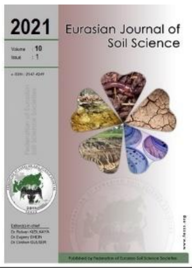
Eurasian Journal of Soil Science 2021, 10(1), 1 - 8

Eurasian Journal of Soil Science

Journal homepage : http://ejss.fesss.org



Variations in soil heat transfer under different land use types in Abia State, South eastern Nigeria

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Article Info

Received : 29.03.2019
Accepted : 03.09.2020
Available online : 21.09.2020

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Abstract

An in-depth knowledge on variations in soil heat transfer under different land uses is essential for proper understanding of the variations in thermal energy transfer under different human activities and modifications on land. This paper presents an investigation on the variations in soil heat transfer under different land use types in Abia State. This study evaluates three land use types: forest land (FL), continuously cultivated land (CC) and excavation site (EX). The parameters investigated in this study include; particle size distribution, bulk density, volumetric moisture content, atmospheric temperature, soil temperature, soil thermal conductivity, soil heat flux, soil volumetric heat capacity and soil thermal diffusivity. The results show that the different land use types studied influenced the soil heat energy transfer and had a significant effect on soil thermal properties. The results revealed that excavation site recorded the highest soil bulk density (1.70 Mg m^{-3}) and soil temperature (42.6^{o}C) while forest land recorded the lowest bulk density (1.36 Mg m^{-3}) and soil temperature (30.3^{o}C). The transmission of heat through a unit length of soil per unit cross-sectional area (2.476 W mk^{-1}) was higher in forest land than the other land use types studied. Soil under continuously cultivated land recorded the highest volumetric heat capacity (1.407 J $(m^3K)^{-1}$). This study will help farmers and land owners in terms of choice and management of different land use types for agricultural and industrial purposes.

Keywords: Soil heat energy transfer, bulk density, soil temperature, soil thermal conductivity, volumetric heat capacity, soil thermal diffusivity.

Introduction

Variations in soil temperature and related soil heat transfer processes are influenced by different land use types and soil management practices (Wang et al., 2018). As a result, it may be able to transform the processes of volumetric heat capacity, thermal conductivity and diffusivity of heat from soil to the surrounding. The knowledge of land use types and soil heat transfer is important for effective soil energy balance at different land uses. The soil thermal properties play a major role in governing the exchange of energy between the soil and atmosphere (Alrtimi et al., 2016). Some land use types in Nigeria include; arable land (Ogeh and Ogwuruike, 2006), excavation and refuse dump sites (Oguike and Onwuka, 2017), oil palm, secondary forest and building sites (Senjobi and Ogunkunle, 2011). Forest land use type allows only about 5 to 20% of the shortwave solar radiation to the surface of the soil (Beltrami, 2001). However, changing forest land use to arable land or excavation sites extensively increases the measure of solar radiation that touches the soil surface, which causes significant modifications in the soil thermal process and energy transfer in soil (Geiger et al., 1995). The presence of leaves from litter fall, tree cover and crop residues reduce the effect of solar radiation impact on the soil thermal properties and heat energy transfer in the soil, thereby reducing

: https://doi.org/10.18393/ejss.797843
: http://ejss.fesss.org/10.18393/ejss.797843
Publisher : Federation of Eurasian Soil Science Societies
e-ISSN : 2147-4249

soil biological and chemical processes (Onwuka, 2016). The transformation of pasture and forest lands into crop lands is known to cause the increase in soil thermal properties and heat energy transfer (Beltrami, 2001) and such soils may become more susceptible to increased oxidation of organic materials and other soil biochemical processes (Fierrer et al., 2005). Excavation sites increases soil temperature and heat transfer in soils which may cause the depletion of organic matter through faster decomposition of organic materials (Broadbent, 2015). Continuous tillage alters soil structure, pore size distribution and break the continuity of macropores in the soil thereby resulting to high soil heat energy transfer. This may cause heat-induced cracks in the sand-sized particles that will consequently result to disintegration and reduced amount of sand-sized particles in the soil (Onwuka, 2016).

Knowledge of the variations in soil heat transfer under different land uses is imperative in the determination of soil heat energy balance for a particular land use as well as the management strategies to be adopted to maintain such energy balance. Therefore, the objectives of the study were to investigate the variations in soil thermal properties under different land use types.

Material and Methods

Study area

The study was executed in three locations in Abia state, South-eastern Nigeria (Figure 1). The locations are characterized by a mean annual rainfall of 2201.92mm (Nigeria Meteorological Agency, 2015). The rainfall of the study area is bimodal, which starts in April and ends in October with peaks observed in June and September (Nigeria Meteorological Agency, 2015). The mean annual temperature of the area ranges from 25 – 27°C. The soil is identified by changes in topography and parent materials as a result of uplands and inland valleys within the rural landscape underlain by coastal plain sands and shale (Chukwu et al., 2014). Due to the changes in topography and parent materials, there is an increased potential for different land uses ranging from arable crop and tree crop production to forestry, animal husbandry and fishery.

Within the study area continuously cultivated land, forestland and excavation site were investigated. The continuously cultivated land was studied in Ikwuano local government area, while forestland and excavation sites were studied in Umuahia south and Ohafia local government areas, respectively. The forestland had stayed for almost 60 years with trees such as Miliciaexcelsa (iroko), Swieteniamahagoni (mahogany) and Gamelinaarborea (gmelina) whereas the continuously cultivated land has been under continuous cultivation of crops such as sweet potato, maize, cassava and fluted pumpkin for about 8 years. The excavation site has been used for mining of laterites (for road construction and housing) for more than 7 years.

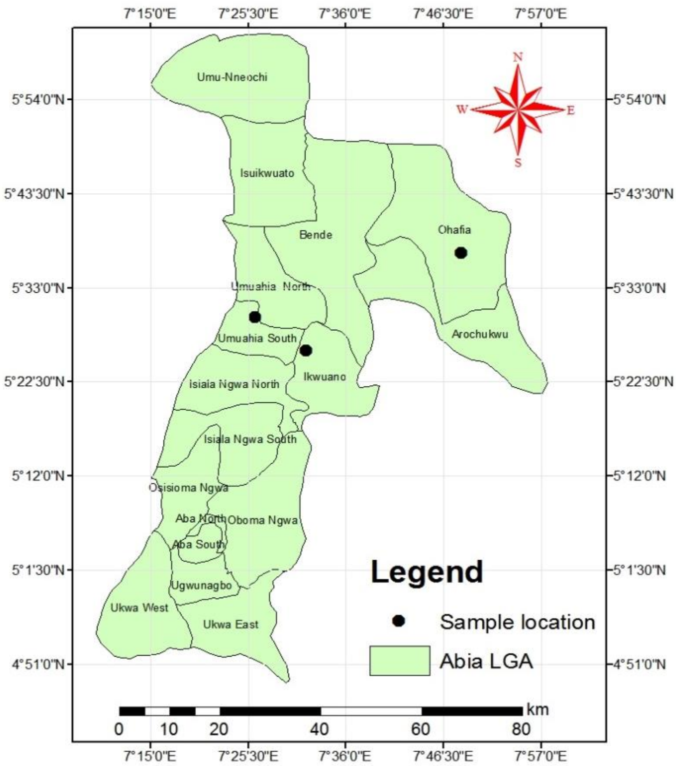

Figure 1. Map of the study area

Field method

Under each of the land use systems, three sampling points were randomly located. In each of the 3 sampling points within a land use, field measurements of soil temperature and volumetric moisture content in 0–5 and 5–10 cm depth were taken daily for a period of 24 weeks (6 months). Soil core samples for bulk density determination were also collected in 0 – 10 cm depth from the designated sampling points within each land use type.

Determination and calculation of soil properties studied

Particle size analysis was determined in the laboratory using Bouyoucos hydrometer procedure as defined by Kettler et al. (2001).

Soil bulk density (Bd) was determined in the laboratory by the method described by Blake (2003) using the equation.

$$\text{Bulk density (Bd)} = \frac{mass\ of\ dry\ soil\,(Mg)}{volume\ of\ the\ soil\ sample} \tag{1}$$

The volumetric moisture content (VMC) was calculated by gravimetric methods of field soil at a depth of 0 – 20 cm as described by Smith (2000) using the equation:

$$\text{Volumetric moisture content (VMC)} = \frac{mc \times Bds}{Bdw} \tag{2}$$

Where mc = moisture content in percentage; Bds = soil bulk density (Mg m^{-3}); Bdw = water density (Mg m^{-3}).

Soil temperature (T) was determined in the field in 0 – 5 and 5 – 10 cm depths using soil mercury-in-glass thermometer as described by Nwankwo and Ogagarue (2012).

Thermal conductivity (K) was determined using Stefan's Boltzmann equation (Gwani et al., 2013).

$$\text{Rt} = K\frac{\Delta T}{\Delta D} \tag{3}$$

Where, Rt = rate of conduction of heat per unit area.

$$\text{Rt} = \delta(\text{TA})^4 \tag{4}$$

(Stefan's Boltzmann equation)

δ = 5.67×10^{-8} MW^{-2}K^{-4}
TA = Temperature of soil at 0 – 5 cm depth
Ts = Temperature of soil at 0 – 10 cm depth
ΔT = Difference between the temperature at 0–5 cm depth (TA) and temperature at 5–10 cm depth (TS)

$$\Delta \text{T} = \text{TS} - \text{TA} \tag{5}$$

ΔD = Depth of the soil
K = Thermal conductivity of the soil

Volumetric heat capacity (CV) was calculated from the volumetric water content (VMC) and soil bulk density (Bd) as described by Evett et al. (2012).

$$\text{Volumetric heat capacity (CV)} = \frac{2.02 \times 10\,Bd}{.65 + 4.19 \times 10\,VMC} \tag{6}$$

Thermal diffusivity (D) was calculated from thermal conductivity (K) and volumetric heat capacity (CV);

$$\text{Thermal diffusivity (D)} = \frac{k}{cv} \tag{7}$$

Soil heat flux (Q) was calculated from thermal conductivity (K) and temperature (T).

$$\text{Heat flux (Q)} = K\frac{\Delta T}{\Delta Z} \tag{8}$$

Statistical analysis

The data generated under soil heat transfer were subjected to time series analysis which was used to determine the effects of different land use types on the measured soil thermal properties over a period of time. The data generated for the selected soil physical properties was subjected to analysis of variance and the means separated using Fisher's least significant difference (FLSD).

Results and Discussion

Particle size distribution and bulk density

The texture of soils was observed to be loamy sand in continuously cultivated land (CC), sandy loam in forest land (FL) and sandy clay in excavation site (EX) (Table 1). The particle sizes of forest land were significantly ($P \leq 0.05$) different from CC and EX. The Table 1 also showed the variations in bulk density under different land use types. Excavation site recorded the highest bulk density (1.70 Mg m^{-3}), while forest land with a bulk density of 1.36 Mg m^{-3} had the lowest.

Table 1. Particle size distribution and bulk density of the soils studied

Land use	Sand (%)	Silt (%)	Clay (%)	Textural class	Bd (Mg m^{-3})
CC	763.00	160.40	76.60	Loamy sand	1.70
FL	721.00	110.00	169.00	Sandy loam	1.36
EX	539.00	20.00	441.00	Sandy clay	1.88
LSD	20.15	11.20	15.60		

CC = continuously cultivated land; FL = forest land; EX = excavation site

The higher sand contents of the soils could be as a result of their being produced from unconsolidated deposits of sand formed over coastal plain sand (Asawalam et al., 2009; Chukwu, 2013). The removal of vegetative cover and top soil in continuously cultivated land due to severe cultivation may have exposed the soil thereby contributing to the high sand content resulting to its loamy sand texture (Jaiyeoba, 2003). The sandy loam texture in forest land, corroborated the observation of Ufot et al. (2016), who recorded sandy loam texture for a tree crop plantation and forest land in Alokwa, Imo State. The higher clay contents observed in excavation site could be due to increased mining activities (Oguike and Onwuka, 2017). This may be as a result of either increase in translocation of clay from the surface to belowground horizons or clay removal from the surface by runoff (Jaiyeoba, 2003). However, Shepherd et al. (2001) reported that changes in particle sizes as a result of land use do not show easily. The variation in bulk density observed under continuously cultivated land and excavation site may be attributed to the mechanical disruption of the pore arrangements by tillage and excavation activities, respectively (Celik, 2005). The lower bulk density of forest land may be due to the minimal soil disturbance and the presence of soil organisms in the forest (Cerdà and Jurgensen, 2008).

Atmospheric temperature

The temperature trend of the location under study over a period of 24 weeks is shown in Figure 2. The graph shows that the mean temperature was highest (28.4^{0}C) in week 14, whereas the 20th week had the lowest (25.2 ^{0}C) mean temperature. However, from 2nd week to the 7th week and from 16th week to 19th week the mean temperature was fairly constant. The location under study had experienced more 25.2 ^{0}C temperature per day. The figure shows an increasing trend in the temperature of the area. The average annual temperature increased in the range of 25.2 – 28.4 ^{0}C per week amid the study period. Erstwhile studies also indicate that warming has occurred across Nigeria (Ogolo and Adeyemi, 2009), at fluctuating rates but largely constant with global and African trends. The increasing temperature trend imposes its impact on crop production and industrial purposes by increasing the evaporative demand especially in regions where rainfall is scarce. Reduced seasonal precipitation with high evaporative demand may enhance the risks of low yields in rainfed crop production.

Soil temperature

The data of soil temperature under different land use types are shown in Figure 3. The result showed that the mean weekly soil temperature under continuously cultivated land (CC) ranged from 35.3^{o}C – 38.5^{o}C. Under forest land (FL) the mean weekly temperature of the soil was observed to fall within 30.3^{o}C – 33.5^{o}C while for excavation site (EX) the mean weekly temperature ranged from 40.0 ^{0}C – 42.6 ^{0}C. In Figure 1, it was observed that soil under excavation site had the highest mean temperature (42.6^{o}C), while forest land had the lowest (30.3 ^{o}C).

The higher soil temperature recorded in excavation site may be as a result of the greater net radiation that passes through the exposed soil surface (Ramakrishna et al., 2006). Savva et al. (2009) observed that the exposed soil surfaces (excavation site) have 10 to 20% lower albedo and higher thermal admittance, thus absorb more energy than that of continuously cultivated and forest land. The lower soil temperature under forest land may be as a result of little soil surface warming due to the dense leaf cover (Lim et al., 2008). Soil surface cooling by transpiration, evaporation and soil moisture associated with surface vegetative cover and tropical humid climate could have contributed to the lower soil temperature of the forest land (Xue and Shukla, 1993).

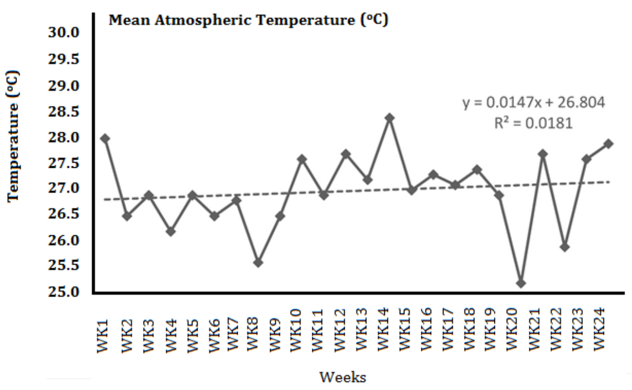

Figure 2. Mean weekly atmospheric temperature of the study area

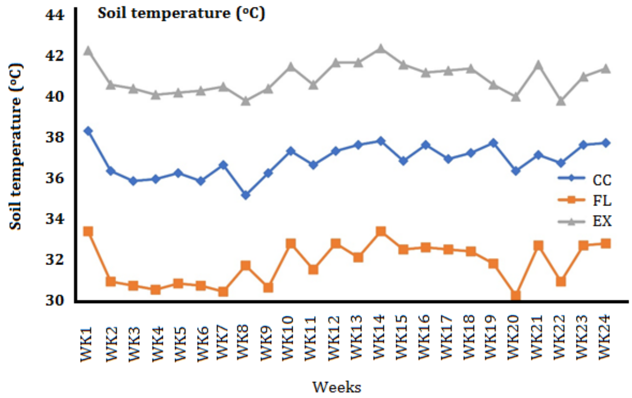

Figure 3. Mean weekly soil temperature studied

Volumetric moisture content

Figure 4 indicates the changes in volumetric moisture content in soil under different land use types. The result showed that the forest land had the highest volumetric moisture content ranging from 43.05 – 43.80 m^3 m^{-3} while excavation site had the lowest of 28.97 to 29.92 m^3 m^{-3}. However, the soil volumetric moisture content under continuously cultivated land varied from 35.71 – 36.22 m^3 m^{-3}. The higher volumetric moisture content recorded under forest and continuously cultivated land than in excavation site could have been caused by the presence of soil organisms which helped in producing high organic matter content which provided a larger surface area needed for the absorption and retention of water molecules (Oguike and Onwuka, 2018). The lower volumetric water content of soils under excavation site may be due to their higher capillary rise (as a result of the high clay content) which may have stimulated the evaporation of soil moisture (Nugraha et al., 2016). Uzoma and Onwuka (2018), reported that continuous evaporation of soil moisture reduced the volumetric moisture content of soil.

Thermal conductivity

The variations in thermal conductivity under different land use types is shown in Figure 5. According to the result, the thermal conductivity was higher in the soil under forest land than that of continuously cultivated land and excavation site. The result showed that the quantity of heat transmitted through a unit length of soil per unit cross-sectional area under continuously cultivated soil ranged from 0.741 – 1.080 W mk^{-1}. Under forest land, the thermal conductivity varied between 1.640 – 2.476 W mk^{-1} while for excavation site the thermal conductivity falls between 0.598 – 0.681 W mk^{-1}. The thermal conductivities were moderate as it falls within the standard range of measurement of 0.02 – 4.00 W mk^{-1} (Oladunjoye et al., 2013).

The higher quantity of heat transmitted through the soil under forest land may be as a result of increase in soil volumetric moisture content (Figure 3). Roxy et al., (2014) observed that the presence of moisture in the soil resulted to the development of a thin water film which bridges the gaps between the soil particles thereby improving the thermal contact between soil particles. O'Donnell et al. (2009) reported that the higher soil moisture content could have enhanced the effective contact area between the soil particles and also replaced the air in the soil pores, resulting to higher heat flow thereby resulting to increased thermal conductivity. The resulting increase in soil volume probably may have provided a larger heat flow and possibly increased the soil thermal conductivity.

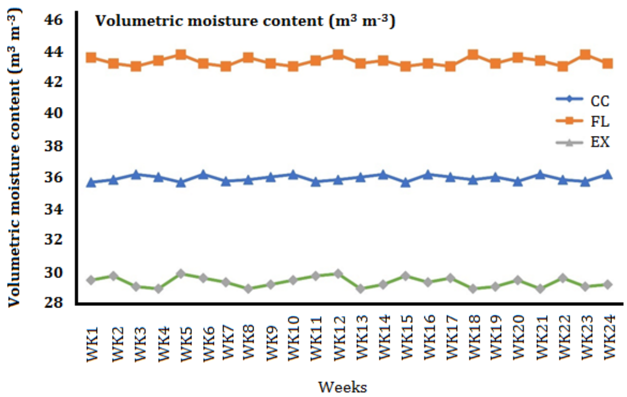

Figure 4. Volumetric moisture content of the soils studied

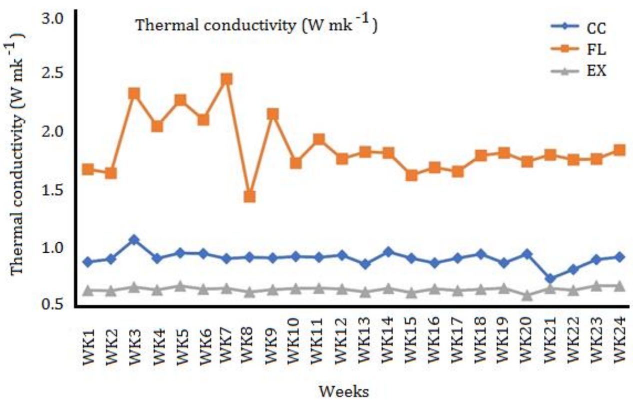

Figure 5. Thermal conductivity of the soils studied

Volumetric heat capacity

Figure 6 indicates the changes in volumetric heat capacity of the soil at different land use types. The result showed that the soil volumetric heat capacity under continuously cultivated land (CC) ranged from 1.386 – 1.407 J $(m^3K)^{-1}$. Under forest land (FL) the volumetric heat capacity of the soil was observed to fall within 1.342 – 1.386 J $(m^3K)^{-1}$ while for excavation site (EX) the soil volumetric heat capacity ranged from 1.267 – 1.290 J $(m^3K)^{-1}$. In Figure 5 it was observed that soil under continuously cultivated land had the highest volumetric heat capacity (1.407 J $(m^3K)^{-1}$), while excavation site had the lowest (1.267 J $(m^3K)^{-1}$). The changes in the volumetric heat capacity varied between the different land use types but it was highly noted in continuously cultivated land and forest land. The implications of increasing volumetric heat capacity in the soils under different land use types showed there is a positive correlation between volumetric water content and volumetric heat capacity. Gülser et al. (2019) showed that volumetric heat capacity increased from 0.497 cal cm^{-3} °C to 0.541 cal cm^{-3} °C by increasing volumetric water content from 0.286 cm^3 cm^{-3} to 0.330 cm^3 cm^{-3}. The higher volumetric heat capacity of the soil under continuously cultivated soil and forest land is probably due to adsorption of water (from soil moisture content) forming thick hulls around the soil particles, which greatly enhanced its effective heat capacity (Abu-Hamdeh, 2003).

Thermal diffusivity

Figure 7 shows the influence of different land use types on thermal diffusivity. According to the result, the soil thermal diffusivity of forest land was higher than that of continuously cultivated land and excavation site. The result showed that thermal diffusivity ranged from (0.534 – 0.779 m^2s^{-1}) under continuously cultivated land, (1.049 – 1.811 m^2s^{-1}) under forest land and (0.469 – 0.538 m^2s^{-1}) in excavation site. From the result, it was observed that the soil under excavation site had the lowest thermal diffusivity (0.469 m^2s^{-1}), while the soil of forest land under study had the highest (1.811 m^2s^{-1}).

The higher soil thermal diffusivity under forest land as compared with that of continuously cultivated land and excavation site agree with the findings of Beltrami (2001). The higher thermal diffusivity of the forest land may be attributed its higher volumetric moisture content (Figure 4) and lower bulk density (Table 1). Roxy et al. (2014) observed that as the soil moisture content increases, the thermal conductivity rises (Figure 5), because water is a good conductor of heat. Furthermore, since thermal diffusivity is directly proportional to thermal conductivity (equation VII), so when the soil moisture content increases, the thermal diffusivity also increases (Arkhangel'skaya, 2009). The soil with higher thermal diffusivity adjust quickly to their temperature to suit that of the environment because they tend to conduct heat quickly when compared to their volumetric heat capacity and they generally do not require much energy from their surroundings to reach thermal equilibrium (Oladunjoye and Sanuade, 2012).

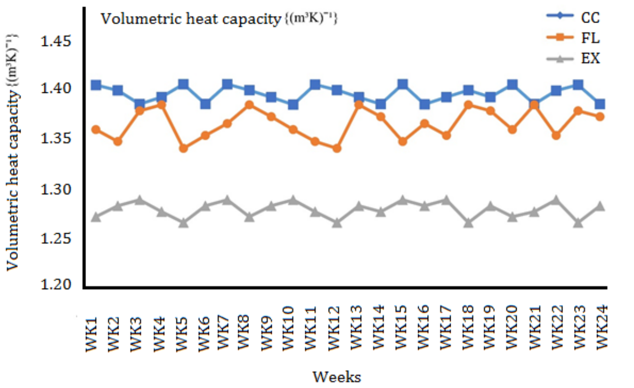

Figure. 6. Volumetric heat capacity of the soils studied

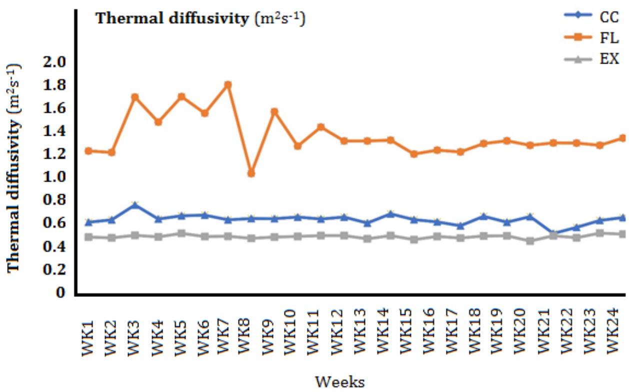

Figure 7. Thermal diffusivity of the soils studied

Heat flux

The data of soil heat flux under different land use types are shown in Figure 8. The result showed that the rate of soil heat transfer per unit area ranged from 27.64 – 38.88 $W.m^{-2}$ under continuously cultivated land, while under forest land the soil heat flux varied from 46.24 – 75.52 $W.m^{-2}$. However, the rate of soil heat transfer per unit area under excavation site ranged from 24.04 – 28.07 $W.m^{-2}$. From the results, it was observed that forest land had the highest soil heat flux followed by continuously cultivated land and excavation site. The higher soil heat transfer recorded in forest and continuously cultivated land may be as a result of the higher soil moisture content of the soil (Figure 4). Abu-Hamdeh (2003) observed that rate of heat transmissivity is faster in the soil with higher moisture content. O'Donnell et al. (2009) observed that changes in soil moisture content largely determine the variability in soil heat flux.

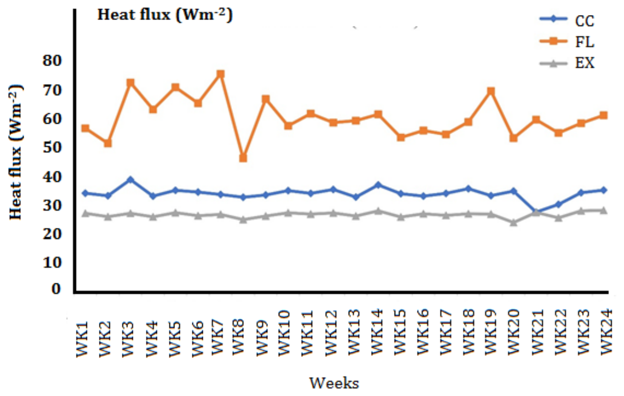

Figure 8. Heat flux of the soils studied

Conclusion

Variations in soil heat transfer under different land use types were studied in Abia state, Southeastern, Nigeria. The principal objective was to study the effects of different land use types on soil heat transfer. The result showed that the soil thermal properties varied among the different land use types. Excavation site had the highest soil temperature while forest land recorded the lowest. Higher soil bulk density and lower volumetric moisture content were observed in excavation site than in other land use types. The higher volumetric moisture content of forest land could have enhanced the increase in the amount of heat transferred and transmitted into the soil. This study suggests that the relationship between soil moisture content and heat transfer is of great importance to agriculture since it directly affects crop production. However, additional studies on the response of soil thermal properties to variations in soil moisture content are recommended.

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