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Assessing Organic Carbon Stocks and Soil Quality in Response to Agroforestry Intervention

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Abstract

Addressing the impacts of climate change on food security and poverty alleviation requires urgent action by institutions, such as the Federal University of Agriculture, Abeokuta (FUNAAB), Nigeria. Through its agroforestry initiatives, FUNAAB can play a vital role in promoting carbon sequestration and enhancing food production, thereby contributing to the achievement of Sustainable Development Goal 2 (Zero Hunger) by 2030. This study assessed Soil organic carbon (SOC) stock and soil quality within FUNAAB's agroforestry plots using geospatial techniques. Soil samples were collected at 0–20 cm depth across various topographic positions and analyzed for their physico-chemical properties. A dendrogram cluster and correlation matrix were employed to evaluate the spatial distribution of soil. The result of the soil quality index demonstrated that the studied soil was good (0.8), fair (0.6 – 0.4), and poor (< 0.4), approximately covering 249.4 (good), 51.9 (fair), and 5.6 (poor) hectares of the area. Consequently, SOC stocks of the area ranged from 124.41 to 59.22, 59.23 to 29.38, and 29.38 to 7.35 Mg C ha−1. The findings from this study concluded that soil nutrient management, like farmyard manure, should be adopted and tailored towards site-specific application to improve soil health and increase carbon stocks of the studied area. Further research on total SOC stocks beyond top-soils and various soil quality indices is necessary and expedient for specific and global empirical evidence to mitigate climate change pressures and ensure sustainable food production.

Keywords: *Soil degradation; Climate change; Cluster analysis; Above-ground biomass: FUNAAB Agroforestry*

1. Introduction

Agroforestry (AGF) is a land-use system that integrates trees with pastures and livestock (silvopastoral), aquatic farming (aquasilviculture), or combinations of trees, crops, and livestock (agrosilvopastoral) to deliver both environmental and socio-economic benefits (Shin et al., 2020; Sinclair, 1999). AGF plays a critical role in safeguarding terrestrial ecosystems, enhancing soil health, and promoting carbon sequestration (Stockmann et al., 2015; Pandit et al., 2013). However, its degradation presents significant threats to environmental sustainability and ecological resilience (Watson et al., 2000; Lal & Stewart, 2019). The extent and direction of climate change impacts on AGF systems remain uncertain, particularly in tropical developing countries (FAO, 2022). Ecosystem degradation, rapid population growth, and unplanned infrastructural development (Thapa, 2020) continue to intensify environmental deterioration at local, regional, and global scales (Chervier et al., 2024). These disruptions not only lead to ecological imbalances (Lal et al., 2012; MEA, 2005) but also significantly alter soil biogeochemical cycles (Zhang et al., 2019; Maharjan et al., 2024). This challenge is especially pronounced in Nigeria (Orobator, 2025), where unsustainable practices, such as extensive bush burning, high carbon dioxide (CO_2) emissions, and widespread land mismanagement are undermining both environmental and human well-being. These pressures contribute to the broader global crisis affecting an estimated 3.2 billion people, as linked to climate change vulnerabilities (Nayak et al., 2019; Lal, 2004).

Notably, AGF degradation is reported to affect 40% of Earth's areas (FAO/UNCCD 2022). The impacts of climate change on AGF systems have been evident for decades, contributing to the depletion of critical natural resources such as soil, air, and water (Obeidat & Awawdeh, 2021; Schuldt et al., 2020; Neumann et al., 2017; Lindner et al., 2014). As climate change intensifies, the need to preserve and expand green space becomes increasingly urgent to reduce atmospheric carbon levels and enhance AGF systems and their landscapes (Schelhas & Hitchner 2020). The connection between AGF and organic carbon sequestration is well-established, highlighting its significant role in climate change mitigation (Roose et al., 2015). There is a pressing need to address the multiple threats facing AGF systems ranging from natural factors such as topography, vegetation cover, and soil types to anthropogenic pressures including overgrazing, deforestation, and unsustainable agricultural practices (Guha et al., 2022; Lal, 2005; Tchotsoua, 1994; United Nations, 2014). Previous studies, conducted in tropical AGF regions,

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have reported considerable improvements in soil physical, chemical, and biological properties (Ofomola et al., 2024; Cardinal et al., 2017; Khaine & Woo, 2018; Ovung et al., 2021). Nevertheless, soil quality, within AGF systems, continues to decline across temporal and spatial scales (Lal, 2004; Fahad et al., 2022; Udawatta & Jose, 2012; Asabere et al., 2018). While AGF soils serve as vital reservoirs for organic carbon, the concurrent decline in food productivity particularly in sub-Saharan Africa presents a major challenge (Henry et al., 2009; Sharma et al., 2024; Tobore et al., 2024). Therefore, a comprehensive evaluation of AGF soil conditions is essential to support ecosystem resilience and promote sustainable food production (Ofomola et al., 2024; Tobore et al. 2021).

Advancements and innovations in modern technology have positioned Geographical Information Systems (GIS) as indispensable tools for analyzing spatial and temporal distributions of soil physical, chemical, and biological properties across natural and human-altered landscapes (Hengl et al., 2018; Zhang et al., 2016). Globally, GIS has empowered researchers to visualize complex historical landscapes and identify escalating ecological threats that could undermine ecosystem biodiversity and stability (Breiman, 2001). As a widely adopted approach for evaluating spatial point data, GIS enhances the precision of environmental assessments by reducing analytical uncertainty and improving sustainability metrics (Hengl et al., 2018; Breiman, 2001). In this context, the use of GIS to evaluate critical agroforestry (AGF) resources, particularly Soil Organic Carbon (SOC) stocks, has become a rational and non-trivial methodological advancement, offering a data-driven pathway for monitoring soil health and supporting climate-resilient land management practices (UNCCD, 2015).

Balancing the need between AGF and SOC stocks is a delicate global challenge (UNCCD, 2015). SOC represents the second-largest carbon reservoir on Earth, playing a critical role in enhancing agricultural productivity and supporting a healthy environment. However, understanding the contribution of AGF soils to carbon storage has become increasingly vital, especially in sub-Saharan Africa, where natural and unchecked human activities continue to degrade AGF systems (Lal, 2005; UNCCD, 2015; Jumaah et al., 2019). Addressing the impact of climate change on food security and poverty alleviation calls for immediate attention of the Federal University of Agriculture, Abeokuta (FUNAAB), Nigeria, through its Agroforestry landscape to facilitate carbon sequestration for a healthy environment and promote optimum food production to meet the Sustainable Development Goal (SDG 2) by 2030. Ultimately, spatially explicit information on safe and healthy food productivity is crucial for assessing soil quality and SOC stocks in the AGF to promote a healthy environment, and sustainability extends beyond the specific findings in the FUNAAB landscape. The study's objectives were to assess (i) soil quality of the area and (ii) evaluate the dynamics of SOC stocks. These insights are expected to support evidence-based local land management policies and contribute broadly to the global knowledge base on AGF and climate-resilient agriculture.

2. Methodology

2.1 Description of study area

The study area, encompassing a total area of 307 hectares (ha), is geographically situated within the Federal University of Agriculture, Abeokuta Agroforestry landscape, bounded by latitudes 7° 19' to 7° 26' and longitudes of 3° 42' to 3° 46'. The terrain features a mix of undulating and flat topography, interspersed with river valleys and seasonal depressions (Ufoegbune et al., 2010). Soil in the area are predominantly Ferric Luvisols, Ferric Cambisols, and Ferric Lixisols (Figure 1), while lowland areas are dominated by Gleyic Luvisols and Lithosols, which are subject to seasonal waterlogging and are generally less gravelly (Soil Science Division Staff, 2017; FAO, 2015; Tobore et al., 2025). The underlying geology is composed of basement complex rocks, with the region experiencing a humid tropical climate characterized by distinct wet and dry seasons (Smyth and Montgomery, 1962). Annual standardized precipitation index (SPI) revealed moderate and very-wet years of the area (Tobore et al., 2021) predominantly occupied by Tectona grandis, and Gmelina arborea (Figure 2).

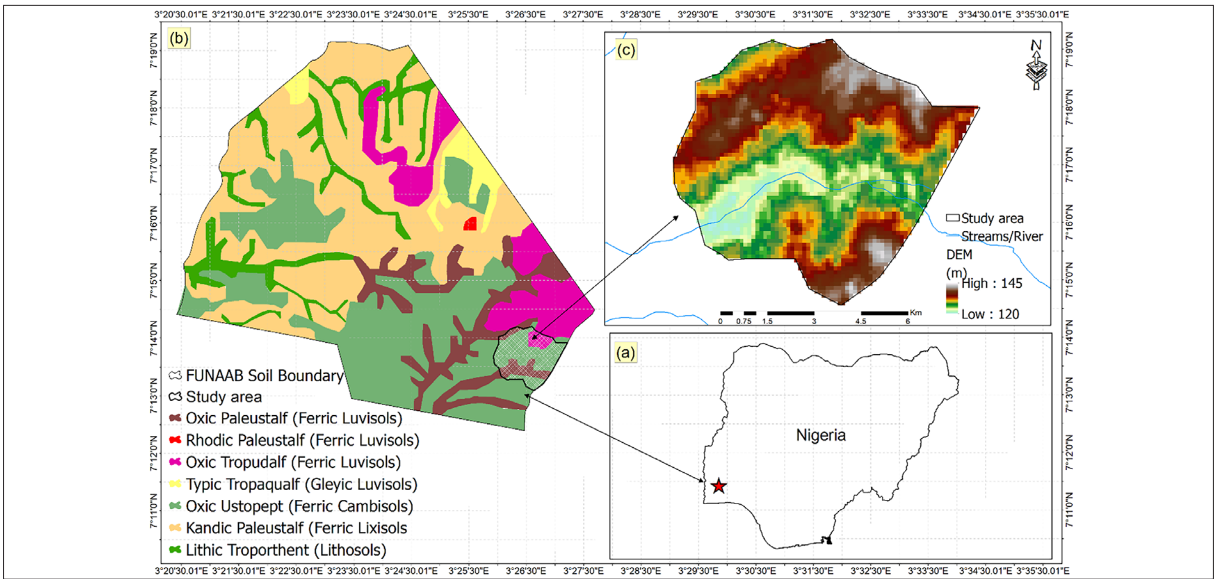

Figure 1. (**a**) Nigeria boundary enclosing FUNAAB as spot (**b**) map of FUNAAB showing soil types modified (Tobore et al,. 2025) and (**c**) study area digital elevation model extracted along the existing rivers and roads network

Figure 2. An example of Agroforestry components of the area

2.2 Soil sampling and design

A modified sampling design by Agroforestry (2023) was adopted to assess soils of the area (Vagen et al. 2013). Soil samples were collected using a grid pattern nested hierarchical approach (FAO, 2007). Sampling design was enabled to cover the studied area terrain and distribution of soil. A total of 48 soil samples were sampled through "create random point". The "create random point" through ArcGIS 10.5 toolbox was employed for statistical representativeness of the studied area for assessing soil properties including total nitrogen, soil pH, particle size distributions, available phosphorus, potassium and organic carbon (Table 1).

Surface soil were sampled from 0 to 20 cm depths along predominant toposequence to capture organic carbon sequestration potential an essential factor for understanding crop productivity and soil health (Sun et al., 2010; Gao et al., 2008). Additionally, three pedological pits (2 m × 1.5 m × 2 m) were excavated on representative slopes, with samples taken from bottom to top to prevent contamination, as recommended by FAO (2009). Elevation mapping was performed using a 30-meter resolution Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM), which helped classify the landscape into three distinct topographic zones (see Fig. 1). In-field assessments included soil structure, color, root concentration, and consistency following standard FAO procedures (2009). Soil bulk density was determined using a core ring sampler (7 cm diameter × 7 cm length) from undisturbed soil at 0–20 cm depth. Latitude and longitude geographic coordinates for representative soil samples were captured by Global positioning system device at <5 m. Subsequently, well labeled zip-locks polythene was used to collect samples for air-drying at controlled room temperature.

Table 1. Methods of soil properties analysis

Soil condition	Method
Total nitrogen	Kjeldahl method (Bremner & Mulvaney, 1982)
Soil texture	Hydrometer method (Gee & Bauder, 1986)
Soil pH	Potentiometry/ Glass calomel pH meter (McLean, 1982)
Organic carbon	Walkley and Black method (Nelson & Sommers, 1983)
Available phosphorus	Colourimetric after extraction with Bray 1 solution (Bray & Kurtz, 1945).
Potassium	Flame Photometer method (Thomas, 1983)
Bulk density	Core sampling method (Blake & Hartege, 1986)
Soil organic matter	Van Bemmelen factor of 1.724
ECEC	Summation of exchangeable cations and acidity
Base saturation	Summation of exchangeable bases divide by ECEC multiply by 100

ECEC: Effective cation exchanged capacity

2.3 Derived soil degradation parameters

In the study, soil vulnerability was assessed using Soil structural stability (SSSI), and Soil susceptibility (CSOM) degradation index (Serme et al., 2015). These two indices denote risk confronting SOC depletion and soil sensitivity to erosion (Isikwue et al., 2012).

SSSI

SSSI is a successful stable index used to assess aggregate resistance of soils after the degree of disruptive forces (Pieri, 1992). In this study, SSSI is expressed as proportion between soil organic carbon and fine soil particles of soil medium (Eq. 1). Consequently, the ranges between < 5% and 7% > values reflect low risk of structurally degraded soils and 7% represent high risk of soil structural degradation while >9% depict SOC with sufficient soils structural stability (Pieri, 1992).

$$SSSI = \frac{1.724\, SOC\ (\%)}{\text{Clay}\ (\%) + Silt\ (\%)} \times 100 \qquad (1)$$

where SSSI is the soil structural stability index, SOC represent soil organic carbon.

CSOM

CSOM is a crucial indicator used to evaluate soil sensitivity to erosion (Brady et al., 2008; Pieri, 1992). In this study, CSOM was utilized to assess soil resistance to degradation based on Equation 2. CSOM values below 5% indicate soils that are highly susceptible to erosion, characterized by loose soil structure prone to rapid degradation. Values ranging between 5% and 7% reflect moderate susceptibility, suggesting partially stable structure but still vulnerable under stress conditions. Conversely, CSOM values of 9% or greater indicate stable soil structures with enhanced resistance to erosion, indicating improved soil health and resilience to environmental pressures.

$$CSOM = \frac{SOM}{[\text{Clay }(\%) + Silt\ (\%)]\ content} \quad (2)$$

where (% Clay + % Silt) content value was obtained from soil texture classification, and SOM was converted (1.724) from the SOC data.

2.4 SOC stocks and soil quality development for the study area

In this study, SOC stocks of the area were calculated by (t ha-1) multiplying SOC (%) concentrations by respective bulk density (g/cm3) multiplied by soil depths (0 to 20 cm). Above-ground (AG) biomass in the studied area was estimated using an algorithm (Eq. 3) described by Chave et al. (2005). Additionally, AG biomass of saplings (Eq. 4) was assessed through the formula described by Haase and Haase (1995). On one hand, the study employed the soil quality index (SQI) to assess the soil quality of the area (Eq. 5) through a formula described by Bajracharya et al. (2006).

$$AGTB = 0.0509 * p\ D^2\ H \quad (3)$$

where AGTB = above-ground tree/pole biomass (kg), = Wood specific gravity (g cm− 3) as expressed by Jackson (1994) for each species, D = tree diameter at breast height (cm), H= tree height (m).

$$Y = aD^b \quad (4)$$

where Y denotes the total dry biomass (kg), D is the diameter at 15 cm above the ground (cm), and 'a ' and 'b' are the constant values represented as 4.264 and 1.0232, respectively.

$$SQI = [(a \times RSTC) + (b \times RpH) + (c \times ROC) + (d \times RNPK)] \quad (5)$$

where RSTC = assigned ranking values for soil textural class, RpH = assigned ranking values for soil pH, ROC = assigned ranking values for SOC, RNPK = assigned ranking values for nitrogen (N), potassium (K) and phosphorus (P). a = 0.2, b =0.1, c = 0.4 and d = 0.3.

3. Spatial distributions of soil properties and quality using GIS-based approach

GIS is a user-friendly technology employed to assess spatial variations of soil properties across extensive geographic areas (Zhang et al., 2019). In this study, the coordinates of the analyzed soil concentrations were interpolated using the Inverse Distance Weighted (IDW) technique in ArcGIS 10.5 (Li and Heap, 2008). IDW offers an unbiased, linear spatial prediction method for estimating point data (Radočaj et al., 2021). Following interpolation, soil property rasters were processed using raster math in the ArcGIS toolbox to derive Soil Quality Index (SQI), Soil Organic Carbon (SOC) stocks, Soil Structural Stability Index (SSSI), and Soil susceptibility (CSOM) across the study area. To further characterize soil variability, Hierarchical Cluster Analysis (HCA) was used to group soil properties based on the similarity of sampled points (Ibrahim, 2015). A correlation matrix was also generated to evaluate the strength and direction of relationships among the soil variables. All statistical analyses and data visualization were carried out using ArcGIS 10.5 and the R programming language (R Core Team, 2018)

4. Results and discussion

4.1 Spatial variation and morphological characteristics of soil properties in the AGF

Cumulative variance (CV) was computed to show variability of analyzed soil properties. Summary statistics of soil properties described high and low CV differences (Wilding 1985). CV indicates accurate normalization of the soil properties around means (Brejda et al., 2000). High variability (0.35) was observed for SOC, TN, P, K, ECEC, Mg, Ca, SOM, and clay concentrations. Conversely, soil pH, sand, and silt contents recorded the least (CV 0.15) variability (Table 2). We may trace variability in soils to inappropriate soil management practices and the intrusion of soil parent material due to the shocks and pressures of climate change (Tsu Wei et al., 2009).

Different soil types exhibits diverse behaviour due to nature and gradual changes in morphological characteristics (Ogunkunle, 2005). Characteristics of the studied soils varied with respect to depths, color, texture, structure and consistency etc. Soil depths showed a strong relationship with topography and thus ranged from 0 to 100 cm (upland), 0 to 110 cm (midland), and 0 to 90 cm (lowland), respectively. Variability of soil depths could be due to abrupt changes in topographic directions and different biological conditions over varying periods of time (Soil survey staff, 1993). Soil color varied from brown (7.5 YR 4/3), to dark brown (7.5 YR 3/3), and gradually changed to reddish color particularly at the sub-surface layers of the pedological pits. The reddish coloration observed in subsurface horizons may indicate oxidation of iron oxides due to the abundance of clay (Buol et al., 2003). Structure examination of the studied soils ranged from weak angular to sub-angular blocky. The soil consistency was not much varied, but clay tends to increase down the pits and thus is classified between slightly sticky and very plastic. The events of changes in the observed consistence especially at sub-surface horizons signify hardness or dryness of the soils especially in the dry state (Raji, 1995). Interestingly, soil boundaries of the profile showed easy demarcation because of clear color variations etc. The clarity in the soil boundaries could be pointing towards flora activities and melanisation of organic matter.

4.2 Physical and chemical soil conditions in the AGF

The soils within the study area exhibited varying textures along the toposequence, with sandy textures predominant in upland areas, sandy loam in midlands, and sandy clay in lowland regions. The particle size distributions of the studied soils were in the order sand > silt > clay. Results showed that clay soil had low values ranging from 2.60 to 25.60%, with a mean of 5.38%. Such textural values showed inadequacy of water retention since clay consolidates soil aggregates and can provides better resistance to water erosion (Tahirou et al., 2022; Tobore et al., 2025). In contrast, a higher value was obtained for sand ranging from 60.40 to 93.40 % with a mean value of 80.77. Also, silt had mean value of 13.85 and a ranged value of 2.40 to 20.00. Therefore, soil texture for the study is classed as sandy clay loam according to USDA (United States Department of Agriculture) criteria.

Eluviation – illuviation processes could be responsible for higher sand concentration obtained (Akinbola et al., 2009). Vulnerability of topography may directly act as a driver washing away surface finer materials and could be responsible for sand accumulation (Adu, 1995). Bulk density values ranged between 1.0 and 1.9 g/cm³. Soils with densities below 1.2 g/cm³ may support high humus content, whereas values approaching 1.9 g/cm³ suggest compaction, which restricts root penetration and water uptake and may affect nutrient cycling (Nam et al., 2021; Odey, 2018).

Table 2. Summary of physical and chemical properties of soils in the AGF. Abbreviation: CV, Coefficient of variation; SD, Standard deviation; SOC, Soil organic carbon; TN, Total nitrogen; SOM, Soil organic matter; ECEC, Effective cation exchanged capacity; Mg, Magnesium; P, Phosphorus; Ca, Calcium; BS, Base saturation.

Soil condition	Mean	Minimum	Maximum	SD	CV (%)
pH H20	6.35	4.68	7.35	0.69	0.10
SOC (%)	1.65	0.51	3.97	0.92	0.54
TN (%)	0.13	0.04	0.22	0.05	0.41
SOM (%)	2.84	0.88	6.84	1.59	0.56
Ca cmol kg -1	3.81	1.71	8.27	1.62	0.42
Mg cmol kg -1	1.60	0.66	3.20	0.94	0.59
P mg kg -1	6.66	2.32	28.00	5.69	0.86
K cmol kg -1	0.23	0.10	0.46	0.12	0.45
Sand (%)	80.77	60.40	93.40	6.70	0.08
Silt (%)	13.85	2.40	20.00	4.15	0.30
Clay (%)	5.38	2.60	25.60	4.75	0.88
Bulk density	1.31	0.67	1.72	0.23	17.53
ECEC cmol kg -1	8.50	3.26	17.66	4.46	0.52
BS (%)	80.95	20.72	99.68	28.13	0.35

Soil pH remains a master variable used to identify many chemical reactions across soil types (Brady & Weil, 2014). In the study, soil pH values ranged between strongly acidic (4.68), neutral (6.6 to 7.3), and alkaline (>7.3), with a mean value of 6.35. Total nitrogen concentration ranged from 0.04 to 0.22%, which means a "medium" to "high" supply for most plants. Variability obtained for soil pH could depict the presence of leaching like basic cations as well as the varying nature of the pedogenic processes (Abdenna et al., 2018). In addition, higher acidic pH could indirectly decrease total nitrogen (TN) as well as phosphorus (P) availability with the high risk of heavy metals contamination (Porta et al. 1994; Azeez et al., 2021). Nevertheless, plants thrive best in different soil pH ranges. Hence, the study pH requires different soil management techniques to achieve optimal agricultural productivity (MSU, 2011).

SOC concentration ranged from 0.51% to 3.91%, with a mean of 1.65%. Additionally, soil organic matter had a mean of 2.84% and ranged from 0.88% to 6.84%. The SOC variations may indirectly reveal the anthropized nature of tropical soils (Obidike-Ugwu et al., 2023; Safadoust et al., 2016). Nevertheless, calcium (Ca), magnesium (Mg), and potassium (K) had mean values of 3.81, 1.60, and 0.23 cmol kg -1 respectively. Effective cation exchanged capacity (ECEC) gave a mean value of 8.50 cmol kg 1 with ranged values between 3.26 and 17.66 cmol kg -1. For the base saturation, a mean value of 80.95 % was obtained, while phosphorus ranged from 2.32 to 28 mg kg -1 with a mean value of 6.6 mg kg -1. The correlation coefficient matrix was utilized to monitor the relevance of soil quality. Therefore, in the study, blue color intensity signifies positive correlation and red indicates a negative correlation among and within the matrix (Figure 3).

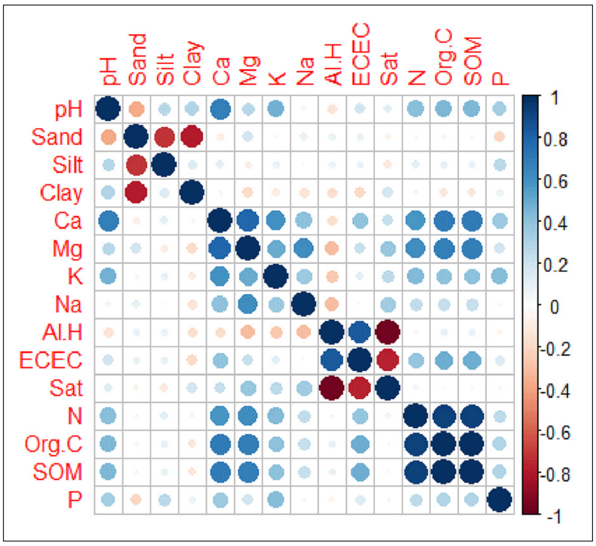

Figure 3. Correlation matrix of soil conditions in the AGF

4.3 Cluster analysis of soil condition in the AGF

Dendrogram (HCA) analysis was used to show the relationship between selected soil properties and a specific grouping of similar clusters (Figure 4). In this study, TN, SOC, P, K, pH, silt, clay and sand concentrations were selected with four major distinct clusters and sub-clusters. The selected soil properties showed that cluster 1 of the sub-cluster consists of SOC and TN, cluster 2 is characterized by silt and clay sub-clusters, while cluster 3 highlights soil pH and K sub-clusters. Cluster 4 signifies sub-clusters of sand and P.

4.4 Soil degradation vulnerability in the AGF

Vulnerability analysis of the present studied soils to degradation was calculated through GIS-based techniques. In the study, SSSI and CSOM susceptibility to soil degradation ranged from 0.53 to 8.69%. Mean and standard deviation of SSSI and CSOM were 0.53 and 4.13. Consequently, SSSI ranged between 5 and 7% (low risk of structurally degraded soils), covering 158.2 ha -1, while sufficient SOC structural stability (9%) covered 148.8 ha -1 of the studied area. So far, CSOM indicated moderate vulnerability (5 and 7%) for the present study. We could trace SSSI and CSOM vulnerabilities to the fragile nature of the pedogenic processes (Sombroek & Zonneveld, 1971; Tesfahunegn & Gebru, 2020).

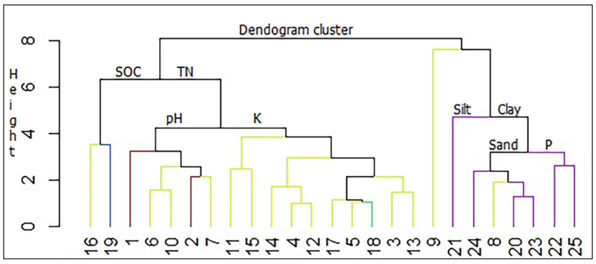

Figure 4. Spatial distribution of selected soil samples within each clusters

4.5 *Above ground biomass and SOC stocks in the AGF*

Tree basal area for the study was 71.24 m2 ha− 1 and vegetation density (tree and sapling) was 1450 ha− 1. Accordingly, value for above ground tree biomass (AGTB) was 87.96 ha− 1 and sapling biomass was 52.36 ha− 1. SOC stocks of the area varied along toposequence with increased in SOC stocks (Figure 5). So far, SOC stocks for up-land spanned from 124.41 Mg C ha−1 to 59.22 Mg C ha−1. In contrast, mid-land SOC stocks ranged from 59.23 Mg C ha−1 to 29.38 Mg C ha−1, while the low-land areas had SOC stocks of 29.38 Mg C ha−1 to 7.35 Mg C ha−1 (Figure 6). According to Sewerniak et al. (2017), topography indirectly affects variation of microclimates, underlying ecological processes and spatial distribution of soil properties.

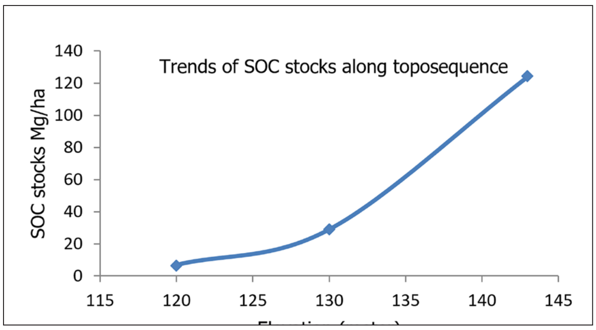

Figure 5. Trend of SOC stocks along topographic elevation

4.6 *Soil quality analysis in the AGF*

The spatial distribution map for the study soil quality is illustrated in Figure 7. Mean and standard deviation values of the soil quality index were 2.13 and 1.11. The result showed that SQI for the present studied soils ranged in the order of good (0.8) > fair (0.6 – 0.4) > poor (< 0.4), respectively. The good (0.8) soil quality was found mostly at central and southern parts of the area covering approximately 249.42 ha. In contrast, fair (0.6 – 0.4) and poor (< 0.4) soil qualities were located mostly at the northern part of the area, occupying 51.91 and 5.60 ha, respectively.

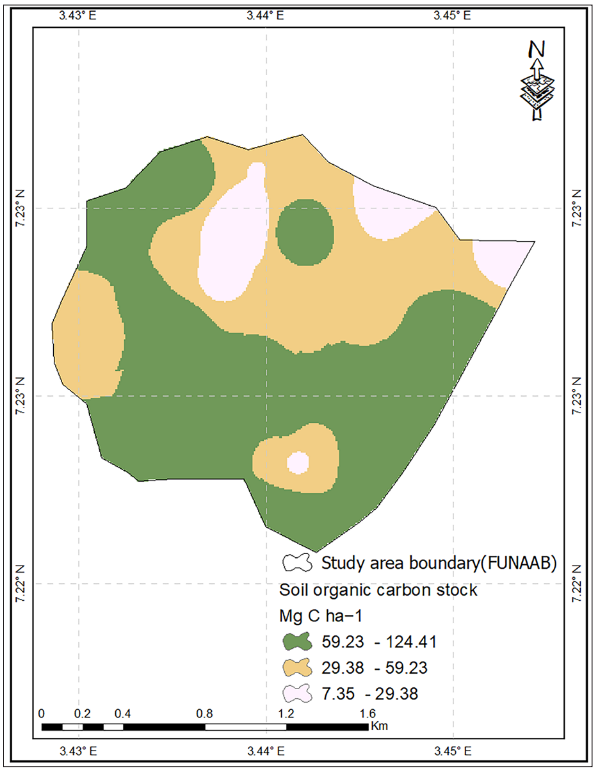

Figure 6. Spatial distributions of soil organic carbon stock in the AGF

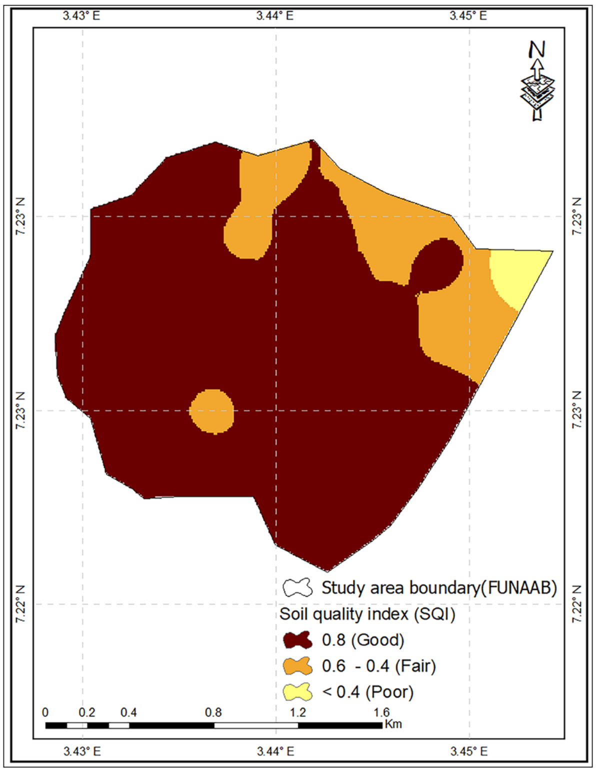

Figure 7. Spatial distribution of soil quality in the AGF

5. Discussion

The particle size distribution of the study area followed the trend of sand > silt > clay, with soils predominantly classified as sandy clay loam, derived from basement complex materials (Smyth & Montgomery, 1962). Such soils, common in Southwestern Nigeria, are often deep and heterogeneous, offering both opportunities and challenges for sustainable land management (Tobore, 2023; Ojanuga, 1979). The high sand content likely results from the underlying parent material and geomorphological processes (Greve et al., 2012), with elevation further influencing pedogenic differentiation (Seibert et al., 2007; Waswa et al., 2013). These findings underscore the role of terrain, geology, and climate-induced variability in shaping soil characteristics (Kosaki & Juo, 1989; Baltensweiler et al., 2020).

SSSI and CSOM mean values showed that the studied soils are classified as sufficient, moderate and low vulnerabilities. This indicates that some portions of the studied soil are susceptible to soil structural degradation. Additionally, absence of a stable soil structure class in the study showed less resistance of studied soils to erosion by water (Igwe and Obalum, 2013; Tobore et al., 2025). Nevertheless, these results are consistent with the findings of Folly (1995). The areas with low and moderate risk vulnerability could be traced to unchecked human actions on the fragile nature of the studied soils (Tobore 2023; Tesfahunegn and Gebru 2020). The dendrogram from Hierarchical Cluster Analysis (HCA) provided insights into the relationships among soil properties, suggesting distinct management needs for different clusters based on soil behavior and morphological variation (McNeill & Hewitt, 2015).

Soil pH is an essential indicator in assessing the fertility of a specific soil (Brady & Weil, 2014). About 75% of the area demonstrated a moderately acidic pH value of 5.69. The Acidic nature could be traced to the close vicinity of the study to major streams or rivers flowing in its valley from different direction (i.e., south, west, and north)s. Nkwunonwo et al. (2020) described the studied region to be naturally endowed with rivers and streams such as Ogun Rivers flowing along several tributaries. These tributaries have commonly been found to accommodate high levels of heavy metals (Olatunde et al., 2020). Nevertheless, Obiora et al. (2016) described Nigeria's soils and immediate environment to be intimidated with household and industrial wastes depositions and thereby leading to soil contamination by heavy metals. This was equally the view and conclusion of Olatunde et al. (2020). Our findings contrast with prior studies that reported that agroforestry soils should be less acidic due to the presence or abundance of vegetation cover (Muchane et al., 2020). On one hand, the present results corroborated the findings of Schwab et al., (2015) describing sub-Saharan Africa agroforestry soils to be higher in soil pH due to emissions of carbon dioxide, uncontrolled bush burning and continuous exploitation of fuel wood for livelihood (Khadijat et al., 2021). More importantly, findings from the study further suggested that nitrogen fertilizers, like ammonium based fertilizers can be used to decrease areas with high soil pH. This explains the availability of phosphorus sorption under low pH (Moody et al., 2008).

Total nitrogen (TN), phosphorus (P), and potassium (K) concentrations of the studied area ranged from medium to high. For instance, the obtained high TN contrasts with the fact that agroforestry lands possess less TN when compared to non-agroforestry lands because of prolonged urea application with a notion to attain high crop yield especially in emerging nations (Muchane et al. 2020; Kuyah et al., 2019). Also, the mineralization of leaf litters fall to bare-soil surface may significantly contributes to increase in the TN concentration of the studied area (Mulat et al., 2021). According to Sharma et al. (2022), increased in microbial activity increase TN because of quick decomposition of organic matter constituents thereby releasing ammonium and nitrate as forms of nitrogen (Maharajan et al., 2017). So far, recent studies in sub-Saharan Africa like Ethiopia and India re-affirmed that agroforestry soils have shown promising and continuous ways of enhancing P availability (Wolle et al., 2021; Dori et al., 2022). Besides, our result aligns perfectly with the previous findings of Chaudhry et al. (2007) and Lamichhane, (2013). Additionally, the application of inorganic phosphorus fertilizers may also be introduced to replenish and maintain P content in the present studied soils especially areas with medium phosphorus concentration (Sharma et al., 2022; Dagar et al., 2020). At the same time, the high K concentration in our study was consistent with prior agroforestry studies (Nath et al., 2015; Singh et al., 2018; Namgial et al., 2020).

High concentration of organic carbon was detected in the northern and southern regions, approximately covering 70 %. Moderate and low organic carbon concentrations covered 20 and 10 % of the area. The area with low organic carbon (OC) was classed below critical threshold limits. This further explains the vulnerability of the studied soils to structural degradation. Nevertheless, the OC concentration in the present study exceeded values reported by Schwab et al. (2015) and Magar et al. (2020) for tropical agroforestry. Interestingly, our study is consistent with the general instincts that proper adequate agroforestry practices can elevate soil organic carbon concentrations due to the abundance of woody trees. Additionally, woody trees deposit more leaf litter, thereby contributing to the decomposition of organic matter accumulation (Kassa et al., 2022). At the same time, the organic matter concentration of our studied soils ranged between high and low contents. Soil organic matter serves as a major contributor to the cation exchange capacity in the soil medium. The low and moderate OC concentration of the area could be traced to greenhouse gases, abrupt changes in slope positions, and lastly gradual to sudden increase of land surface temperature due to sea level rise intrusion (Tobore & Samuel 2022; Rezaei & Gilkes, 2005). Therefore, soils with low soil organic matter reduce water holding capacity and can cause soil nutrients to be unavailable (Tittonell et al., 2010).

SOC stocks of the area ranged between 7.35 and 124.41 Mg C ha−1 respectively. The variability in the SOC stocks might be traced to the differences in density of vegetative cover, tree populations and topography nature of the studied soils (Feliciano et al., 2018). Although De Stefano and Jacobson (2018) asserted that healthy vegetative cover can grow taller trees and thus make them tap more sunlight, water, and nutrients easily to support above-ground biomass. Nevertheless, SOC stocks, obtained for our study, were higher than the reported studies of Besar et al. (2020). Although Kay et al. (2019) mentioned that adoption of different agroforestry system of practices plays a pivotal role in increasing SOC stocks stability and availability. A similar result was also obtained under agroforestry in Northern Ethiopia (Gebrerneskel et al., 2021). Hence, our study underscores the agroforestry potential systems of practicing healthy vegetation cover density, particularly to mitigate a changing climate and thus increase SOC stocks.

Spatial trends of soil quality for the present study showed more accurate areas classified as good (0.8), fair (0.6 – 0.4), and poor (<0.4). The portion covered by fair (0.6 – 0.4), and poor (<0.4) soil quality could be traced to unchecked human actions, leading to a low percentage of SOC and low soil structural stability. Zhang et al. (2016) described soil pH, bulk density, and SOC, among others, as the most influential predictors for accurate assessment of soil quality. This further confirmed the crucial importance of using these parameters in the present study. Moreover, the results obtained for our study also align with previous studies of agroforestry reported by Ramirez et al. (2022) and Guillot et al. (2021). More importantly, since soils are an essential medium for crop growth as well as a critical resource base where food supplies come from (Brevik 2013), developing soil nutrient recommendations for soils of agroforestry calls for immediate intervention of researchers to salvage the soil quality of the agroforestry. Interestingly, these actions will eventually help in reducing management cost and input wastage. Therefore, more emphasis should be placed on managing the potential of agroforestry resources and their significant contributions to carbon stocks for increasing food productivity and enhancing a sustainable environment.

6. Conclusion

The agroforestry system remains a multifunctional land-use strategy with significant benefits for both human well-being and environmental sustainability. Understanding the variability of soil properties and the extent of anthropogenic influence on agroforestry soils is essential for mitigating the impacts of climate change and enhancing food production. This study assessed soil quality and organic carbon (SOC) stocks at the Federal University of Agriculture, Abeokuta, Ogun State, Nigeria. A total of 48 soil samples were collected from 0–20 cm depth along a representative toposequence. The soils, derived from basement complex parent materials, were classified as sandy clay loam, exhibiting notable variations in physical and chemical properties. These variations significantly influenced SOC stocks and the overall soil quality across the study area. Spatial analysis revealed that SOC stocks ranged from 124.41 to 7.35 Mg C ha^{-1}, and the soil quality index (SQI) ranged from good (≥0.8), to fair (0.6–0.4), and poor (<0.4). Our findings demonstrate that agroforestry soil possesses considerable potential to enhance SOC stocks and improve soil quality—both of which are critical for climate change mitigation and sustainable food systems. The study underscores the importance of integrating sustainable soil fertility management practices, such as farmyard manure application or integrated soil fertility management techniques, to boost soil health and increase carbon sequestration capacity.

However, this study focused exclusively on surface soils (0–20 cm), thereby limiting our ability to assess SOC stocks in deeper horizons. Future research should incorporate deeper soil layers, quantify below-ground biomass, and examine the influence of climatic variables on SOC dynamics. Such efforts will provide robust empirical evidence at national, regional, and global scales—further strengthening the role of agroforestry in addressing climate change challenges, ecological resilience, and sustainable agricultural development.

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Declaration of Competing Interest

The author(s) declared no known competing moral or financial interests in relation to the work article.

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