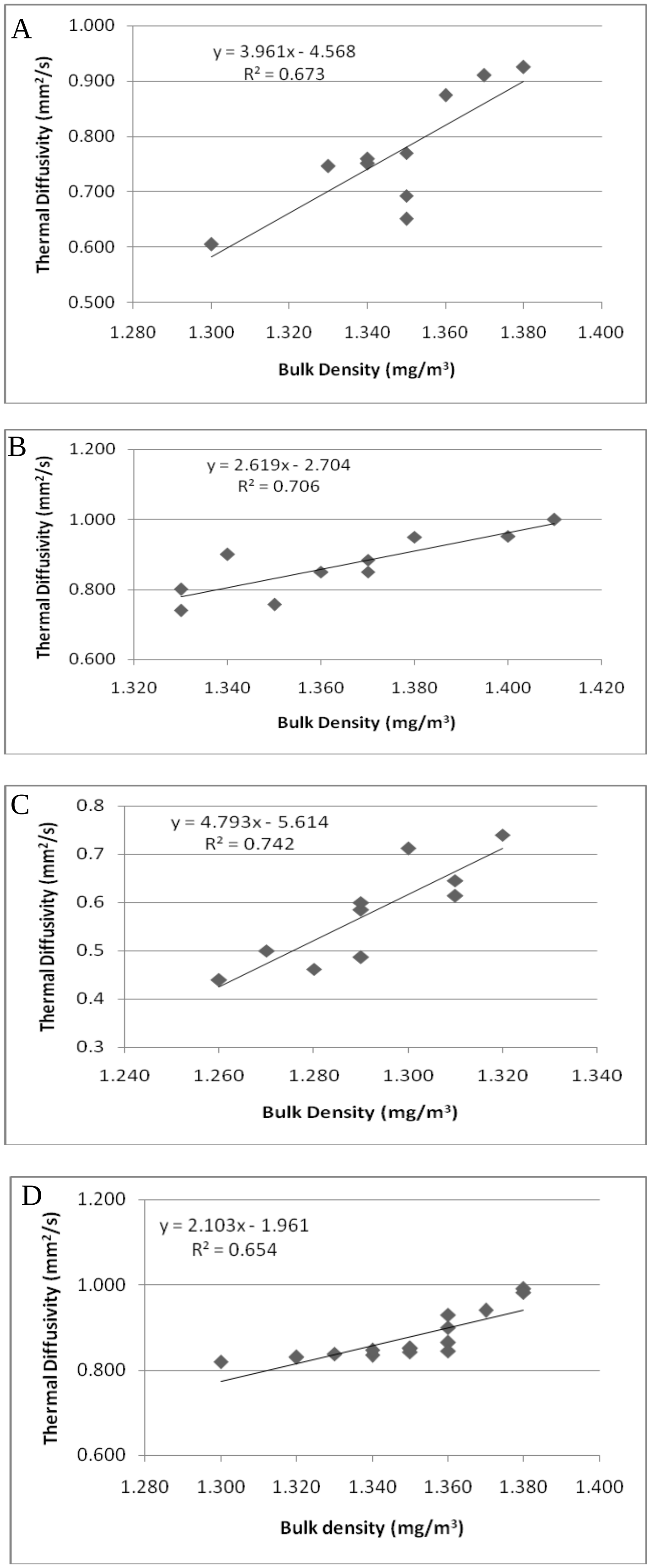


Figure 14 : Influence of Bulk density on thermal diffusivity in (A) maize (B) pineapple (C) cowpea and (D) Okro+vegetable fields

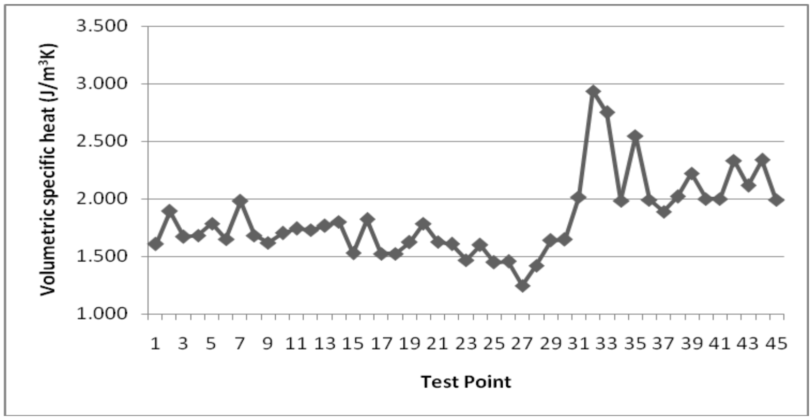


Figure 15 : Variation of volumetric specific heat in all the study sites

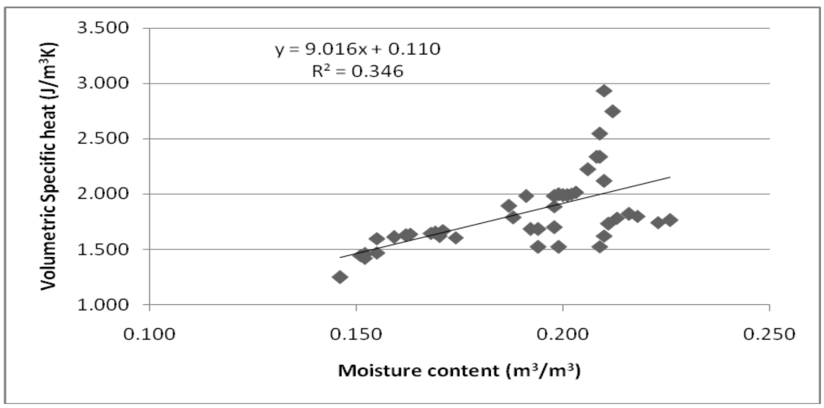


Figure 16 : Variation of volumetric specific heat with moisture content in the whole study site

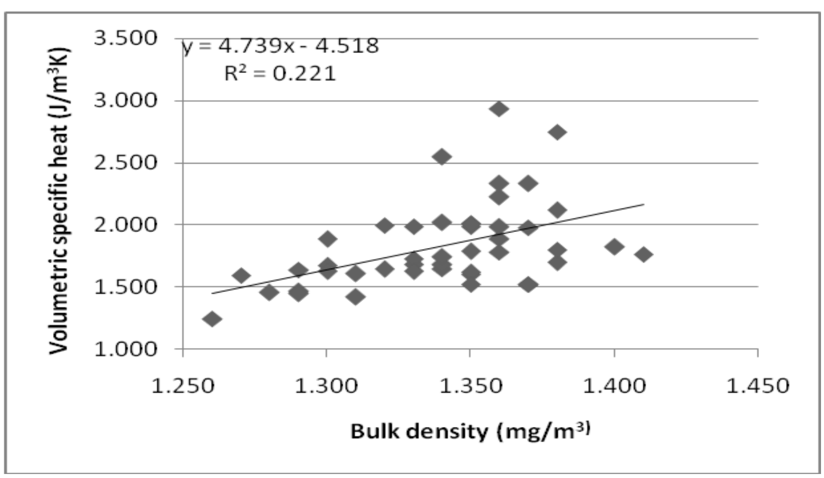


Figure 17 : Variation of volumetric specific heat with Bulk density in the whole study site

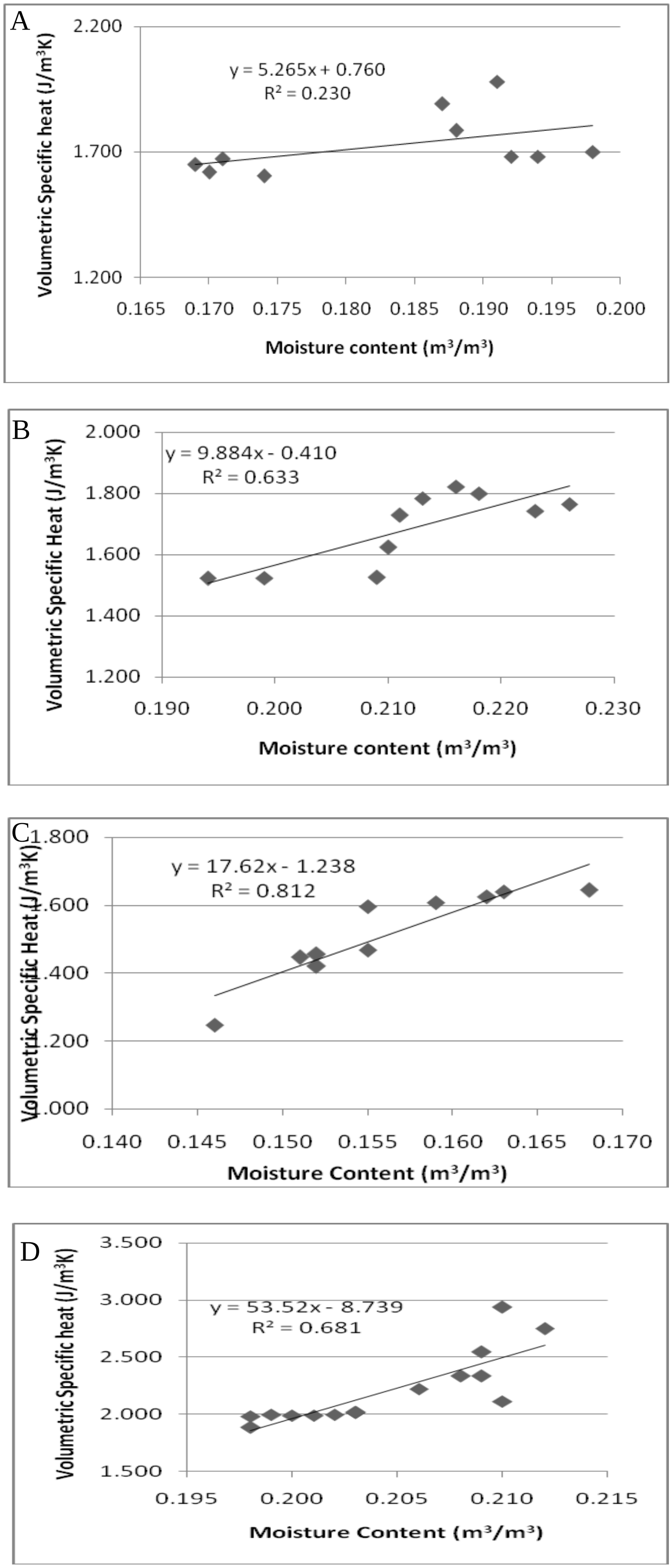


Figure 18 : Variation of volumetric specific heat with moisture content in (A) maize (B) pineapple (C) cowpea and (D) okro+vegetable fields

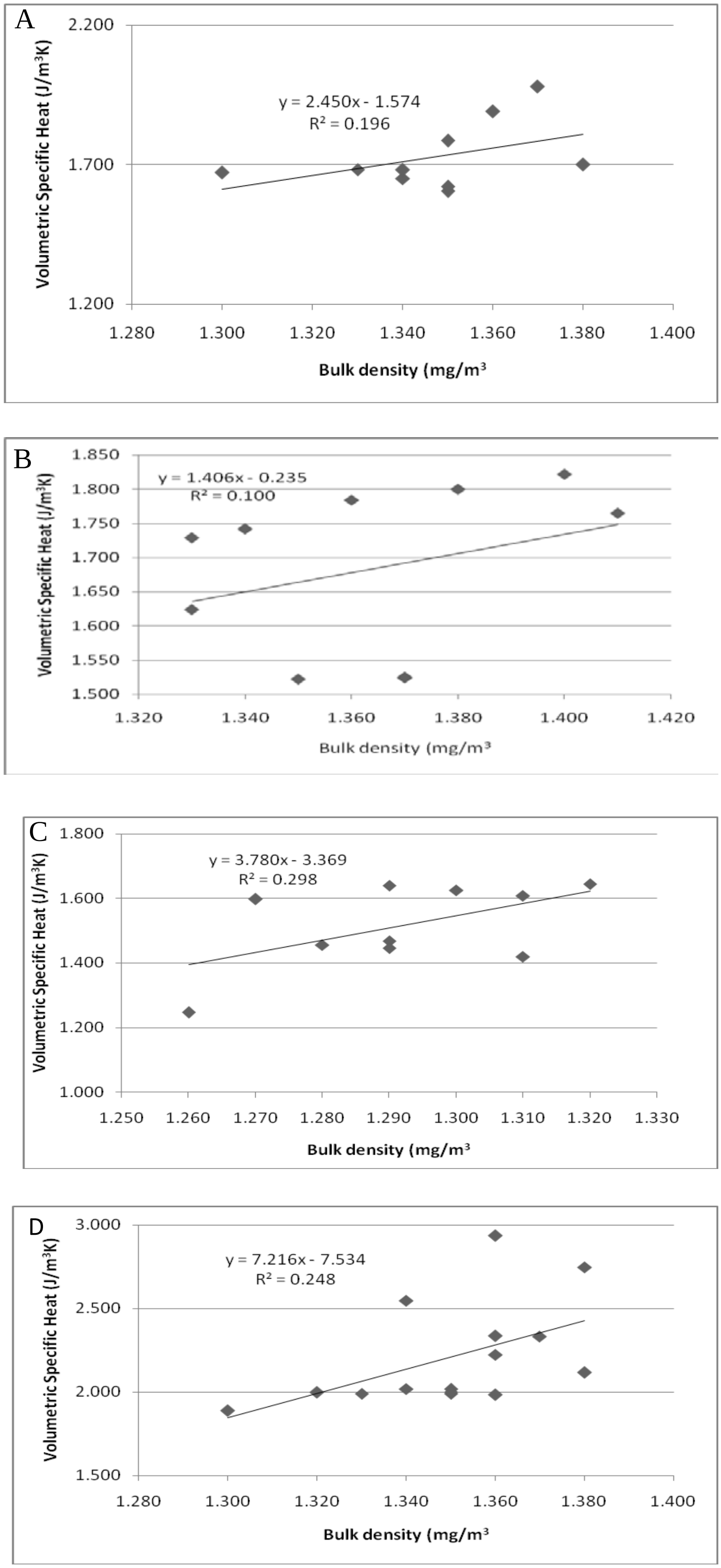


Figure 19 : Variation of volumetric specific heat with moisture content in (A) maize (B) pineapple (C) cowpea and (D) okro+vegetable fields

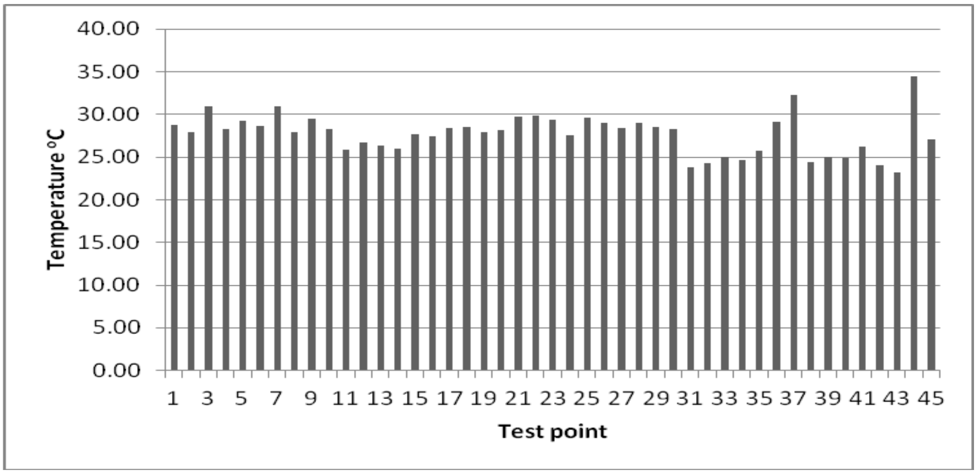
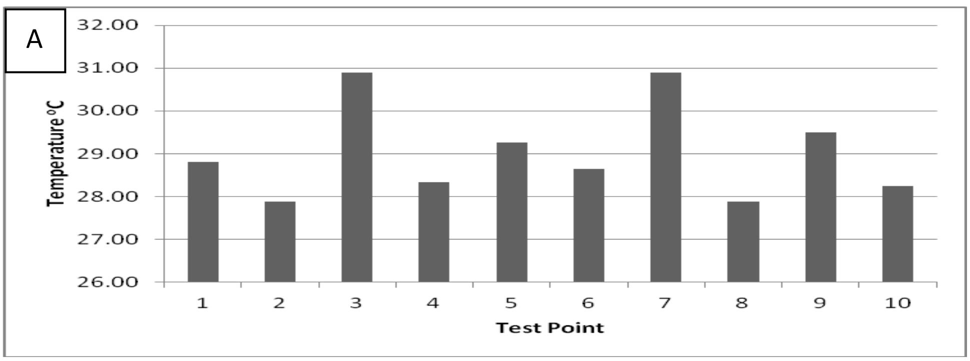
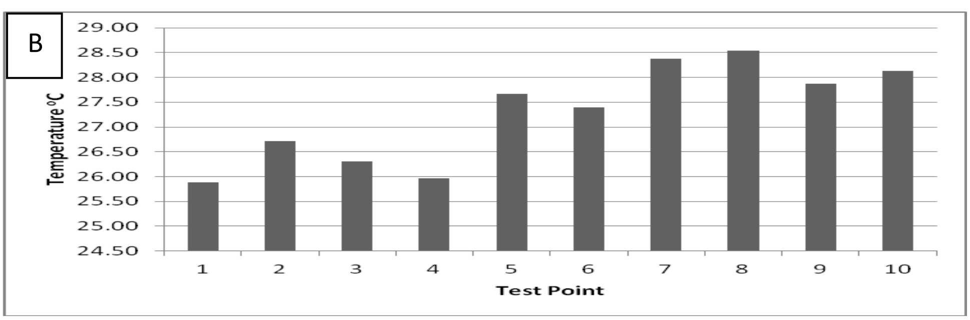
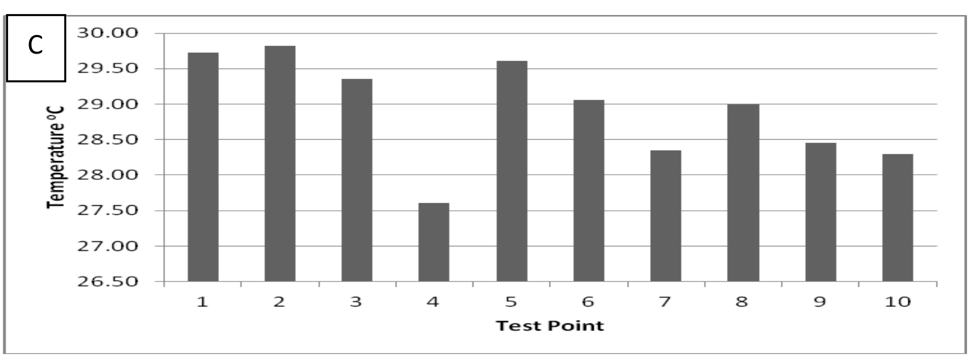


Figure 20 : variation of temperature in the whole site







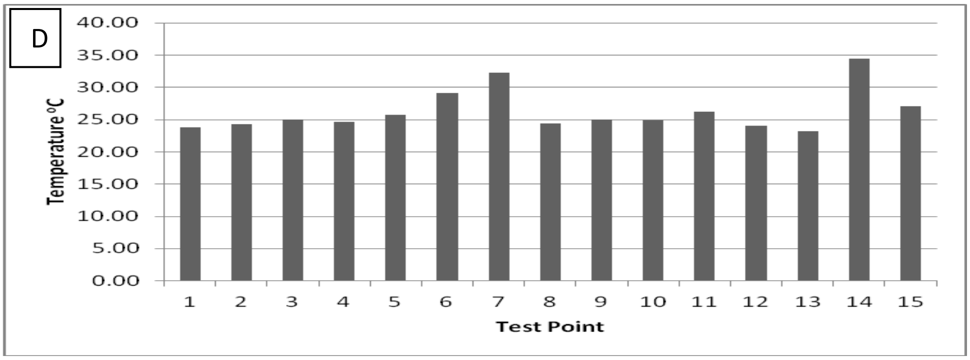


Figure 21 : Distribution of temperature in (A) maize (B) pineapple (C) cowpea and (D) okro+vegetable fields

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