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Sustainable Earth Trends

Journal homepage: http://sustainearth.sbu.ac.ir

Variations in Soil Microclimate Under Different Land Use Systems in Umuahia South Area, Abia State, Nigeria

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ABSTRACT

A study was carried out to investigate the variations in soil microclimate under different land use systems in the Umuahia South area of Abia State, to evaluate the variations in soil microclimate (temperature and moisture) under different land use systems (arable land, pasture land, and a bush fallow land). The soil moisture content and temperature measurements were carried out at 0–20 and 20–40 cm depths from December 2023 to September 2024. Meteorological data (rainfall, temperature, soil temperature, and soil moisture) used for this study were obtained through remote sensing from the National Oceanic and Atmospheric Administration/National Centre's for Environmental Prediction (NOAA/NCEP) for the period. Time series analysis showed the trend and variations of the soil microclimate in the different land uses while regression analysis showed the relationship between soil temperature and moisture. The study showed that land use systems significantly influenced atmospheric temperature and rainfall, with arable land recording the highest temperature (26.265-28.882 °C). Bush fallow received higher rainfall (487.8709 mm) than arable land and pasture land. The result also showed that bush fallow maintained higher soil moisture (1.30 m^3m^{-3}) levels than other land uses. Land use systems significantly influenced soil temperature patterns, with arable land recording the highest soil temperature (28.76 °C). There was also a significant inverse relationship between soil temperature and soil moisture. The findings of this study have important implications for sustainable land management practices, particularly in regions with limited water resources.

ARTICLE INFO

Keywords:
Climate
Hydrology
Temperature
Rainfall

Article history:
Received: 01 Dec 2024
Accepted: 26 Jan 2025

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Citation:
Onwuka, B.M. et al., (2025). Variations in Soil Microclimate Under Different Land Use Systems in Umuahia South Area, Abia State, Nigeria, *Sustainable Earth Trends:* 5(4), (11-21).

DOI: 10.48308/set.2025.237788.1089

1. Introduction

The interplay between land use systems and soil microclimate is a critical subject for study, particularly in regions undergoing rapid environmental changes. Umuahia South, a location characterized by diverse land use systems ranging from agricultural to urbanized zones, presents a unique opportunity to evaluate the variations in soil climate (temperature and moisture) under different land use systems. These soil microclimates are vital indicators of soil health and fertility, influencing not only plant growth and yield but also the broader ecological balance (Zhang et al., 2022). The way land is used affects the state of the soil which consequently, influences changes in temperature, heat storage, and dissipation. Land according to Lech-hab et al. (2015) is a delineable part of the earth's surface containing all the attributes of the atmosphere and individual soil units that collectively cover most of the earth's land surface. Soil is heterogeneous in nature, therefore microclimate conditions are not uniform due to the variability in pore sizes, water content, and composition of the solid materials (Abu-Hamdeh et al., 2020). Land use systems enhance considerable alterations which cause variations in the soil temperature and moisture (Tang et al., 2022).

Various activities are carried out on the land during its use like tilling, planting, mulching, fertilizer application, weeding, and harvesting which influence the soil properties. The transfer of heat in soil during land use activities is the primary cause of variations in soil temperature (Zhang et al., 2022). These activities dictate the retention and transmission of heat within and out of the soil and also influence temperature and heat flux with time and depth (Chishala et al., 2019). Tilling soil to break the natural structure reduces heat conductance, heat, and moisture loss (Nugroho et al., 2023). Cultivated land reduces organic matter and soil moisture but increases bulk density (Bizuhoraho et al., 2018), and increasing the bulk density of soil lowers porosity and improves thermal contact between the solid particles (Xiong et al., 2023). On arable land, the amount of organic matter is commonly lower because harvest decreases its input to soil (Zhou et al., 2022) and a great amount of organic matter decreases thermal conductance due to the insulating characteristics of the soil organic matter and acts as a barrier to heat transport (Zhu et al., 2019). In bush fallow, the type of vegetation cover is a factor influencing the soil temperature and moisture (Ni et al., 2019). When the soil is cultivated, the heat capacity of the cultivated soil layer decreases, as a result, the temperature of the loosened soil layer becomes lower (Zhang et al., 2022). As a result of the heating and cooling of the various soils, large temperature ranges are associated with bare land, and low ranges are found in vegetation cover (Gupta et al., 2020).

In Umuahia South, land is not only a resource but a legacy, passed down through generations and intertwined with cultural and economic activities. However, with the advent of modern agricultural techniques and the pressure of urbanization, traditional land use systems have undergone significant changes. These alterations have a profound impact on the soil's hydrothermal properties, potentially leading to altered soil temperature regimes and moisture content. The consequences of such changes are far-reaching, affecting not only plant growth and microbial activity but also the broader environmental processes such as carbon cycling and climate regulation. Therefore, this study was carried out to evaluate the variations in soil microclimate (temperature and moisture) under different land use systems.

2. Material and methods

2.1. Study area

This study was done in Umuahia South Area (Fig. 1) located within latitudes $5^0 27'$-$5^0 34'$N and longitudes $7^0 28'$-$7^0 32'$E (Chigbu, 2015). Umuahia South Area has an average population density of 1301 inhabitants per square kilometer (City population, 2020). The total area of Umuahia South LGA is 140 km^2, (City population, 2020).

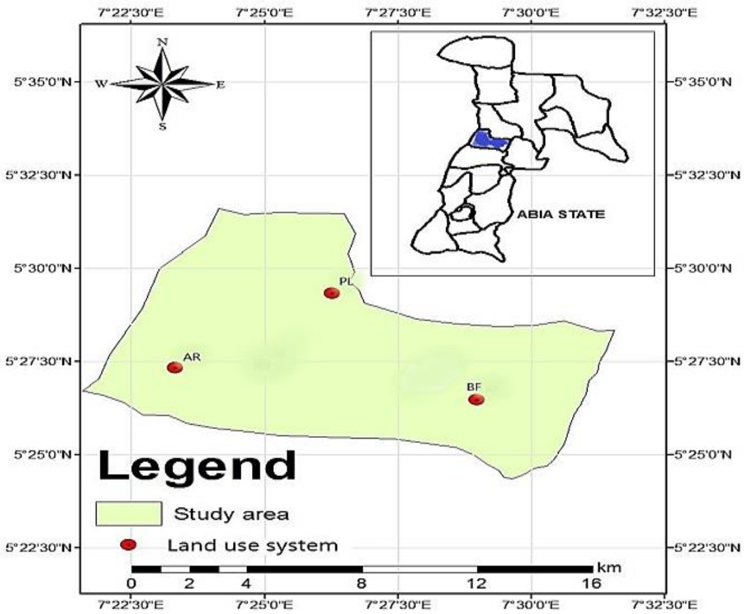

Fig. 1. Map of the study area (AR: Arable land; BF: Bush fallow land; PL: Pasture land).

2.2. Climate

The location is within the tropical rainforest belt. The climate is typically hot humid tropical with a mean annual rainfall of about 3000 mm (Nigeria Meteorological Agency, 2015). The mean annual temperature is generally uniform, ranging from 26 °C to 28 °C (Nigeria Meteorological Agency, 2015). The climate is divided into the wet season (April to October) and the dry season (November to March). The rainy season is characterized by a bimodal rainfall pattern with peaks occurring in July and September and a short dry spell of about three weeks between the peaks known as the August break (Nigeria Meteorological Agency, 2015). Relative humidity varies between 75 and 90 %.

2.3. Vegetation and landscape

The location lies in the rain forest area of the country which has been almost completely replaced by a secondary forest of predominantly rubber plantation and oil palm trees of various densities of coverage inter-mixed with tall grasses, herbaceous and woody shrubs such as Chromolaena odorata (Siam weed). The average elevation range was from 120 to 180 m above sea level (Abia State Government, 2012). The location is characterized by a great variety of landscapes ranging from rolling hills to dissected escarpments, and has major geomorphologic regions (plains and lowlands) such as the Niger River Basin and the Delta; the Coastal Plain and the Cross-River Basin; and the plateau and the escarpment (John et al., 2015).

2.4. Geology

The area is composed of clay, sand, and sand rock, also moderately sorted sands and clays are found. But generally, the geology is Benin Formation which consists of shale/sand sediments with intercalation of thin clay beds (Amos-Uhegbu et al., 2012)

2.5. Description of land uses

From the location of the study, three land uses {arable land (AR), pasture land (PL), and bush fallow land (BF)} were selected for the study (Fig. 1). Arable land has been used over the years to cultivate crops like fluted pumpkin, cassava, maize, etc. using organic farming system. Pasture land has been used for growing Panicum maximum, and Pennisetum purpureum over the years for animal grazing and consumption. Cow dung is usually used to enhance fertility. The bush fallow land has been under fallow for four years Grasses and broadleaf that dominate the area are Panicum maximum, Elusine indica, Axonopus compressus, and Pennisetum purpureum. Broadleaf weeds like Chromolena odorata, Calapogonium mucunoides.

2.6. Field study

For each of the three land uses, three sampling points were randomly selected. Around each of the three sampling points within each land use, soil core samples were collected at a depth of 0–20 and 20–40 cm for analysis of soil moisture content. A total of 18 core soil samples were collected. Also, soil temperature readings at depths of 0–20 cm and 20–40 cm were measured daily (morning, afternoon, and evening) for a period of 10 months (December 2023–September 2024). This was done for ground-truthing (to compare with the meteorological data obtained from the National Oceanic and Atmospheric Administration/National Centre's for Environmental Prediction). The ground-truthing was carried out monthly.

2.7. Climate data collection

Meteorological data used for this study were obtained from the National Oceanic and Atmospheric Administration/National Centre's for Environmental Prediction (NOAA/NCEP) under the National Weather Service, United States of America (NOAA/NCEP, 2023). The data was collected using the non-hydrostatic mesoscale weather and multi-scale weather models for a period of 10 months (December 2023 – September 2024). This was actualized through remote sensing using the geographic information system (GIS). The hourly data was transformed into monthly data. The climate parameters measured include the following: Rainfall, temperature, soil temperature, and soil moisture.

2.8. Laboratory analysis

Soil moisture content was calculated using the gravimetric method where 18 soil samples were placed into ceramic crucibles and weighed to get the fresh weight and then oven-dried at 105 °C to constant weight for about 48 hours and the dry weight was recorded. These values were then used to calculate the moisture contents of the soils using the Eq. 1:

$$SMC\ (\%) = (fw - dw)/dw \times 100 \quad (1)$$

where SMC soil moisture content (%), fw fresh weight (g) of soil sample, dw dry weight (g) of soil sample.

This was done to validate the values of soil moisture content obtained from the National Oceanic and Atmospheric Administration/National Centre's for Environmental Prediction (NOAA/NCEP) under the National Weather Service, United States of America.

2.9. Statistical analysis

The data generated was subjected to analysis of variance and the means were separated using the least significant difference (LSD). A line graph was used to show the trend and variations of the soil microclimate in the different land uses while regression analysis was used to show the relationship between soil temperature and moisture.

3. Results and discussion

3.1. Atmospheric temperature

The result presented in Fig. 2. revealed the variability of atmospheric temperature under three different land use systems - bush fallow (BF), arable land (AR), and pasture (PL) - over a period of 10 months (December to September). The data showed that atmospheric temperature varied significantly across the three land use systems, with notable fluctuations over time. Arable land (AR) consistently recorded the highest temperature throughout the study period, while bush fallow (BF) was observed to have the lowest temperature. In December, the temperature difference between the land use systems was minimal, ranging from 27.457 °C (BF) to 28.882 °C (AR). However, as the months progressed, the temperature disparities became more pronounced. Notably, in June, the temperature in arable land (AR) was 1.27 °C higher than in bush fallow (BF). Seasonal changes also impacted temperature patterns. The lowest temperatures were recorded in July (24.847 °C in BF, 26.265 °C in AR, and 25.479 °C in PL), coinciding with the wet season. As the dry season progressed, the temperature increased, peaking in March (27.395 °C in BF, 28.352 °C in AR, and 27.589 °C in PL). The temperature variations across land use systems could be attributed to vegetative cover. Bush fallow's dense vegetation provides shading and evaporative cooling, reducing temperature (Armson et al., 2012). In contrast, arable land's sparse vegetation cover exposes the soil to direct solar radiation, increasing temperature (Kafy et al., 2022). Zepp et al. (2023), observed that the albedo (reflectivity) of each land use system differs, influencing temperature. Arable land's darker soil surface absorbs more solar radiation, thereby increasing temperature (Cierniewski and Ceglarek, 2018). Also, Nistor et al., (2018) noted that bush fallow and pasture land exhibit higher evapotranspiration rates due to vegetation cover, and this could enhance the cooling the of atmosphere.

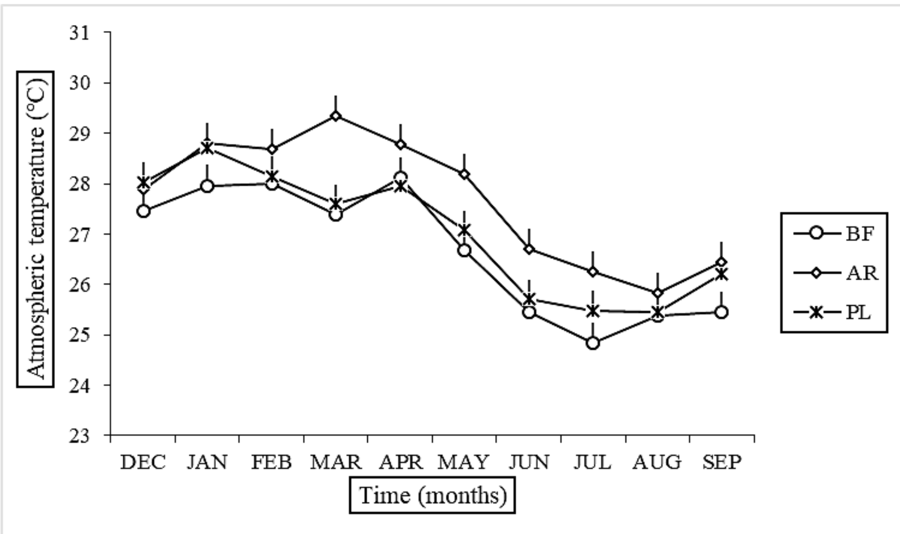

Fig. 2. Variability of atmospheric temperature under different land use systems (AR: Arable land; BF: Bush fallow land; PL: Pasture land).

3.2. Rainfall

Fig. 3. shows the variability of rainfall under three different land use systems - bush fallow (BF), arable land (AR), and pasture (PL) - over 10 months (December to September). The result indicates that rainfall varied significantly across the three land use systems, with notable fluctuations over time. Bush fallow (BF) consistently recorded the highest rainfall from March to September, while arable land (AR) received the lowest rainfall during this period. In December, arable land (AR) had the lowest rainfall (19.48491 mm), whereas bush fallow (BF) received moderate rainfall (24.09238 mm). However, from January onwards, bush fallow (BF) started receiving significantly higher rainfall, peaking in June (487.8709 mm). This increase can be attributed to the dense vegetation cover in bush fallow, which enhances evapotranspiration and creates a microclimate conducive to rainfall (Zeng et al., 2022). Pasture land (PL) received relatively consistent rainfall throughout the study period, with minimal fluctuations. This stability may be due to the grass cover, which maintains soil moisture and moderate rainfall variability (Fehmi, et al., 2014). The variation in rainfall patterns could also be a result of the local climate of the area, influenced by topography and proximity to water bodies (Liang et al., 2024). Seasonal variations also played a significant role in rainfall patterns. The wet season, typically from March to September, brought significantly higher rainfall to all land use systems. The dry season, from December to February, received relatively lower rainfall.

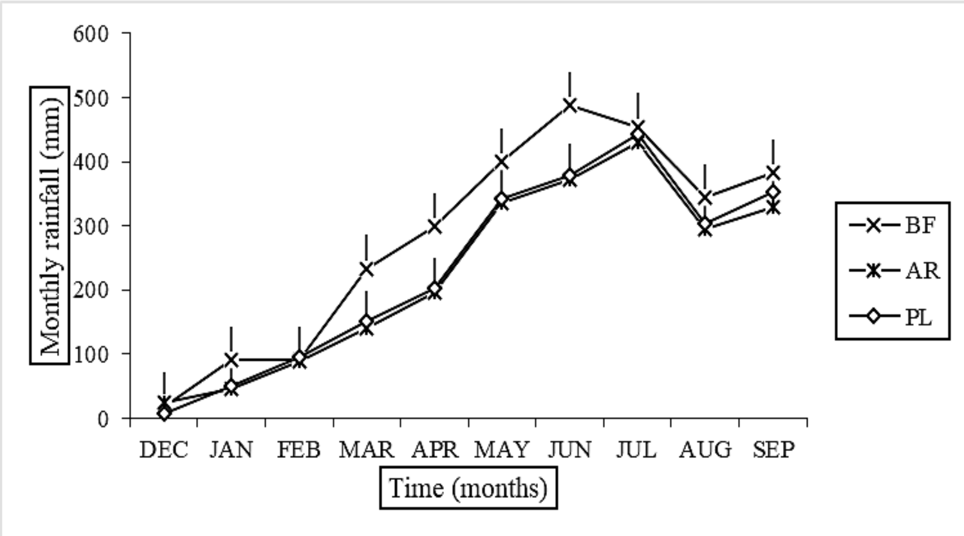

Fig. 3. Variability of rainfall under different land use systems (AR: Arable land; BF: Bush fallow land; PL: Pasture land).

3.3. Soil moisture at 0–20 cm

The result presented in Fig. 4. showed the variability of soil moisture at 0-20 cm depth under three different land use systems - bush fallow (BF), arable land (AR), and pasture (PL)-over 10 months (December to September). From the result, it was observed that soil moisture varied significantly across the three land use systems, with notable fluctuations over time. Bush fallow (BF) generally maintained higher soil moisture levels than arable land (AR), while pasture (PL) exhibited variable soil moisture levels. In December, bush fallow (BF) had the highest soil moisture (1.08 m^3m^{-3}), whereas arable land (AR) recorded the lowest (0.27 m^3m^{-3}). This difference can be attributed to the dense vegetation cover in bush fallow, which enhances soil water retention and reduces evaporation (Liang, et al., 2024). From January to February, pasture (PL) exhibited increased soil moisture (0.29 m^3 m^{-3} to 1.09 m^3m^{-3}), likely due to the grass cover, which helps maintain soil moisture. Arable land showed a significant increase in soil moisture in May (1.08 m^3m^{-3}), possibly due to irrigation or rainfall events. The higher moisture content observed in BF than in AR and PL could be attributed to vegetation cover (Yang et al., 2023). The bush fallow's dense vegetation could have enhanced soil water retention and reduced evaporation. Also, bush fallow and pasture land have improved soil structure, which may have played a role in increasing water-holding capacity Adekiya et al., (2021).

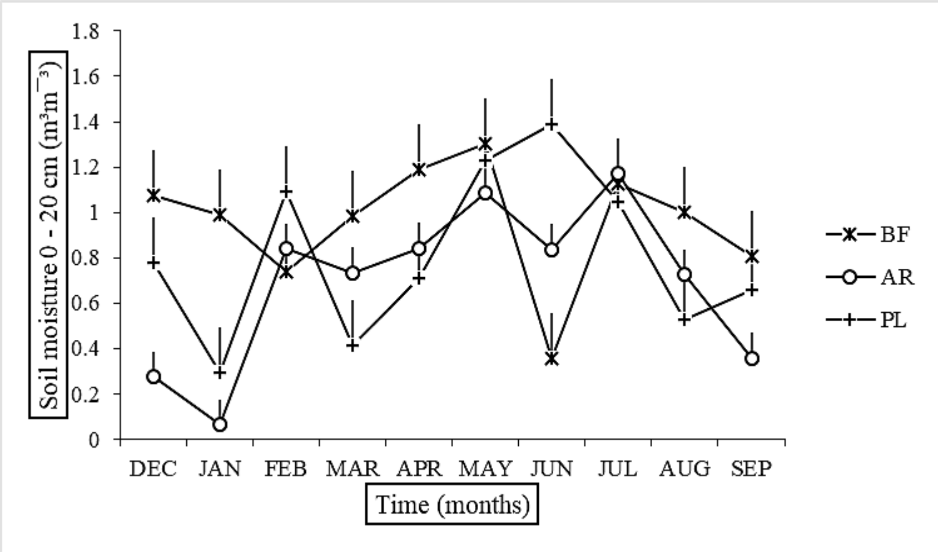

Fig. 4. Variability of soil moisture (0–20 cm) under different land use systems (AR: Arable land; BF: Bush fallow land; PL: Pasture land).

3.4. Soil moisture at 20–40 cm

Fig. 5. revealed the variability of soil moisture at 20-40 cm depth under three different land use systems-bush fallow (BF), arable land (AR), and pasture (PL) - over 10 months (December to September). The result showed that soil moisture varied significantly across the three land use systems, with notable fluctuations over time. In December, pasture land had the highest soil moisture (0.76 m^3m^{-3}), whereas arable land recorded relatively higher soil moisture (0.69 m^3m^{-3}) compared to bush fallow (BF) (0.39 m^3m^{-3}). From January to February, arable land (AR) exhibited increased soil moisture (0.20 to 1.13 m^3m^{-3}), likely due to irrigation or rainfall events. Bush fallow (BF) showed a significant increase in soil moisture in April (1.30 m^3m^{-3}), possibly due to increased rainfall. Seasonal variations also affected soil moisture patterns. The wet season, typically from March to September, brought increased rainfall, leading to higher soil moisture levels in all land use systems. The variations in soil moisture content could be attributed to the structure of the soil. Pasture and bush fallow land may have improved soil structure, thereby increasing water-holding capacity (Zhang et al., 2021). Ogban (2017), observed that bush fallow's dense vegetation cover enhances water infiltration, which could accelerate the recharging of soil moisture. Arable land has lower vegetation cover and this triggers higher evapotranspiration rates which could reduce soil moisture (Ni et al., 2019).

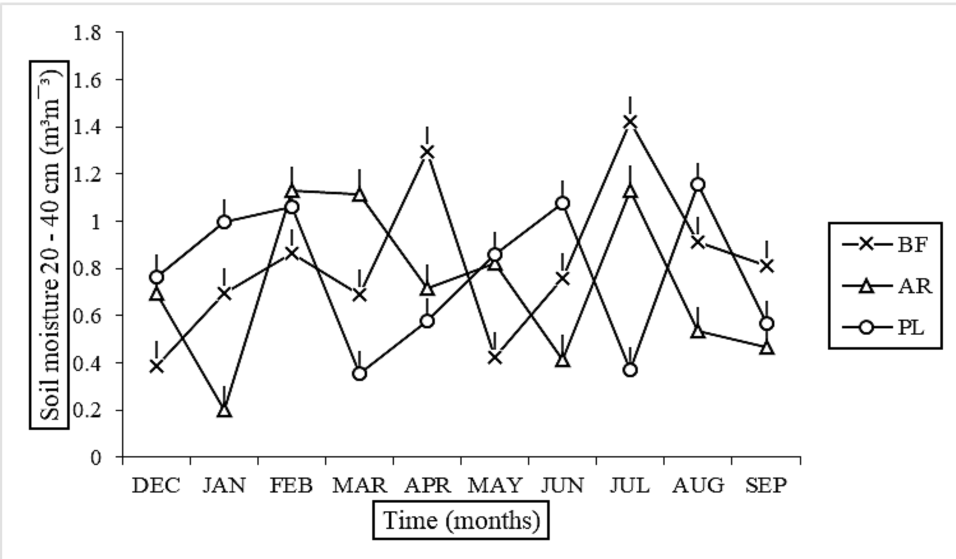

Fig. 5. Variability of soil moisture (20–40 cm) under different land use systems (AR: Arable land; BF: Bush fallow land; PL: Pasture land).

3.5. Soil temperature at 0–20 cm

The variability of soil temperature at 0–20 cm depth under three different land use systems - bush fallow (BF), arable land (AR), and pasture (PL)-over 10 months (December to September) is presented in Fig. 6. The result showed that soil temperature varied significantly across the three land use systems, with notable fluctuations over time. Arable land consistently recorded the highest soil temperature throughout the study period, while bush fallow (BF) recorded the lowest soil temperature. In December, arable land (AR) had the highest soil temperature (27.62 °C), whereas bush fallow (BF) had the lowest (26.96 °C). This difference can be attributed to the exposure of soil to direct solar radiation in arable land, leading to increased soil temperature (Onwuka, 2018). From January to February, pasture (PL) exhibited increased soil temperature (28.08 to 29.11 °C), likely due to the decomposition of organic matter and root activity. Bush fallow (BF) showed a significant decrease in soil temperature in March (26.16 °C), possibly due to increased vegetation cover and shading. Seasonal variations also had an impact on the soil temperature patterns. The highest soil temperatures were recorded in February (28.08 °C in BF, 28.86 °C in AR, and 29.11 °C in PL), coinciding with the dry season. The lowest soil temperatures were recorded in June (24.71 °C in BF, 26.54 °C in AR, and 25.91 °C in PL), coinciding with the wet season. The lower soil temperature observed in bush fallow land than the other land uses may be attributed to the dense vegetation cover in the bush fallow land, which provides shading, thereby reducing soil temperature (Palanisamy et al., 2024). The variation in soil temperature in pasture land could be a result of the presence of high organic matter content which generates heat through decomposition (Moinet et al., 2020). The tillage activities carried out in the arable could disrupt soil structure, which could also increase soil temperature (Liu et al., 2021).

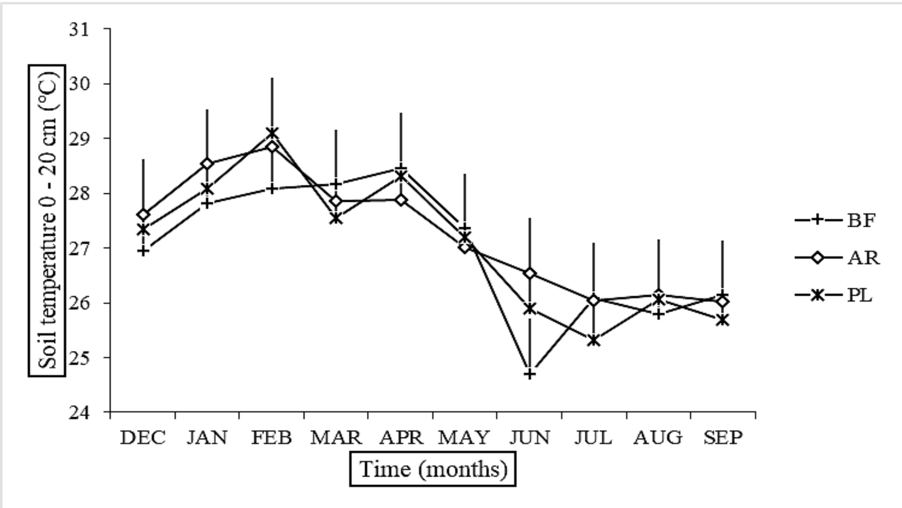

Fig. 6. Variability of soil temperature (0–20 cm) under different land use systems (AR: Arable land; BF: Bush fallow land; PL: Pasture land).

3.6. Soil temperature at 20–40 cm

Fig. 7. revealed the variability of the soil temperature at a depth of 20-40 cm under three different land use systems - Bush Fallow (BF), Arable Land (AR), and Pasture (PL)-over 10 months (December to September). The result showed that soil temperature varied significantly across land use systems and over time. The overall trend showed a decline in soil temperature from December to June, followed by a gradual increase from July to September. This pattern was consistent across all three land use systems. Bush Fallow (BF) exhibited the most consistent soil temperature, ranging from 28.08 °C in December to 25.79 °C in June. This suggests that BF maintained relatively stable soil temperature throughout the year. Arable land showed slightly higher soil temperatures than BF, with a range of 28.76 °C in December to 25.56 °C in June. This could be attributed to the disturbance of soil through tillage, leading to increased soil temperature (Wang et al., 2022). Pasture land displayed the most variability in soil temperature, with values ranging from 28.48 °C in December to 25.84 °C in July. This fluctuation may be due to the presence of vegetation, which can influence soil

temperature through shading and evapotranspiration (Ni et al., 2019). Bush fallow and arable land exhibited similar soil temperature patterns, while PL shows distinct variations. This suggests that vegetation cover and land management practices significantly impact soil temperature. The result also revealed significant seasonal variations in soil temperature. The coolest temperatures occurred in June (25.79 °C, 25.55 °C, and 25.73 °C for BF, AR, and PL, respectively), while the warmest temperatures occurred in December (28.08 °C, 28.76 °C, and 28.48 °C for BF, AR, and PL, respectively). This could be attributed to temperature fluctuations over time which are driven by seasonal variations in solar radiation, air temperature, and precipitation.

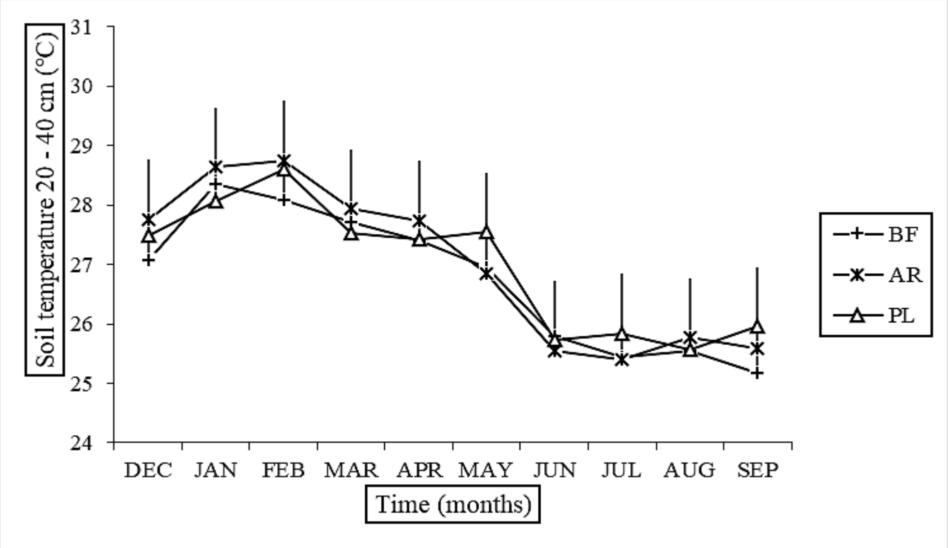

Fig 7. Variability of soil temperature (20–40 cm) under different land use systems (AR: Arable land; BF: Bush fallow land; PL: Pasture land).

3.7. Relationship between soil temperature and moisture content

Fig. 8. presented the plot of regression analysis of soil temperature with soil moisture. The relationship between soil temperature and soil moisture content showed the regression model (SMC = -0.0562ST + 1.6617). The slope of the regression line was +1.6617, which means that for every 1℃ increases in soil temperature, the soil moisture content decreased by 1.6617 m^3m^{-3} on average. The intercept of the regression line was 1.3969, which means that when the soil temperature was zero, the soil moisture content was 1.3969 m^3m^{-3}. The coefficient of determination (R^2) was 0.5657, which means that 56.57 % of the variation in soil moisture content can be explained by the variation in soil temperature. The result showed that there was a significant inverse relationship between soil temperature and soil moisture. This means that as the soil temperature increases, the soil moisture decreases, and vice versa. One possible explanation for this phenomenon is that higher soil temperature causes more evaporation of water from the soil surface, reducing the amount of water available for plant uptake and soil storage (Khamidov et al., 2023). Furthermore, higher soil temperature affects the biological activity of microorganisms and plants in the soil, altering their water consumption and release patterns (Wang et al., 2021). Lower soil temperature may have the opposite effect, slowing down the metabolic processes and water fluxes in the soil. These explanations are consistent with a previous study (Zhang, 2016).

Soil temperature also affects the components of soil water potential (Zhang, 2016). As soil temperature increases, the matric potential decreases due to the decrease in surface tension and viscosity of water. This means that water is less strongly held to the soil particles and more likely to move downward or laterally in response to gravity or hydraulic gradients. As soil temperature increases, the osmotic potential also decreases due to the increase in solute concentration as water evaporates from the soil surface or transpires from the plant roots. This means that water is more strongly attracted to the solute-rich regions in the soil and less likely to move upward or outward in response to evaporation or transpiration.

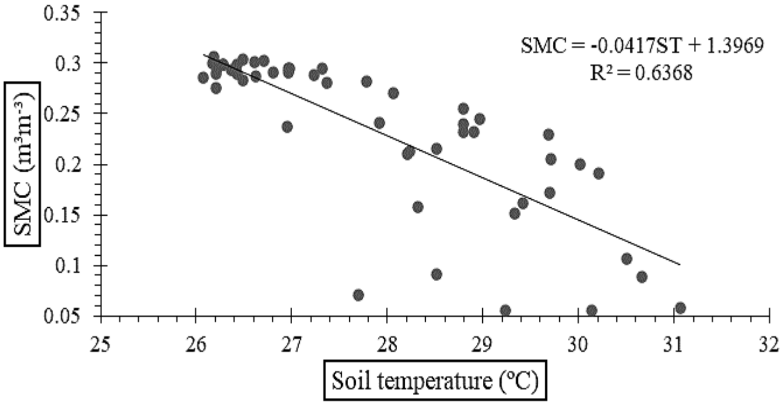

Fig. 8. Relationship between soil temperature and moisture content.

4. Conclusion

This study investigated the variations in soil microclimate (temperature and moisture) under different land use systems (bush fallow, arable, and pasture land) within the Umuahia South area of Abia State. The result showed variations in soil moisture and temperature across the land use systems. The study demonstrates that land use systems significantly influenced atmospheric temperature, with arable land recording higher temperatures than bush fallow and pasture land. The land use systems significantly influenced rainfall patterns, with bush fallow receiving higher rainfall than arable land and pasture land. The study showed that bush fallow maintained higher soil moisture levels than arable and pasture land. The results also present that land use systems significantly influenced soil temperature patterns, with arable land recording higher soil temperatures than bush fallow and pasture land. Future research should focus on investigating the mechanisms underlying land use-induced soil moisture variations, examining the impact of land use on other soil properties, and developing strategies for optimizing land use to enhance soil water retention and mitigate climate change effects.

Acknowledgments

We acknowledge and appreciate the contribution of the National Oceanic and Atmospheric Administration/National Centre's for Environmental Prediction (NOAA/NCEP) under the National Weather Service, United States of America. The financial cost and funding for this project were carried out by the authors.

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