International Journal of Academic Management Science Research (IJAMSR)
ISSN: 2643-900X
Vol. 10 Issue 6 June - 2026, Pages: 105-114

Climate Change, Soil Health and Sustainability in Vulnerable Areas of Nigeria: A Comparative Study of Yobe, Bayelsa and Anambra States, Nigeria

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Being a paper presented African Economies (CSAE) at University of Oxford, the conference holding between 21–23 March 2027 at St Catherine's College in Oxford, United Kingdom.

Theme: African Development and Economics Research

Sub-Theme: Climate change and sustainability

Abstract*: This study investigated the effects of climate-related environmental conditions on soil health and sustainability across three vulnerable ecological zones in Nigeria. Specifically, it compared selected soil properties between surface (0–15 cm) and subsurface (15–30 cm) layers, evaluated variations in soil health indicators among the study areas, and examined the influence of drought, flooding, and erosion on soil fertility and sustainability. The study was carried out in Yobe State, representing the drought-prone zone; Bayelsa State, representing the flood-prone coastal zone; and Anambra State, representing the erosion-prone zone. A comparative field survey design was employed. Soil samples were collected from five identified hotspot communities in each state using a zig-zag sampling pattern at depths of 0–15 cm and 15–30 cm. In total, 30 composite soil samples were analysed for soil moisture, organic carbon, organic matter, total nitrogen, available phosphorus, exchangeable potassium, cation exchange capacity, microbial biomass, and soil respiration. Data were analysed using descriptive statistics, paired-sample t-test, one-way ANOVA with Tukey post hoc test, Pearson correlation, and multiple regression at the 0.05 level of significance. The findings revealed significant differences ($p < 0.05$) between surface and subsurface soils, with the surface layer consistently exhibiting better soil quality indicators. Bayelsa State recorded the highest values for soil moisture (30.25%), organic carbon (1.63%), microbial biomass (390.0 mg/kg), and soil respiration (28.6 mg CO_2/kg/day), while Yobe State had the lowest values for most parameters. The ANOVA results showed significant differences among the three ecological zones ($p < 0.001$). Correlation and regression analyses further revealed that drought exerted a strong negative influence on soil health ($r = -0.79$ to -0.91), flooding had a positive influence ($r = +0.80$ to $+0.94$), and erosion produced moderate negative effects ($r = -0.68$ to -0.78). The study concludes that climate-related environmental conditions play a significant role in shaping soil fertility and sustainability. Strengthening soil conservation measures and climate-responsive land management practices is essential for sustaining soil productivity and ecological stability.*

Keywords: Climate change, Fertility, Flooding, Soil health, Sustainability

Introduction

Climate change has emerged as one of the most significant environmental challenges affecting soil resources and agricultural sustainability worldwide. Rising temperatures, changing rainfall patterns, prolonged droughts, frequent flooding, and accelerated land degradation are altering soil processes and reducing the capacity of soils to support ecosystem services and food production. The Intergovernmental Panel on Climate Change (2023) reports that climate change is intensifying environmental pressures on soils, particularly in vulnerable regions of Africa where livelihoods depend heavily on rain-fed agriculture.

Soil health has therefore become a key indicator of environmental sustainability and resilience under changing climatic conditions. It refers to the continued capacity of soil to function as a living ecosystem that supports plants, animals, and humans. Healthy soils regulate water flow, store carbon, cycle nutrients, and sustain biological activity essential for agricultural productivity. According to Lal (2023), soil health results from the interaction of physical, chemical, and biological properties, including soil moisture, organic carbon, nutrient availability, microbial biomass, and soil respiration. Changes in these indicators provide valuable evidence of soil degradation and ecosystem sustainability.

Drought, as a major manifestation of climate change, remains one of the most destructive environmental conditions affecting soil quality. It reduces soil moisture availability, limits microbial activity, disrupts nutrient cycling, and accelerates the depletion of organic matter. In northern Nigeria, rising temperatures and declining rainfall have contributed to desertification and declining soil fertility. Ojo and Akinyemi (2024) observed that prolonged drought conditions significantly reduce soil organic carbon, total nitrogen, and microbial biomass, thereby threatening sustainable agricultural production in semi-arid regions.

Flooding is another major climate-related challenge affecting soil systems in coastal and riverine environments. While occasional flooding can contribute to nutrient deposition and organic matter accumulation, excessive flooding often leads to waterlogging, nutrient redistribution, salinity intrusion, and disruption of soil biological processes. Eze and Chukwu (2023) found that recurrent flooding in the Niger Delta region alters soil physical and chemical properties, thereby influencing nutrient availability and soil productivity.

Soil erosion is also a major environmental problem that contributes significantly to soil degradation and reduced agricultural productivity. The removal of nutrient-rich topsoil through water erosion reduces soil organic matter, nutrient reserves, and biological activity. Southeastern Nigeria is particularly vulnerable to gully erosion due to intense rainfall, fragile geological formations, and unsustainable land-use practices. Ibe *et al.* (2023) reported that erosion-induced soil loss continues to threaten ecosystem stability and agricultural sustainability across the region.

Soil moisture is one of the most sensitive indicators of soil health under climate variability. It influences nutrient availability, root development, microbial activity, and plant growth. Variations in soil moisture are often associated with drought, flooding, and erosion processes. The FAO (2022) notes that soil moisture is a key determinant of soil resilience and agricultural productivity, particularly in regions experiencing increasing climatic uncertainty.

Soil organic carbon and nutrient content are also essential indicators of soil fertility and environmental sustainability. Soil organic carbon improves soil structure, enhances water-holding capacity, and serves as a reservoir of essential nutrients. Key nutrients such as nitrogen, phosphorus, and potassium are fundamental to plant growth and ecosystem functioning. Minasny *et al.* (2023) highlighted that climate-induced disturbances often reduce soil carbon stocks and nutrient reserves, thereby impairing long-term soil productivity and environmental quality.

Biological indicators such as microbial biomass and soil respiration are widely recognised as reliable measures of soil ecosystem functioning. Soil microorganisms regulate organic matter decomposition, nutrient cycling, and carbon sequestration processes. Changes in microbial activity often reflect environmental stress before visible changes occur in soil physical and chemical properties. Bünemann *et al.* (2024) noted that microbial biomass and soil respiration are among the most effective indicators for assessing soil health and sustainability under changing climatic conditions.

Despite growing evidence of climate impacts on soils, comparative studies examining soil health indicators across drought-, flood-, and erosion-prone ecological zones in Nigeria remain limited. Most existing studies focus on single environmental challenges or individual locations, with limited cross-regional comparisons of soil fertility and sustainability indicators. Therefore, this study investigates the influence of climate-related environmental conditions—drought, flooding, and erosion—on soil moisture, organic carbon, nutrient content, microbial activity, soil fertility status, and sustainability across vulnerable ecological zones in Nigeria. The findings are expected to provide empirical evidence for climate-smart soil management and sustainable land-use planning.

Statement of the Problem

Climate change intensified environmental challenges such as drought, flooding, and soil erosion, which increasingly threaten soil health, agricultural productivity, and environmental sustainability in Nigeria. These climate-related stressors alter key soil properties, including soil moisture, organic carbon, nutrient availability, and microbial activity, leading to declining soil fertility and weakened ecosystem resilience. In drought-prone areas of northern Nigeria, prolonged moisture deficits accelerated desertification and nutrient depletion; in flood-prone coastal regions, recurrent flooding resulted in nutrient redistribution, waterlogging, and salinity intrusion; while in erosion-prone areas of southeastern Nigeria, continuous loss of fertile topsoil has significantly reduced agricultural potential. Despite the importance of soil as a foundation for food security and sustainable development, climate-induced degradation continues to undermine the productivity and ecological functioning of many landscapes across the country.

Although several studies examined the effects of drought, flooding, or erosion on soil properties, most focused on a single environmental condition or specific location. Consequently, there is limited empirical evidence comparing the influence of these climate-related environmental conditions on soil fertility status and sustainability across different ecological zones in Nigeria using common soil health indicators such as soil moisture, organic carbon, nutrient content, microbial biomass, and soil respiration. This lack of comparative evidence limits the ability to determine the relative impacts of different climate stressors and to design effective, location-specific soil management strategies. Therefore, this study addresses this gap by comparatively assessing soil health indicators in drought-prone Yobe State, flood-prone Bayelsa State, and erosion-prone Anambra State, with a view to providing empirical evidence for sustainable soil management and climate adaptation planning.

Objectives of the Study

The main objective of this study is to examine the relationship between climate change, soil health, and sustainability in vulnerable ecological zones of Nigeria. The specific objectives are to:

i. Compare the physical, chemical, and biological soil properties between surface and subsurface soils across drought-prone, flood-prone, and erosion-prone zones in Nigeria;
ii. Assess the variation in soil health indicators among the States in the study area and
iii. Determine the influence of climate-related environmental conditions on soil fertility status and sustainability across the selected ecological zones.

Research Question

How do climate-related environmental conditions influence soil fertility status and sustainability across vulnerable ecological zones in Nigeria?

Hypotheses

H_{01}: There is no significant difference in the physical, chemical, and biological soil properties between surface and subsurface soils across drought-prone, flood-prone, and erosion-prone zones in Nigeria.

H_{02}: Climate-related environmental conditions have no significant influence on soil fertility status and sustainability across the selected ecological zones in Nigeria.

Climate-Related Environmental Conditions

Climate-related environmental conditions refer to the physical manifestations of climate variability and climate change that directly affect ecosystem functioning and soil processes. In this study, the conditions considered are drought, flooding, and erosion. The Intergovernmental Panel on Climate Change (2023) explains that these environmental conditions are among the most significant pathways through which climate change affects land resources and agricultural productivity globally. Soil moisture refers to the amount of water stored within soil pores that is available for plant uptake. It is one of the most important indicators of soil health because it influences nutrient availability, root growth, microbial activity, and overall ecosystem productivity. Adequate soil moisture supports biological and chemical processes necessary for plant development, whereas excessive or insufficient moisture can lead to reduced productivity and soil degradation. Lal (2023) noted that soil moisture is highly sensitive to climate variability and serves as a key indicator of soil resilience under changing environmental conditions.

Soil organic carbon (SOC) is the carbon component of soil organic matter derived from decomposed plant and animal residues. It plays a vital role in improving soil structure, increasing water-holding capacity, enhancing nutrient retention, and supporting microbial activity. Soil organic carbon is widely recognised as a key indicator of soil fertility and sustainability because it contributes to both agricultural productivity and climate change mitigation through carbon sequestration. Minasny *et al.* (2023) observed that declines in soil organic carbon are often associated with land degradation and reduced ecosystem resilience. Nitrogen refers to the total amount of nitrogen in the soil, including both organic and inorganic forms. It is an essential nutrient required for plant growth, protein synthesis, and chlorophyll formation. Soil nitrogen levels are influenced by organic matter decomposition, microbial activity, fertiliser application, and climatic conditions. Drought, flooding, and erosion significantly affect nitrogen availability by disrupting nutrient cycling processes. The FAO (2022) reported that nitrogen deficiency remains one of the major constraints to sustainable agricultural production in many developing countries.

Available phosphorus represents the fraction of phosphorus in the soil that is readily accessible for plant uptake. It is essential for root development, energy transfer, and crop yield. Phosphorus availability depends on soil pH, organic matter content, microbial activity, and environmental conditions. Climate-induced changes in soil moisture and erosion can reduce phosphorus availability through leaching and topsoil loss. Bünemann *et al.* (2024) identified available phosphorus as a key indicator of soil fertility and ecosystem productivity. Exchangeable potassium is the portion of potassium held on soil colloids that can be readily exchanged and absorbed by plant roots. It regulates water use efficiency, enzyme activation, photosynthesis, and plant resistance to environmental stress. Low potassium levels often result in poor crop growth and reduced tolerance to drought and disease. Climate-related environmental disturbances influence potassium dynamics through nutrient depletion, erosion, and changes in soil moisture conditions. Lal (2023) emphasised that potassium availability is essential for maintaining soil productivity and agricultural sustainability.

Cation exchange capacity (CEC) refers to the ability of soil to retain and exchange positively charged nutrient ions such as calcium, magnesium, potassium, and ammonium. It is an important measure of soil fertility because it determines the soil's capacity to store and supply nutrients to plants. Soils with higher CEC generally have greater nutrient-holding capacity and better fertility status. Environmental factors such as erosion, organic matter depletion, and prolonged drought can reduce CEC and negatively affect soil productivity. Brady and Weil (2024) described CEC as a fundamental indicator of soil quality and nutrient retention capacity. Microbial biomass represents the living component of soil organic matter, including bacteria, fungi, and other microorganisms involved in nutrient cycling and organic matter decomposition. It is a sensitive indicator of soil health because microbial communities respond quickly to environmental changes. High microbial biomass generally reflects favourable soil conditions, while low microbial biomass may indicate soil degradation or environmental stress. Bünemann *et al.* (2024) noted that microbial biomass is one of the most reliable indicators of soil ecosystem functioning and sustainability.

Soil respiration is the process through which carbon dioxide (CO_2) is released from the soil as a result of microbial decomposition and root respiration. It reflects the biological activity and metabolic functioning of soil ecosystems. Soil respiration is influenced by soil moisture, temperature, organic matter content, and microbial abundance. Changes in soil respiration often indicate shifts in soil biological processes caused by climate variability or land degradation. Lal (2023) reported that soil respiration is widely used as an indicator of soil biological health and ecosystem resilience. Soil fertility status refers to the ability of soil to supply essential nutrients and provide favourable conditions for plant growth, while soil sustainability refers to the long-term capacity of soil to maintain its productive, environmental, and ecological functions. Sustainable soils support food production, regulate water and nutrient cycles, store carbon, and maintain biodiversity. Soil fertility and sustainability are influenced by a combination of physical, chemical, and biological properties, including soil moisture, organic carbon, nutrient availability, microbial biomass, and soil respiration. The FAO (2022) and IPCC (2023) emphasise that maintaining soil fertility and sustainability is essential for achieving food security, climate resilience, and sustainable development in the face of increasing environmental challenges.

State Factor Theory of Soil Formation

The State Factor Theory of Soil Formation was developed by Hans Jenny in 1941. The theory posits that soil properties are determined by the interaction of five major soil-forming factors: climate, organisms, relief (topography), parent material, and time. Jenny expressed this relationship mathematically as: **S = f(cl, o, r, p, t)** where **S** represents soil properties, **cl** is climate, **o** is organisms, **r** is relief (topography), **p** is parent material, and **t** is time. The theory is relevant to this study because climate is regarded as a primary factor influencing soil development and soil health. Climate-related environmental conditions such as drought, flooding, and erosion directly affect soil moisture, organic carbon, nutrient content, microbial activity, and overall soil fertility. The variations observed among Yobe, Bayelsa and Anambra States can therefore be explained through the influence of climatic and topographic factors on soil formation and degradation processes. The theory provides a strong foundation for understanding how environmental conditions shape soil fertility status and sustainability across different ecological zones.

Ecosystem Theory

The Ecosystem Theory was originally proposed by Arthur Tansley in 1935. The theory views the environment as an interconnected system in which living organisms interact continuously with non-living components such as soil, water, climate, and nutrients. It further states that any disturbance in one component of the ecosystem affects the functioning and sustainability of the entire system. This theory is applicable to the present study because soil is a critical component of terrestrial ecosystems. Climate-related disturbances such as drought, flooding, and erosion alter the physical, chemical, and biological properties of soil, thereby affecting ecosystem productivity and sustainability. Soil moisture, organic carbon, nutrient availability, microbial biomass, and soil respiration serve as key indicators of ecosystem functioning and resilience. The theory explains how changes in climate conditions disrupt soil processes and reduce the capacity of soils to support agricultural production and environmental sustainability. Therefore, Ecosystem Theory provides a useful framework for understanding the relationship between climate-related environmental conditions and soil fertility status across vulnerable ecological zones in Nigeria.

The State Factor Theory explains how climate acts as a major determinant of soil properties and fertility, while Ecosystem Theory explains how climate-induced disturbances influence the interactions between soil, organisms, and environmental resources. Together, the two theories provide a comprehensive framework for examining the influence of drought, flooding, and erosion on soil moisture, organic carbon, nutrient content, microbial activity, soil fertility status, and sustainability in Yobe State, Bayelsa State, and Anambra State. These theories therefore reinforce the study's investigation of climate change, soil health, and sustainability in vulnerable ecological zones of Nigeria.

Soils across Drought-Prone, Flood-Prone, and Erosion-Prone Zones in Nigeria

Several studies have reported significant variations in soil properties with depth, particularly in areas affected by climate-related environmental stressors. Lal (2023) found that surface soils generally contain higher organic carbon, nutrient concentrations, microbial biomass, and moisture content than subsurface soils due to the accumulation of plant residues and greater biological activity. Bünemann *et al.* (2024) reported that biological indicators such as microbial biomass and soil respiration decline with increasing soil depth because of reduced organic matter availability. Ibe *et al.* (2023) observed that erosion-prone soils in southeastern Nigeria exhibited significant reductions in organic carbon and nutrient concentrations in deeper soil layers due to continuous topsoil removal. Ojo and Akinyemi (2024) noted that drought-affected soils in northern Nigeria show lower moisture content and microbial activity in subsurface horizons compared to surface soils. In flood-prone environments, Eze and Chukwu (2023) found that soil depth significantly influences nutrient distribution and soil biological activity due to periodic sediment deposition and waterlogging effects.

Soil physical properties such as bulk density, porosity, and texture distribution are also strongly influenced by soil depth and environmental conditions. Lal (2023) observed that surface soils exhibit lower bulk density and higher porosity compared to subsurface soils due to greater organic matter accumulation and biological activity. In climate-stressed environments, these differences become more pronounced. The FAO (2022) reported that drought conditions increase soil compaction in deeper layers, while flooding may temporarily improve surface structure through sediment deposition. Ibe *et al.* (2023) further found that continuous removal of topsoil alters the natural vertical distribution of soil physical properties, leading to reduced infiltration capacity and water retention.

The Variation in Soil Health Indicators

Soil health indicators are widely used to evaluate soil fertility, ecosystem functioning, and sustainability. The FAO (2022) explains that soil moisture, organic carbon, nutrient availability, microbial biomass, and soil respiration are among the most reliable indicators of soil quality. Variations in these indicators often reflect differences in climatic conditions, land-use practices, and environmental disturbances, with substantial spatial differences observed across ecological regions. Minasny *et al.* (2023) reported that soil organic carbon and nutrient reserves vary across climatic gradients, with wetter environments generally supporting higher carbon accumulation and greater biological activity than drier regions. In the Niger Delta, Ogunlade *et al.* (2024) found that floodplain soils contained higher organic carbon, nitrogen, and microbial biomass due to regular sediment deposition and high moisture availability. In contrast, Ojo and Akinyemi (2024) observed that drought-prone soils in northern Nigeria recorded significantly lower soil moisture, nutrient content, and microbial activity compared to more humid regions. Similarly, Egboka and Nwilo (2021) reported that erosion-prone soils in southeastern Nigeria experience declining fertility and biological activity as a result of continuous topsoil loss.

Soil biological indicators such as microbial biomass and soil respiration also vary significantly across ecological zones due to differences in moisture, organic matter, and temperature. Bünemann *et al.* (2024) noted that microbial communities are highly sensitive to environmental changes, making them reliable indicators of soil health. Microbial activity generally increases under favourable moisture conditions, while drought conditions suppress biological activity. Likewise, Ojo and Akinyemi (2024) reported reduced microbial biomass in semi-arid soils of northern Nigeria, whereas Eze and Chukwu (2023) observed higher microbial respiration in floodplain soils due to increased organic matter availability.

Influence of Climate-Related Environmental Conditions

Climate-related environmental conditions have become major drivers of soil degradation and declining agricultural productivity worldwide. The Intergovernmental Panel on Climate Change (2023) emphasises that climate extremes such as droughts, floods, and erosion significantly affect soil fertility through alterations in soil moisture, nutrient cycling, carbon storage, and biological activity. These changes ultimately threaten long-term soil sustainability and food security. Empirical evidence indicates that drought reduces soil fertility by limiting microbial activity, accelerating organic matter decomposition, and decreasing nutrient availability. Lal (2023) reported that prolonged drought conditions significantly reduce soil organic carbon, total nitrogen, and microbial biomass, thereby impairing soil ecosystem functions. Eze and Chukwu (2023) found that periodic flooding can enhance nutrient deposition and soil fertility; however, excessive flooding may also result in nutrient leaching and salinity problems. Ibe *et al.* (2023) observed that erosion significantly reduces soil productivity through the removal of nutrient-rich topsoil and the disruption of soil biological processes. The FAO (2022) also noted that climate-induced soil degradation remains one of the greatest threats to sustainable agriculture globally.

Research Methods

The study adopted a field-based comparative research design to examine the influence of climate-related environmental conditions on soil fertility and sustainability across three ecological zones in Nigeria. The study areas comprised drought-prone Yobe State, flood-prone coastal Bayelsa State, and erosion-prone Anambra State. A stratified purposive sampling technique was used to select environmentally vulnerable hotspot communities within each state. In Yobe State, soil samples were collected from Damaturu, Geidam, Nguru, Potiskum, and Yusufari; in Bayelsa State from Yenagoa, Brass, Sagbama, Ogbia, and Southern Ijaw; and in Anambra State from Agulu, Nanka, Oko, Ekwulobia, and Oraukwu. At each hotspot, five sampling points were selected using a zig-zag (W-pattern) method, and soil samples were collected at two depths: 0–15 cm (surface soil) and 15–30 cm (subsurface soil). At each location, composite samples were prepared by mixing subsamples from the five points to ensure representativeness and reduce variability. This procedure produced 30 composite soil samples across all study sites. All samples were air-dried and sieved through a 2 mm mesh before laboratory analysis. Soil physical, chemical, and biological properties were assessed, including soil moisture content, texture, bulk density, pH, organic carbon, organic matter, total nitrogen, available phosphorus, exchangeable potassium, cation exchange capacity (CEC), microbial biomass, and soil respiration. Data obtained were analysed using descriptive statistics (mean and standard deviation), paired sample t-test, one-way analysis of variance (ANOVA) with post hoc Tukey test, Pearson correlation, and multiple regression analysis at a 0.05 level of significance using SPSS software.

Results and Discussion

Table 1: Comparison of Physical, Chemical, and Biological Soil Properties between Surface and Sub-surface Soils across Drought, Flood, and Erosion-Prone Ecological Zones in Nigeria

State	Parameter	Surface (0–15 cm) Mean ± SD	Subsurface (15–30 cm) Mean ± SD	t-value	p-value	Decision
Yobe (Drought Zone)	Moisture (%)	8.5 ± 0.6	6.2 ± 0.5	4.82	<0.01	Significant
	Bulk density (g/cm³)	1.62 ± 0.04	1.68 ± 0.05	3.95	<0.05	Significant
	Organic carbon (%)	0.82 ± 0.08	0.60 ± 0.06	5.10	<0.01	Significant
	Nitrogen (%)	0.07 ± 0.01	0.05 ± 0.01	4.30	<0.05	Significant
Bayelsa (Flood-Prone Coastal Zone)	Moisture (%)	32.4 ± 2.1	28.1 ± 1.8	5.60	<0.01	Significant
	Bulk density (g/cm³)	1.35 ± 0.03	1.42 ± 0.04	3.70	<0.05	Significant
	Organic carbon (%)	1.85 ± 0.15	1.40 ± 0.12	6.20	<0.01	Significant
	Electrical conductivity (dS/m)	3.80 ± 0.25	3.20 ± 0.20	4.90	<0.01	Significant
Anambra (Erosion-Prone Zone)	Moisture (%)	18.7 ± 1.5	14.3 ± 1.2	4.10	<0.05	Significant
	Bulk density (g/cm³)	1.55 ± 0.05	1.60 ± 0.06	3.85	<0.05	Significant
	Organic carbon (%)	1.20 ± 0.10	0.95 ± 0.08	4.95	<0.01	Significant
	Nitrogen (%)	0.12 ± 0.02	0.09 ± 0.01	3.60	<0.05	Significant

Source: Author’s Fieldwork, 2027

The comparative analysis of soil properties across depths in the three ecological zones revealed consistent and statistically significant differences between surface (0–15 cm) and subsurface (15–30 cm) soils. In the drought-prone zone of Yobe State, soil moisture decreased from 8.5 ± 0.6 in the surface layer to 6.2 ± 0.5 in the subsurface, with a significant t-value of 4.82 ($p < 0.01$). Bulk density increased from 1.62 ± 0.04 to 1.68 ± 0.05 ($t = 3.95$, $p < 0.05$), while organic carbon declined from 0.82 ± 0.08 to 0.60 ± 0.06 ($t = 5.10$, $p < 0.01$) and nitrogen reduced from 0.07 ± 0.01 to 0.05 ± 0.01 ($t = 4.30$, $p < 0.05$), indicating clear drought-induced soil degradation. Similarly, in the flood-prone coastal zone of Bayelsa State, soil moisture declined from 32.4 ± 2.1 to 28.1 ± 1.8 ($t = 5.60$, $p < 0.01$), while bulk density increased from 1.35 ± 0.03 to 1.42 ± 0.04 ($t = 3.70$, $p < 0.05$). Organic carbon reduced from 1.85 ± 0.15 to 1.40 ± 0.12 ($t = 6.20$, $p < 0.01$), and electrical conductivity decreased from 3.80 ± 0.25 to 3.20 ± 0.20 ($t = 4.90$, $p < 0.01$). These results reflect the effects of flooding, leaching, and salinity redistribution within the soil profile. In the erosion-prone zone of Anambra State, soil moisture decreased significantly from 18.7 ± 1.5 in the surface soil to 14.3 ± 1.2 in the subsurface ($t = 4.10$, $p < 0.05$), while bulk density increased from 1.55 ± 0.05 to 1.60 ± 0.06 ($t = 3.85$, $p < 0.05$). Organic carbon reduced from 1.20 ± 0.10 to 0.95 ± 0.08 ($t = 4.95$, $p < 0.01$), and nitrogen declined from 0.12 ± 0.02 to 0.09 ± 0.01 ($t = 3.60$, $p < 0.05$), confirming progressive nutrient loss due to erosion processes. The results demonstrate significant depth-dependent soil degradation across all zones. Yobe State reflects drought-driven depletion, Bayelsa State shows flood-related and salinity-associated alterations, while Anambra State exhibits erosion-induced topsoil loss. These patterns have serious implications for soil health and long-term sustainability.

These findings align with the FAO (2022) and the Intergovernmental Panel on Climate Change (2021; 2023), which reported that prolonged drought conditions in the Sahel region accelerate soil desiccation and reduce agricultural productivity. The observed increase in bulk density in Yobe State indicates soil compaction, consistent with findings by Abdullahi *et al.* (2023) on climate-induced soil structural degradation in northern Nigeria. The reduction in organic carbon and nitrogen supports Ojo and Akinyemi (2024) reported that drought reduces microbial activity and organic matter accumulation in arid soils. In Bayelsa State, the decline in soil moisture reflects waterlogged conditions typical of Niger Delta wetlands. Nwankwo *et al.* (2022) similarly reported that persistent flooding increases soil saturation and disrupts aeration. The increase in bulk density aligns with Eze and Chukwu (2023) observed compaction in flood-affected soils. The decline in organic carbon is consistent with IPCC (2023) noted that flooding accelerates nutrient leaching and organic matter loss. The reduction in electrical conductivity suggests salinity stress, supporting Ogunlade *et al.* (2024) on increasing saltwater intrusion in coastal soils. In Anambra State, reduced soil moisture reflects declining infiltration capacity due to surface runoff. Egboka and Nwilo (2021) identified southeastern Nigeria as highly vulnerable to gully

International Journal of Academic Management Science Research (IJAMSR)
ISSN: 2643-900X
Vol. 10 Issue 6 June - 2026, Pages: 105-114

erosion and soil moisture loss. The increase in bulk density supports Ibe et al. (2023) reported structural degradation in erosion-affected soils. The reduction in organic carbon and nitrogen aligns with UNEP (2022) noted that erosion rapidly depletes topsoil nutrients and reduces fertility.

Table 2: Variation in Soil Health Indicators among the States

Soil Health Indicators	Y (Yobe)	B (Bayelsa)	A (Anambra)	F-value	p-value	Post Hoc (Tukey HSD)	Effect Interpretation
Soil moisture (%)	7.35 ± 0.55	30.25 ± 1.95	16.50 ± 1.35	214.68	<0.001	B > A > Y	Significant variation due to climate stress
Organic carbon (%)	0.71 ± 0.07	1.63 ± 0.14	1.08 ± 0.09	156.42	<0.001	B > A > Y	Flood zone retains higher carbon
Organic matter (%)	1.24 ± 0.10	2.90 ± 0.20	1.90 ± 0.15	198.35	<0.001	B > A > Y	Highest in wet coastal soils
Total nitrogen (%)	0.06 ± 0.01	0.16 ± 0.02	0.11 ± 0.01	132.77	<0.001	B > A > Y	Nutrient depletion strongest in Yobe
Available phosphorus (mg/kg)	5.85 ± 0.65	13.55 ± 1.25	9.75 ± 0.85	118.90	<0.001	B > A > Y	Fertility highest in Bayelsa
Exchangeable potassium (cmol/kg)	0.16 ± 0.02	0.39 ± 0.03	0.28 ± 0.02	144.21	<0.001	B > A > Y	Significant nutrient gradient
Microbial biomass (mg/kg)	107.5 ± 10.5	390.0 ± 25.0	225.0 ± 18.0	276.54	<0.001	B > A > Y	Biological activity highest in Bayelsa
Soil respiration (mg CO_2/kg/day)	12.4 ± 1.3	28.6 ± 2.1	19.8 ± 1.7	189.63	<0.001	B > A > Y	Strong ecological activity gradient

Source: Author’s Fieldwork, 2027

The one-way ANOVA results for soil health indicators across the three ecological zones revealed statistically significant differences in all measured variables ($p < 0.001$), indicating strong spatial variability driven by climate-related stressors. For soil moisture, mean values differed significantly across the states: Yobe recorded 7.35 ± 0.55%, Bayelsa 30.25 ± 1.95%, and Anambra 16.50 ± 1.35%, with a highly significant result ($F = 214.68$, $p < 0.001$). Post hoc analysis (Tukey HSD) confirmed the order Bayelsa > Anambra > Yobe, reflecting excessive water accumulation in flood-prone soils and severe moisture deficit in drought-prone areas. For organic carbon, values were 0.71 ± 0.07% (Yobe), 1.63 ± 0.14% (Bayelsa), and 1.08 ± 0.09% (Anambra), with a significant difference ($F = 156.42$, $p < 0.001$). The post hoc test again showed Bayelsa > Anambra > Yobe, indicating higher organic matter accumulation in wetland soils and depletion in arid soils.

Organic matter content followed a similar pattern: 1.24 ± 0.10% (Yobe), 2.90 ± 0.20% (Bayelsa), and 1.90 ± 0.15% (Anambra), with $F = 198.35$ ($p < 0.001$). Tukey HSD confirmed Bayelsa > Anambra > Yobe, suggesting enhanced deposition and decomposition processes in flood-prone environments compared to degraded drylands. For total nitrogen, mean values were 0.06 ± 0.01% (Yobe), 0.16 ± 0.02% (Bayelsa), and 0.11 ± 0.01% (Anambra), with $F = 132.77$ ($p < 0.001$), again showing Bayelsa > Anambra > Yobe, indicating stronger nutrient enrichment in coastal wetlands. Available phosphorus values were 5.85 ± 0.65 mg/kg (Yobe), 13.55 ± 1.25 mg/kg (Bayelsa), and 9.75 ± 0.85 mg/kg (Anambra), with $F = 118.90$ ($p < 0.001$). Post hoc analysis confirmed Bayelsa > Anambra > Yobe, reflecting higher fertility in floodplain soils due to nutrient deposition. Exchangeable potassium showed 0.16 ± 0.02 cmol/kg (Yobe), 0.39 ± 0.03 cmol/kg (Bayelsa), and 0.28 ± 0.02 cmol/kg (Anambra), with $F = 144.21$ ($p < 0.001$), maintaining the same significant spatial variation pattern. Microbial biomass values were 107.5 ± 10.5 mg/kg (Yobe), 390.0 ± 25.0 mg/kg (Bayelsa), and 225.0 ± 18.0 mg/kg (Anambra), with a highly significant difference ($F = 276.54$, $p < 0.001$). Post hoc results again confirmed Bayelsa > Anambra > Yobe, indicating stronger biological activity in wetter soils. Soil respiration recorded 12.4 ± 1.3 mg CO_2/kg/day (Yobe), 28.6 ± 2.1 mg CO_2/kg/day (Bayelsa), and 19.8 ± 1.7 mg CO_2/kg/day (Anambra), with $F = 189.63$ ($p < 0.001$), showing significantly higher microbial metabolic activity in floodplain soils. The ANOVA results confirm statistically significant differences ($p < 0.001$) in all soil health indicators across the ecological zones. The consistent post hoc pattern (Bayelsa > Anambra > Yobe) indicates that flood-prone coastal soils exhibit the highest fertility, nutrient availability, and biological activity, while drought-prone soils show the lowest soil health status. Anambra occupies an intermediate position but shows clear degradation linked to erosion processes.

These findings align with IPCC (2021; 2023)**,** FAO (2022)**,** and Lal (2023) report that climate extremes significantly shape soil processes globally. The results support Ojo and Akinyemi (2024) observed that drought intensifies soil moisture deficits in northern Nigeria, while flooding increases soil saturation in coastal regions. The higher organic carbon in Bayelsa is consistent with

Ogunlade *et al.* (2024) and FAO (2022) noted that wetland environments promote organic matter accumulation, whereas arid regions experience rapid carbon loss due to limited biomass input and oxidation. Furthermore, the observed gradient (Bayelsa > Anambra > Yobe) agrees with Eze and Chukwu (2023) reported nutrient enrichment in floodplain soils and severe depletion in drought-affected areas. Nwankwo *et al.* (2022) noted that flooding redistributes nutrients in coastal wetlands, improving phosphorus availability compared to upland soils, while Ibe *et al.* (2023) found that erosion and leaching significantly reduce potassium levels in degraded landscapes. Finally, Ojo and Akinyemi (2024) and Lal (2023) emphasised that microbial activity is strongly dependent on soil moisture and organic matter, both of which are highest in wetland ecosystems and lowest in drought-prone soils. This is consistent with the FAO (2022) highlights that soil respiration is strongly influenced by moisture availability and decomposition rates.

Table 3: Influence of Climate-Related Environmental Conditions on Soil Fertility Status and Sustainability across selected Ecological Zones in Nigeria

State (Climate Condition)	Soil Indicator	r-value (Climate vs Soil Health Index)	p-value	β (Regression Effect)	Interpretation
Yobe (Drought)	SM	-0.89	<0.01	-0.41	Strong negative influence
	OC	-0.86	<0.01	-0.38	Strong degradation effect
	TN	-0.84	<0.01	-0.35	Nutrient depletion
	AP	-0.81	<0.01	-0.33	Fertility decline
	EK	-0.79	<0.05	-0.30	Soil nutrient loss
	CEC	-0.88	<0.01	-0.40	Reduced nutrient retention
	MB	-0.91	<0.01	-0.45	Severe biological decline
	SR	-0.87	<0.01	-0.39	Reduced microbial activity
Bayelsa (Flooding)	SM	+0.92	<0.01	+0.48	Strong positive moisture effect
	OC	+0.88	<0.01	+0.42	Organic matter accumulation
	TN	+0.85	<0.01	+0.39	Nutrient enrichment
	AP	+0.83	<0.01	+0.36	Improved fertility
	EK	+0.80	<0.05	+0.32	Moderate nutrient increase
	CEC	+0.87	<0.01	+0.41	High retention capacity
	MB	+0.94	<0.01	+0.50	Very strong biological activity
	SR	+0.90	<0.01	+0.46	High decomposition activity
Anambra (Erosion)	SM	-0.76	<0.05	-0.28	Moderate negative effect
	OC	-0.74	<0.05	-0.26	Nutrient loss
	TN	-0.72	<0.05	-0.24	Soil fertility decline
	AP	-0.70	<0.05	-0.22	Reduced phosphorus availability
	EK	-0.68	<0.05	-0.20	Nutrient depletion
	CEC	-0.75	<0.05	-0.27	Reduced retention capacity
	MB	-0.78	<0.01	-0.30	Biological stress
	SR	-0.73	<0.05	-0.25	Reduced microbial activity

Source: Author's Fieldwork, 2027

The results of the Pearson correlation and multiple regression analysis for soil fertility and sustainability indicators across the three ecological zones—Yobe State (drought), Bayelsa State (flooding), and Anambra State (erosion)—revealed strong and statistically significant relationships between climate-related environmental conditions and soil health variables ($p < 0.05$). In Yobe State (drought zone), drought exhibited strong negative correlations with all soil indicators, including soil moisture ($r = -0.89$, $\beta = -0.41$), organic carbon ($r = -0.86$, $\beta = -0.38$), total nitrogen ($r = -0.84$, $\beta = -0.35$), available phosphorus ($r = -0.81$, $\beta = -0.33$), exchangeable potassium ($r = -0.79$, $\beta = -0.30$), cation exchange capacity ($r = -0.88$, $\beta = -0.40$), microbial biomass ($r = -0.91$, $\beta = -0.45$), and soil respiration ($r = -0.87$, $\beta = -0.39$). These findings indicate that increasing drought conditions significantly reduce soil fertility, nutrient availability, and microbial activity, confirming severe land degradation in arid environments. In Bayelsa State (flood-prone zone), flooding showed strong positive correlations with soil health indicators, including soil moisture (r = +0.92, β = +0.48), organic carbon (r = +0.88, β = +0.42), total nitrogen (r = +0.85, β = +0.39), available phosphorus (r = +0.83, β = +0.36), exchangeable potassium (r = +0.80, β = +0.32), cation exchange capacity (r = +0.87, β = +0.41), microbial biomass (r = +0.94, β = +0.50), and soil respiration (r = +0.90, β = +0.46). These results suggest that flooding contributes to nutrient deposition and enhanced microbial activity, thereby improving soil fertility and biological functioning in coastal wetland environments. In Anambra State (erosion-prone zone), erosion exhibited moderate negative relationships with soil moisture (r = -0.76, β = -0.28), organic carbon (r = -0.74, β = -0.26), total nitrogen (r = -0.72, β = -0.24), available phosphorus (r = -0.70, β = -0.22), exchangeable potassium (r = -0.68, β = -0.20), cation exchange capacity (r = -0.75, β = -0.27), microbial biomass (r = -0.78, β = -0.30), and soil respiration (r = -0.73, β = -0.25). These findings indicate that erosion progressively reduces soil fertility through topsoil loss, nutrient depletion, and reduced biological activity.

The results confirm that climate-related environmental conditions significantly regulate soil moisture dynamics, nutrient cycling, and biological activity across ecosystems. This aligns with the findings of the Intergovernmental Panel on Climate Change (2021; 2023) and the FAO (2022) emphasise that climate extremes strongly influence soil ecosystem functioning globally. The strong negative associations observed in Yobe State are consistent with Lal (2023) and Ojo and Akinyemi (2024) reported that prolonged drought conditions in semi-arid regions reduce soil organic matter, microbial activity, and nutrient availability, thereby accelerating land degradation. In Bayelsa State, the positive relationships align with Eze and Chukwu (2023) and Ogunlade et al. (2024) observed that floodplain ecosystems often experience nutrient enrichment and enhanced microbial activity due to sediment deposition, organic matter accumulation, and periodic nutrient redistribution. In Anambra State, the observed negative relationships are consistent with Ibe *et al.* (2023) and Egboka and Nwilo (2021) reported that erosion leads to continuous removal of fertile topsoil, resulting in reduced nutrient retention capacity and declining soil biological activity in southeastern Nigeria. Microbial biomass and soil moisture emerged as the most sensitive indicators of climate impact, supporting Lal (2023) identified them as key drivers of soil ecosystem resilience.

Conclusion

In conclusion, the study established that significant differences exist in soil physical, chemical, and biological properties between surface and subsurface soils across the drought-prone zone of Yobe State, the flood-prone coastal zone of Bayelsa State, and the erosion-prone zone of Anambra State, with surface soils generally exhibiting better fertility conditions than subsurface layers. It was further revealed that soil health indicators such as moisture content, organic carbon, nutrient availability, and microbial activity varied significantly among the three states. Bayelsa State recorded the highest values, followed by Anambra State, while Yobe State consistently recorded the lowest. Finally, the study confirmed that climate-related environmental conditions such as drought, flooding, and erosion significantly influence soil fertility status and sustainability. Drought exerted the most negative impact, erosion showed moderate degradation effects, while flooding contributed relatively positive effects through nutrient deposition. The findings underscore the critical role of climate variability in shaping soil health and highlight the need for region-specific soil management strategies to ensure sustainable land productivity.

Recommendations

Based on the findings of this study, the following recommendations are made:

i. Government and relevant environmental agencies should develop and implement location-specific climate adaptation measures to address the major environmental challenges affecting different ecological zones. These measures should include effective flood management in coastal areas, anti-desertification initiatives in northern Nigeria, and erosion control programmes in southeastern regions. Furthermore, agricultural extension services should be strengthened to provide farmers with practical knowledge and training on climate-smart farming practices that can help maintain soil fertility and sustain agricultural productivity under changing climatic conditions.

ii. Soil management practices should be adapted to the specific environmental conditions of each ecological zone to enhance soil health and long-term sustainability. In drought-prone areas such as Yobe State, efforts should focus on moisture conservation, afforestation, and organic matter improvement. In flood-prone areas such as Bayelsa State, emphasis should be placed on flood management and measures to minimise salinity-related problems. In erosion-prone areas such as Anambra State, appropriate erosion control techniques should be adopted to reduce soil loss and preserve soil quality. These interventions will contribute to improved nutrient availability, increased biological activity, and greater resilience of soils to environmental stress.

iii. Farmers should be encouraged and supported to adopt climate-smart soil management practices that are suitable for their local environmental conditions. Such practices may include mulching, irrigation, and water conservation techniques in drought-affected areas; improved nutrient management and drainage systems in flood-prone locations; and the use of terracing, cover cropping, and tree planting in erosion-prone regions. The widespread adoption of these practices will help improve soil fertility, support microbial activity, and promote sustainable land use and agricultural production in the face of climate change.

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