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Emerging ecological trends in West Africa: implications on soil organic matter and other soil quality indicators

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Abstract

Aims In West Africa, savannas are changing to either forest islands or arable lands arising from anthropogenic interference with the natural ecosystem. This study aimed at quantifying the trade-offs of this land use conversion on major soil quality indicators.

Methods We evaluated soil organic matter (SOM) and other soil quality indicators such as macro- and micronutrients (including the absence of some hazardous trace metals) using standard methodologies across 11 settlements in Burkina Faso, Ghana, and

Nigeria. The degree of soil quality improvement/degradation and soil quality were assessed using empirical models.

Results The effects of savanna conversion were manifold and varied depending on the type of land use change, soil depth, and soil quality indicator. In savanna-forests, there was a substantial rise in SOM (37%—794%) and exchangeable cations (15% to 800%) and changes in SOM in the topsoil quadrupled that of the subsoil. A general loss in SOM (1% -74%) and soil macro- and micronutrients occurred under savanna-arable lands. Potassium, calcium and magnesium increased by $\geq 12\%$, $\geq 15\%$ and 27% respectively while increases in Mn and Zn were 37% and $\geq 250\%$

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in the forests over the savannas. Trace quantities of Pb were detected which were below the contamination threshold. About 63% forest islands, 18% arable land, and 9% savannas had SQI % \geq 50.

Conclusion In marginal lands, land use conversion to forest islands presents great potential for improving soil fertility and overall ecosystem health as shown in the high organic matter and improved soil quality.

Keywords African dark earths · Ethnopedology · Land use change · Soil fertility · Soil organic matter

Introduction

In West Africa, it is a popular indigenous assumption that the settlement, which includes people, animals, and spirits, transforms the soils from originally poor state to fertile and productive soils otherwise referred to as African Dark Earths (Frausin et al. 2014). Forest patches now exist in the savanna zones of West Africa due to indigenous soil-human interactions with the environment in a variety of socio-cultural activities (Fairhead and Leach 1998, 2009; Hennenberg et al. 2005; Mesele et al. 2024). The type of forests that emanate from such community-based efforts have been referred to as anthropogenic forests or forest islands and more recently studied by Bougma et al. (2022) and Mesele et al. (2024). Forest islands are thus the product of active human transformation of savanna rather than remnants of original forest vegetation surrounded by degraded forest lands (savanna) as suggested in colonial times (Mayer 1951; Jones 1963; Morgan and Moss 1965). Such forests demonstrably provide important ecosystem services such as wood and energy supply, but also non-timber forest products (fruits and medicine) as well as improving local climate conditions (Chazdon 2008; Brockerhoff et al. 2017). Today we see savannas being transformed into arable land or converted to forest islands. The latter is particularly true in areas close to the community settlement. The soil quality implication of this land use change presents an important research area in the context of ecosystem and agricultural sustainability (Pessenda et al. 2004; Baude et al. 2019).

Soil quality is the capacity of soil to function within managed or natural ecosystem boundaries to sustain plant and animal productivity; and support human health and habitation (Doran and Parkin 1994).

Assessing soil quality changes, aids in maintaining global environmental quality and sustainable food production (Doran and Parkin 1994). Soil properties that can be influenced by land use dynamics are often referred to as soil quality indicators that can be used when taking action on land-related issues (Muñoz-Rojas et al. 2016). For instance, management choices affect the amount of soil organic matter, soil structure, depth, and water and nutrient holding capacities (Amacher et al. 2007; Mesele et al. 2016). Measurement of soil fertility attributes provides indices of soil quality for plant growth and development (Muñoz-Rojas et al. 2016). According to Zhang et al. (2013), soils such as those of the forest islands that receive considerable and frequent amounts of organic wastes may accumulate trace metals including lead (Pb), manganese (Mn), zinc (Zn), iron (Fe), copper (Cu), and chromium (Cr). While Cr and Pb are primarily heavy metals and represent hazardous elements in the environment when they exceed tolerable limits; manganese, zinc, iron, and copper are soil micronutrients that are required in small amounts for plant productivity but become toxic to plants and humans when present at high concentrations (Lucchini et al. 2014).

To identify early changes in soil quality, it is crucial to examine soil properties during land conversion (Soleimani et al. 2019). Savanna conversion to agricultural land potentially also presents ecological challenges in relation to soil organic matter and other soil quality indicators. Converting natural ecosystems to agricultural systems often comes with attendant ecological risks arising from increased rate of soil erosion (Marques et al. 2019; Mesele et al. 2016), loss of biodiversity (Yang et al. 2022), nutrient mining, loss of water retention services which has a consequence of potential desertification and many others through changes in land use and land cover characteristics as well as improper land management practices. Information on changes in soil quality arising from savanna conversion to arable lands is important for the design of early monitoring systems and for the creation of adaptation and mitigation strategies to offset the negative effects of this type of land use conversion.

On the other hand, savanna conversion to forest could be easily seen as a positive ecological contribution to enhancing soil quality. It is, however, important to have a full understanding of the impact of the practices that led to the creation of the forest islands as some of those activities could introduce hazardous

materials such as trace metals (Azeez et al. 2014) into the environment that may bio-accumulate in plant tissues (Olayiwola et al. 2023), thereby causing ecological damage instead of the perceived ecological benefits of savanna conversion to forests. There is thus a risk of trace metal contamination in soils receiving a significant and frequent influx of household wastes, human and animal dung, and other wastes. The ecological safety of forest islands is therefore in question and needs urgent research attention.

The objectives of this study were, therefore, to examine what changes can be observed in soil as a result of land use change from savanna to forest and compare this with changes from savanna to arable land in West Africa. We aimed at quantifying the effects of land use change on the topsoil and subsoil layers, focused on soil organic matter and other soil quality indicators as well as the bio-available trace metals in forest islands.

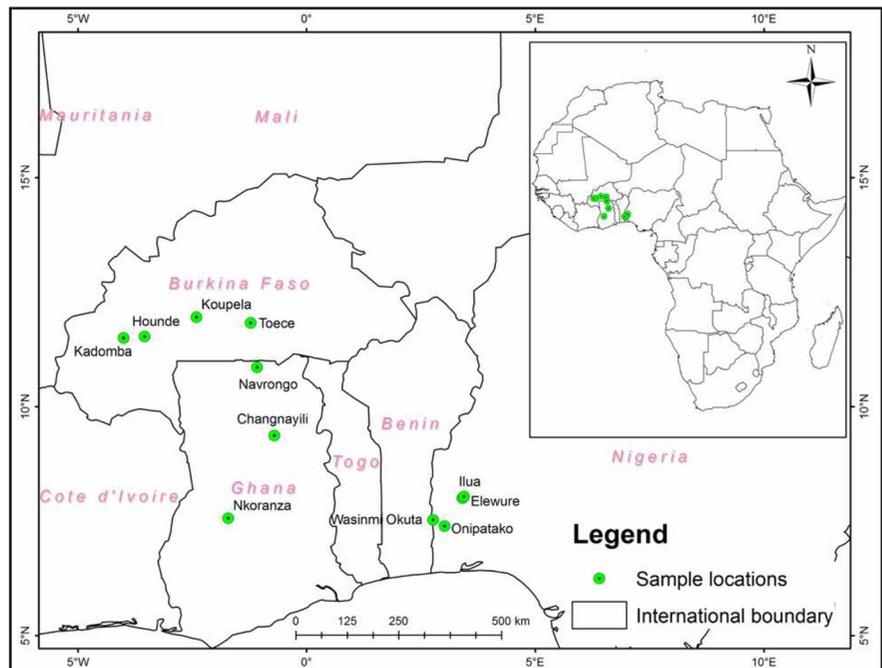
Materials and Methods

The Study Area

The study was conducted across three countries in West Africa, namely: Nigeria, Ghana, and Burkina

Faso (Map 1). The research sites in Nigeria were located at Elewure–Okeho (ELE, 8°27.6"N 3°26'30.2"E), Ilua (ILU, 8°0'1.1"N 3°24'32.3"E), Onipatako (ONP, 7°23'23.3"N 3°1'12.6"E), and Wasimi-Okuta (WSM, 7°31'41.8"N 2°46'7.9"E). These settlements are within the Guinea savanna agro-ecological zone and each of the settlements consists of at least a forest island. In Ghana, two of the study sites form part of the country's Interior Savanna agro-ecological zone, consisting of the Guinea and Sudan savanna, which cover more than one-third of the country's land area. These study locations were Changnayili (CHN, 9°22'19.9"N 0°42'13.5"E), Navrongo (NAG, 10°51'52.8"N 1°45'1.3"E), and Nkoranza (NKZ, 7°33'48.3"N 1°42'46.9"E) which was in the forest-savanna transition zone. In Burkina Faso, the study sites were Houndé (HOU, 11°31'39.9"N 3°32'31.9"W), Kadomba de Bobo Dioulasso (KAD, 11°29'55.3"N 3°59'52.1"W), Koupéla de Koudougou (KPL, 11°57'1.8"N 2°24'19.3"W), and Toécé (TOE, 11°49'32.8"N 1°13'17.1"W). The forest stands were generally over 100 years old as of 2016/2017 when the fieldwork was conducted. The arable lands were typically African smallholder farms with little or no external nutrient input and the crop yields were generally low below the world average (Fermont and Benson 2011). See Tables S1 (Supplementary file) for

Map 1 Map showing the study areas within West Africa



more details on the geographical locations, soil type, climatic variables, vegetation, farming systems, and crop types of the study areas. Plate 1 shows a typical forest island in Ghana.

Soil sampling and sample processing

In each location, forest island, arable land, and natural savanna land were identified. In each of these ecosystems, 4 plots each measuring 20×20 m were established. Four soil samples were randomly collected per plot representing a particular ecosystem type at each soil depths of 0–20 cm and 20–50 cm, being the topsoil and subsoil respectively. Soil samples collected per plot per ecosystem type per depth were bulked, and thoroughly mixed, and subsamples taken and packed in well-labeled bags and transported to the laboratory. The samples were air-dried and sieved with a 2 mm diameter sieve and kept for laboratory analysis.

Laboratory analysis of soil samples

Particle size analysis was conducted using the Robinson-Kohn method (Mathieu 1998). Bulk density was determined using the core method as the mass of oven-dried soil to a unit volume of the sample. Soil pH and EC were determined following the procedures

of Kalra and Maynard (1991). The soil organic carbon and total nitrogen were determined with an Elementar analyzer (Elementar Vario Macro cube, Germany) using dry chemistry procedures (Santi et al. 2006). Available phosphorus in the soils was determined as recommended by Bray and Kurtz (1945). The soil exchangeable bases were extracted with ammonium acetate solution at pH 7 (1.0 N NH₄OAc pH 7; Van Reeuwijk 2002) and measured with Inductively Coupled Plasma Optical Emission Spectrometer (ICP OES; iCAP 7400 Duo, Thermofisher Scientific). Effective Cation Exchange Capacity was determined by the summation of exchangeable cations and exchangeable acidity. Trace metals such as Zn, Cu, Mn, Cr, and Pb were extracted in soil samples with 0.1 M hydrochloric acid (1:6) solution and the extracts were read using ICP-OES. This was done as outlined by Donisa et al. (2000) and Lindsay and Cox (1985). The concentrations of the trace metals were compared with each metal's thresholds presented in Table S5 (Supplementary material).

Determination of the extent of soil deterioration/improvement on managed ecosystems

The soil deterioration index (Adejuwon and Ekanade 1988) was computed based on the hypothesis that the

Plate 1 Typical Forest island in Ghana



level of individual soil nutrient/property under forest islands and arable lands was once the same as that of soils under the open savannas. Mesele et al. (2024) provided a detailed comparative analysis of the mineralogical and nutrient characteristics of the forest islands and adjacent ecosystems providing evidence for this assumption. The index (Eq. 1) is computed using the summative difference method in the topsoil layer and subsoil layer.

The positive value shows improvement of the soils (the greater the value the better the level of improvement), whereas the negative value indicates deterioration of the soils. Where the index was greater than -5%, this indicates no deterioration of soils. The soils have light deterioration for the index between -5% and -10%, moderate deterioration ranging from -10% to -20% and severe deterioration less than -20%.

$$RX = (X - U)/U * 100 \quad (1)$$

Total SQI = \sum individual soil property index values
 SQI, % = (total SQI / maximum possible total SQI for properties measured) \times 100

Statistical Analysis

Statistical analyses were performed using R statistical program implemented in Rstudio. Analysis of Variance (ANOVA) was conducted after having checked for data normality based on the Shapiro–Wilk test. Pearson correlation was conducted on all the soil quality indicators using the Multi-Environment Trial Analysis (metan) package in R as described by Olivoto and Dal’Col Lúcio (2020). Multivariate Exploratory Data Analysis and Data Mining such as principal component analysis was performed using FactoMineR procedures which were implemented in Factoshiny version 2.4 (Le et al. 2008; Vaissie et al. 2021). Significant means were separated using the Tukey Honest Significant difference (Tukey HSD) method in R. The Scientific Graphing Functions for Factorial Designs (Sciplot) package were used to generate some of the graphs. The total SQI% values were computed and presented in percentages.

where:

RX	the relative change in the soil property.
X	the adjusted mean of the soil property from the land use under consideration (forest island or arable land)
U	the mean of the same soil property from a reference land use at the site in question (open savanna)

Assessment of soil quality potential

Soil quality assessment was carried out using the soil quality indices developed by Amacher et al. (2007). The soil quality indicators were assessed using direct method by matching the results of the chemical properties of the soil quality indicators with the Soil Quality Index (SQI) proposed by Amacher et al. (2007). The individual index values for all the mineral soil properties measured were summed to give a total SQI.

Results

Effects of land use change on the topsoil layer with key soil quality indicators

Soil organic matter (SOM)

Land use conversion had varying effects on the soil organic matter within the topsoil layer which was dependent on the type of land use change (Fig. 1). See Table S6 (Supplementary file) for the analysis of variance of the soil organic matter and for the nutrient concentrations. Topsoil organic matter varied from decline (-74%) to enrichment (16%) when savanna was converted to arable land (ms-farm). All the locations except CHN had varying levels of soil organic matter decline. The situation was more critical at TOE and KAD both of which are located in Burkina Faso. Changes in land use, however, from savanna to forest (ms-forest) led to increases in the soil organic matter of the topsoil layer (Fig. 1). KAD

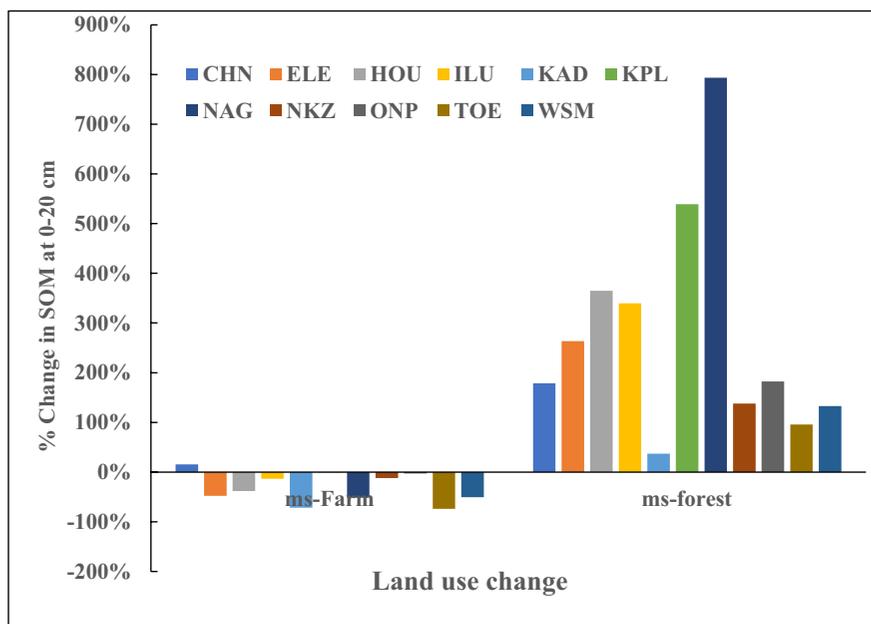


Fig. 1 Effect of savanna conversion to forest and arable land on the soil organic matter in the 0 -20 cm soil layer. ms-farm=Land conversion from savanna to agricultural land; ms-forest=Land conversion from savanna to forest island; SOM=Soil organic matter; CHN=Changnayili, Ghana; ELE=Elewure -Okeho, Nigeria; HOU=Houde, Burkina

Faso; ILU=Ilua, Nigeria; KAD=Kadamba de Bobo Dioulasso, Burkina Faso; KPL=, Koupéla de Koudougou, Burkina Faso; NAG=Navrongo, Ghana; NKZ=and Nkonranza, Ghana; ONP=Onipatako, Nigeria; TOE=Toécé, Burkina Faso; WSM=Wasimi - Okuta, Nigeria

had the lowest improvement (37%) while NAG had the highest enrichment (794%) under land conversion to forest. The typical topsoil layer of the forest islands showed significantly very dark to black coloration relative to the other ecosystem types (Plate 2).

Exchangeable potassium (K)

Land use change from savanna to forest island led to improvement in the soil K status from 12 to > 500% increase at some of the locations. ONP



Plate 2 Soil profile photos of the ecosystem types at Elewure community (ELE), Nigeria

had the highest level of soil K improvement while HOU recorded the highest soil K decline in the topsoil under savanna conversion to forest island (Table 1). Tables S2–S4 present the concentration values of potassium including all the soil nutrients under each of the land use types. Land use conversion from savannas to arable lands had a positive impact on soil K at ONP, KAD, TOE, CHN, NAG and NKZ in the topsoil. The percent increase of K in these arable lands over the savannas varied from 53 to > 500% (Table 1). While ONP and NKZ gave the highest levels of soil improvement, HOU gave the highest level of soil K decline when the land was converted from savanna to arable land.

Exchangeable sodium (Na)

Land use change from savanna to forest island led to an increase in the soil Na content from 29% in the ONP to > 500% in the TOE and CHN (Table 1). Other locations deteriorated in their soil Na content ranging from -33 to -79%. TOE and CHN showed the greatest improvements in Na status while NAG had the highest decline in Na arising from the conversion of savanna to forest island. Similarly, land use change from savanna to arable land had positive effects on the Na content in the top soils of HOU, TOE, CHN and NAG.

Table 1 Effects of land use change on soil macronutrients and ECEC in the topsoil

Location	Land use change	K	Na	Ca % change	Mg (cmol/kg)	ECEC
ELE	MS-Farm	-79(0.19)	-97(0.21)	-45(2.01)	-73(1.00)	-29(4.0)
ILU	MS-Farm	-10(0.30)	-50(0.20)	-4(3.52)	-13(2.11)	-26(7.0)
ONP	MS-Farm	1550(0.20)	-100(0.40)	23(4.03)	3(2.51)	-27(7.0)
WSM	MS-Farm	-45(0.17)	-67(0.13)	-17(2.01)	-30(1.04)	-8(4.0)
HOU	MS-Farm	-100(0.20)	100(0.23)	121(3.50)	-41(1.00)	31(5.8)
KAD	MS-Farm	54(0.20)	-100(0.48)	1(1.51)	-52(1.00)	-1(4.0)
KPL	MS-Farm	-45(0.33)	-36(0.19)	0(4.03)	-12(2.21)	-22(7.0)
TOE	MS-Farm	190(0.21)	2133(0.68)	83(2.49)	424(1.50)	-15(6.0)
CHN	MS-Farm	230(2.11)	800(0.12)	15(6.40)	9(4.01)	32(13.0)
NAG	MS-Farm	114(0.33)	44(0.30)	58(8.01)	77(4.51)	37(13.0)
NKZ	MS-Farm	750(0.32)	-67(0.30)	-8(3.01)	-11(1.79)	-8(6.0)
ELE	MS-Forest	12(0.92)	-97(0.50)	15(5.90)	-34(2.20)	-2(10.4)
ILU	MS-Forest	14(0.60)	325(0.41)	-29(5.01)	-1(2.01)	-19(8.5)
ONP	MS-Forest	1550(0.30)	29(0.33)	-45(3.00)	-58(1.00)	3(6.0)
WSM	MS-Forest	-16(0.20)	-117(0.20)	-53(4.00)	-52(1.40)	-83(7.0)
HOU	MS-Forest	100(0.83)	350(0.30)	-7(4.38)	18(3.40)	42(9.8)
KAD	MS-Forest	-23(0.20)	0(0.10)	-63(1.50)	-48(1.00)	27(3.0)
KPL	MS-Forest	69(0.71)	-73(0.10)	78(6.00)	11(3.50)	9(11.0)
TOE	MS-Forest	480(0.30)	1656(1.82)	30(3.00)	323(2.00)	-8(6.0)
CHN	MS-Forest	-44(0.34)	500(0.31)	-2(3.81)	-3(2.40)	103(7.5)
NAG	MS-Forest	2129(2.21)	-33(0.20)	78(6.94)	141(3.80)	67(13.0)
NKZ	MS-Forest	130(0.39)	67(0.18)	-32(3.00)	-55(1.80)	-19(6.0)
Mean	MS-Farm	237	233	21	24	-3
SD	MS-Farm	22	21	2	2	0
Mean	MS-Forest	369	258	-3	22	11
SD	MS-Forest	34	23	1	2	1

Values in the parentheses are the mean concentrations of the nutrient (farmland for ms-farm and forest island for ms-forest) in cmol/kg soil. MS-Farm = land use change from savanna to arable land; MS-Forest = land use change from savanna to forest island. Negative value implies decline in soil quality parameter. Positive value implies improvement in soil quality.

Exchangeable calcium (Ca)

Changes in land use from savanna to forest island as well as from savanna to arable land both had positive and negative implications on the soil exchangeable calcium in the topsoil but this was dependent on the geographic location (Table 1). There was an improvement in soil Ca ranging from 15% in ELE to 78% in the NAG topsoil. ELE, KPL, TOE and NAG, i.e., 4 locations out of 11, had improvement in the soil Ca due to ms-forest. The remaining 7 locations, had their soil Ca declining from -7% (HOU) to -63% (KAD), respectively. Similarly, ms-farm had positive and negative impacts on calcium in the topsoil. Improvement in soil Ca varied from 15% at CHN to 121% at HOU. In addition to these, ONP, TOE and NAG had improvements in Ca content in the topsoil.

Exchangeable magnesium (Mg)

Improvements in soil magnesium arising from land use change from savanna to forest island ranged from 1 to 322% between ILU and TOE topsoils (Table 1). HOU, KPL and NAG were the other locations that had improvements in Mg status, and in all, 5 out of 11 sites were in this category. Decline in Mg status, however, occurred in the other 6 locations, with the level of decline varying between -3% at CHN to -55% at NKZ. Likewise, land use change from savanna to arable land, had positive impacts on the soil Mg and this impact varied from 3% at ONP to 424% at TOE. Three (3) out of 11 sites fell into the Mg improvement category while the other 8 locations had their Mg declined. ELE recorded the highest level of magnesium.

Soil effective cation exchange capacity

In the topsoil, the positive impact of land use change (savanna to forest island) on the soil ECEC was pronounced and range from 3% increase at ONP to 103% increase at CHN (Table 1). Also, land use change from savanna to arable land reduced the soil ECEC of 8 out of 11 sites. The remaining 3 sites, namely; HOU, CHN and NAG had improved ECEC (>31% increase) after savanna conversion to arable land.

Effects of land use change on the subsoil

Soil organic matter

In the subsoil layer, changes in soil organic matter occurred as a result of land use conversion. Among the 11 locations across West Africa, only CHN had an increase in subsoil organic matter while the other locations recorded varying levels of SOM decline with the most severe occurrence at KAD and WSM (Fig. 2). On the other hand, savanna conversion to forest had mixed effects on the soil organic matter in the subsoil layer. In most of the locations, ms-forest had a positive influence on the SOM but in locations such as ONP, TOE and WSM, converting the savanna to forest island led to a decline the soil organic matter in the subsoil.

Exchangeable K

There were improvements in the soil K status when savanna lands were converted to forest islands at ILU, HOU, KPL, TOE, and NAG (Table 2). These improvements varied from 8% at HOU to >500% at ILU. Other locations experienced decline in K content due to land conversion from savanna to forest islands. However, savanna land conversion to arable land had a declining effect on soil K at ELE, WSM, HOU, KAD, and NKZ while in other locations, soil K increased ($\geq 50\%$) when savanna lands were converted to arable lands.

Exchangeable Na

Land use change from savanna to forest island had positive effects (increase in $\text{Na} \geq 500\%$) on the Na content in the subsoils of HOU, TOE, NAG and NKZ (Table 2). Other locations, experienced decline in Na status of the subsoil (-75 to -99%). Also, land use change from savanna to arable land led to increases in the soil Na content from 33% at NKZ to >500% at ILU subsoil. Other locations declined in their soil Na contents, ranging from -88% at KPL to -97% at ELE. ONP and TOE had the highest increases in Na status.

Exchangeable Ca

Changes in land use from savanna to forest island as well as from savanna to arable land both had positive

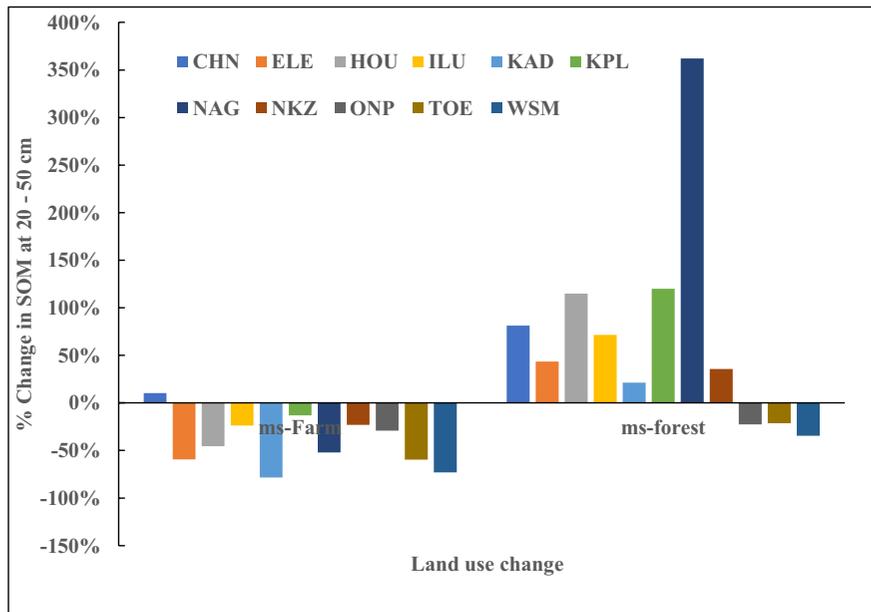


Fig. 2 Effect of savanna conversion to forest and arable land on the soil organic matter in the subsoil layer (20 – 50 cm). ms-farm=Land conversion from savanna to agricultural land; ms-forest=Land conversion from savanna to forest island; SOM=Soil organic matter; CHN=Changnayili, Ghana; ELE=Elewure –Okeho, Nigeria; HOU=Houde, Burkina

Faso; ILU=Ilua, Nigeria; KAD=Kadomba de Bobo Dioulasso, Burkina Faso; KPL=, Koupéla de Koudougou, Burkina Faso; NAG=Navrongo, Ghana; NKZ=and Nkonranza, Ghana; ONP=Onipatako, Nigeria; TOE=Toécé, Burkina Faso; WSM=Wasimi – Okuta, Nigeria

and negative implications on the soil exchangeable calcium in the subsoil (Table 2). There was an improvement in soil Ca ranging from 6% at HOU to >500% at ONP, KPL and NAG subsoils. Eight out of 11 locations had improvement in the soil Ca due to land use change from savanna to forest island. The remaining 3 locations had their soil Ca declining from -22% (TOE) to -75% (KAD). Similarly, land use change from savanna to arable land had positive and negative impacts on calcium in the subsoil. Improvement in soil Ca varied from 6% at ILU to >500% at NAG.

Exchangeable Mg

Changes in land use had mixed effects on Mg content of the soil. Savanna land conversion to forest island increased soil Mg from 5% at HOU to >500% at NAG. Other sites with Mg improvement were ILU, ONP, KPL, TOE, and CHN (Table 2). Savanna conversion to forest island however had a declining effect on Mg (Mg decline $\geq 29\%$) at ELE, WSM, KAD

and NKZ. On the other hand, land use change from savanna to arable land had both positive and negative impacts. Increase in Mg (Mg > 44%) occurred at ILU, ONP, KPL, TOE, CHN, NAG and NKZ while decreases in Mg were at ELE, WSM, HOU and KAD subsoils.

Exchangeable ECEC

In the subsoil, the positive impact of land use change (savanna to forest island) on the soil ECEC was pronounced and ranged from 4% increase at KAD to 117% increase at WSM (Table 2). Nine (9) out of 11 sites were in this category while the remaining 2 locations (ONP and NKZ) experienced decline in ECEC. Land use change from savanna to arable land, similarly, improved the ECEC with a minimum of 6% increase at locations such as ELE, WSM, HOU, KPL, TOE and NAG. Tables S2 – S4 contain the raw profile detail of the soil physical and chemical properties of the ecosystems at the different locations.

Table 2 Effects of land use change on soil macronutrients and effective cation exchange capacity in the subsoil

Location	Land use change	K	Na	Ca % change	Mg /(cmol/kg)	ECEC
ELE	MS-Farm	-74 (0.09)	-97(0.09)	-9(2.90)	-79(0.90)	6(3.90)
ILU	MS-Farm	1700(0.33)	-94(0.05)	6(1.36)	44(2.64)	-14(4.40)
ONP	MS-Farm	50(0.02)	780(0.03)	265(2.65)	3290(2.55)	-80(3.40)
WSM	MS-Farm	-100(0.11)	-92(0.04)	-95(3.98)	-87(0.61)	18(2.45)
HOU	MS-Farm	-83(0.11)	200(0.03)	15(3.98)	-65(1.22)	35(5.10)
KAD	MS-Farm	-100(0.26)	-71(0.07)	-76(2.82)	-65(2.52)	-58(2.90)
KPL	MS-Farm	170(0.17)	-88(3.62)	568(5.88)	365(3.67)	14(8.40)
TOE	MS-Farm	142(0.29)	7140(3.62)	119(5.11)	195(4.75)	80(14.40)
CHN	MS-Farm	495(2.93)	-94(0.02)	141(5.39)	55(3.98)	-53(11.0)
NAG	MS-Farm	171(0.21)	1600(0.68)	4911(8.85)	840(5.93)	32(16.50)
NKZ	MS-Farm	-33(0.02)	33(0.08)	16(5.17)	72(3.68)	0(9.0)
ELE	MS-Forest	-38(0.21)	-96(0.04)	16(3.69)	-54(1.94)	27(6.0)
ILU	MS-Forest	6550(0.81)	-94(0.15)	305(2.39)	82(2.54)	13(6.0)
ONP	MS-Forest	-100(0.07)	-100(0.05)	1327(2.45)	600(2.00)	-28(4.7)
WSM	MS-Forest	-71(0.26)	-99(0.01)	-57(1.67)	-47(1.21)	117(3.2)
HOU	MS-Forest	8(0.30)	500(0.30)	6(3.41)	5(2.23)	28(6.4)
KAD	MS-Forest	-77(0.41)	-71(0.07)	-75(3.48)	-64(4.36)	4(8.4)
KPL	MS-Forest	310(0.40)	-75(0.10)	535(5.95)	416(3.42)	82(9.5)
TOE	MS-Forest	283(0.40)	9380(3.59)	-22(5.21)	176(4.38)	76(14.0)
CHN	MS-Forest	-10(0.2)	-81(0.03)	111(4.73)	38(3.54)	19(9.0)
NAG	MS-Forest	657(1.70)	1425(0.17)	4737(8.53)	813(5.85)	31(16.5)
NKZ	MS-Forest	-33(0.10)	567(0.05)	23(3.26)	-29(0.93)	-40(6.0)
<i>Mean</i>	MS-Farm	213	1476	533	415	-2
<i>SD</i>	MS-Farm	19	134	48	38	1
<i>Mean</i>	MS-Forest	680	1023	628	176	30
<i>SD</i>	MS-Forest	62	93	57	16	3

Values in parentheses are the mean concentrations of the nutrient (farmland for ms-farm and forest island for ms-forest in cmol/kg soil. MS-Farm = land use change from savanna to arable land; MS-Forest = land use change from savanna to forest island. Negative value implies decline in soil quality parameter. Positive value implies improvement in soil quality.

Trace metals distribution per ecosystem types across the locations

Manganese varied considerably but inconsistently across the locations (Fig. 3). For instance, at CHN and NAG, Mn concentration was in the order of forest island > arable land > open savanna while at ILU and WSM, it was open savanna > forest island > arable land. Significant differences in Zn concentrations exist at ELE, ILU, KPL, NAG, NKZ and ONP; with the forest islands having greater concentrations than the other ecosystems. In all the locations, there were no major differences between the arable lands

and the open savannas. Iron concentrations varied considerably ($P < 0.05$) across the ecosystems and locations and in most cases, the open savanna had significantly the highest iron concentration. There were major differences in Pb concentrations across the ecosystems and locations (Fig. 3). There was significant Pb accumulation in the NKZ forest island and TOE open savanna. In most cases, lead concentration was greater in the open savanna than in their respective forest islands or adjacent arable lands. Chromium and cadmium were not detected in any of the ecosystems.

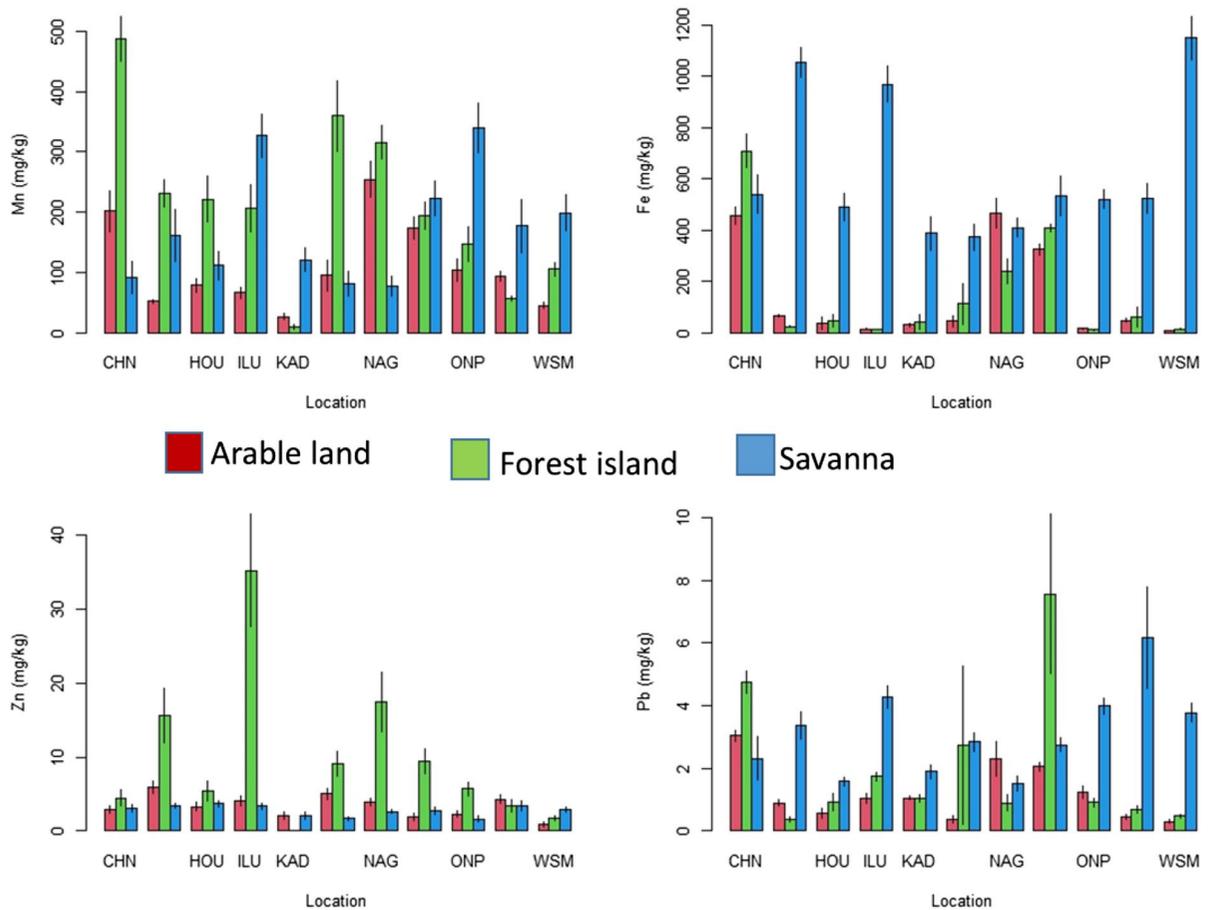


Fig. 3 Comparative distribution of some metals across the ecosystem types

Effects of land use change on soil concentrations of Mn and Zn

Land use change from savanna to forest island resulted in 37 to >900% increase in Mn (Table 3). Improvement in the Zn status varied from 250% at KPL to >900% at ILU, CHN, NAG and NKZ. In 8 out of 11 locations, there were improvements in the Mn (200 to >900% increase) and Zn (64 to >900% increase) contents due to savanna conversion to arable land (Table 3). In the subsoil layer, land use change from savanna to forest island resulted in 10% increase at ELE to >900% increase in Mn at NAG (Table 4). Improvement in the Zn status varied from 17% at NAG to >900% at TOE. At HOU and NKZ, the Zn content was maintained under the land conversion from savanna to forest island. Savanna land conversion into arable lands led to >12% in Mn at locations

such as ELE, HOU, KPL, CHN and NAG (Table 4). At other locations, there was >39% decrease in Mn. Increment in Zn content ($Zn \geq 20\%$) of the subsoil occurred at ELE, WSM, HOU, KPL, TOE and CHN while ILU, ONP and NAG had a decrease (>16%) in Zn due to land conversion from savanna to arable lands.

Co-variations of soil organic carbon with soil nutrients, bulk density, particle size, and precipitation among the land use types

Soil physical parameters such as bulk density, sand, and clay contents had strong relationships with many of the soil chemical parameters (Fig. 4). Clay content had a strong positive relationship with CEC, Mg, Ca, and phosphorus while it tended to

Table 3 Effects of land use change on manganese and zinc in the topsoil

Location	Land use change	Mn % change	Zn
ELE	MS-Forest	260	914
ELE	MS-Farm	-53	-68
ILU	MS-Forest	319	2926
ILU	MS-Farm	355	316
ONP	MS-Forest	1513	425
ONP	MS-Farm	718	4
WSM	MS-Forest	690	-62
WSM	MS-Farm	1793	65
HOU	MS-Forest	37	475
HOU	MS-Farm	-36	-50
KAD	MS-Forest	-99	-67
KAD	MS-Farm	-61	-97
KPL	MS-Forest	1203	250
KPL	MS-Farm	890	650
TOE	MS-Forest	4380	900
TOE	MS-Farm	2243	700
CHN	MS-Forest	3278	1700
CHN	MS-Farm	1066	200
NAG	MS-Forest	443	2010
NAG	MS-Farm	-99	2500
NKZ	MS-Forest	1093	4590
NKZ	MS-Farm	200	2290

MS-Farm=land use change from savanna to arable land; MS-Forest=land use change from savanna to forest island. Negative value implies decline in soil quality parameter. Positive value implies improvement in soil quality.

have strong negative correlation with precipitation and bulk density (Fig. 4). The relationship between bulk density and total nitrogen, as well as available phosphorus, was strong but negative. Bulk density and clay content had the highest contributions to the observed variations among the soil's physical properties (Fig. 5). Among the physical properties, bulk density only had a significant but negative correlation with soil organic carbon under the various land use types (Fig. 4). Soil organic carbon had significant positive relationships with soil nutrients such as total nitrogen, available phosphorus, and calcium content. Electrical conductivity, sodium content, phosphorus, potassium, calcium, magnesium, base saturation, and CEC were positively connected with soil pH. Precipitation only had a significant and

Table 4 Effects of land use change on manganese and zinc in the subsoil

Location	Land use change	Mn % change	Zn
ELE	MS-Forest	10	-73
ELE	MS-Farm	13	20
ILU	MS-Forest	-44	-61
ILU	MS-Farm	-99	-83
ONP	MS-Forest	-45	300
ONP	MS-Farm	-99	-75
WSM	MS-Forest	-18	120
WSM	MS-Farm	-100	120
HOU	MS-Forest	71	0
HOU	MS-Farm	345	100
KAD	MS-Forest	-98	-75
KAD	MS-Farm	-84	-50
KPL	MS-Forest	1698	125
KPL	MS-Farm	847	50
TOE	MS-Forest	-50	1100
TOE	MS-Farm	-80	200
CHN	MS-Forest	189	-100
CHN	MS-Farm	185	7190
NAG	MS-Forest	659	17
NAG	MS-Farm	403	-17
NKZ	MS-Forest	-26	0
NKZ	MS-Farm	-39	0

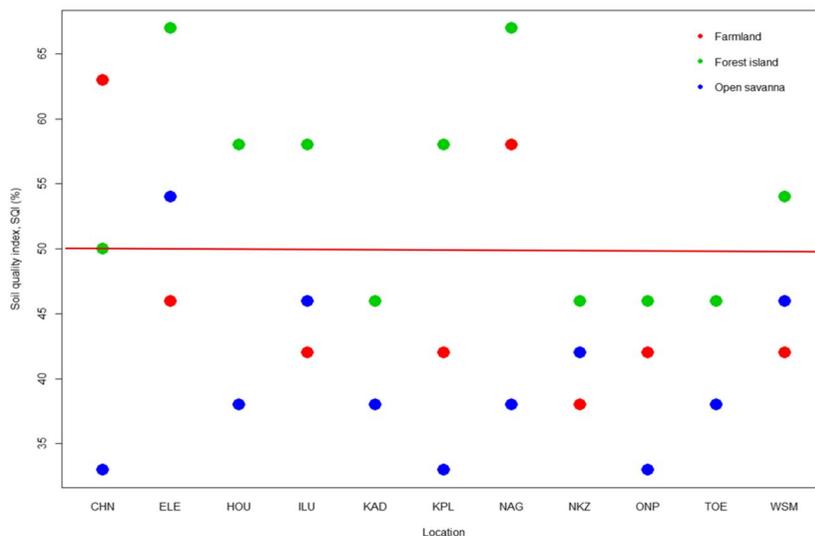
MS-Farm=land use change from savanna to arable land; MS-Forest=land use change from savanna to forest island. Negative value implies decline in soil quality parameter. Positive value implies improvement in soil quality.

negative correlation with magnesium content and electrical conductivity of the soils (Fig. 4). Electrical conductivity showed strong positive relationships with sodium, potassium, calcium, magnesium, and CEC while it has a negative correlation with precipitation. Electrical conductivity and soil macronutrients had a strong influence on land use dynamics. Precipitation and sand content showed a negative influence on all the soil quality indicators (Fig. 5).

Soil quality potentials of the ecosystem types

Soil quality index (SQI%) varied at the different locations per ecosystem type and the forest island significantly had the highest SQI value (Fig. 6). At CHN,

Fig. 6 Soil quality index of the land use types across the locations



now increasingly recognized (Fairhead and Leach 1996; Mesele et al. 2024). Understanding the lessons that could be learned from the indigenous approaches to sustainable land management practices within the socio-economic competencies of the local people may aid efforts towards developing mitigation and adaptation strategies to reduce the adverse effects of climate change in resource-poor agrarian communities.

Anthropogenic interference with the natural savanna ecosystem resulted in the creation of forest islands and arable lands in West Africa (Bougma et al. 2022; Mesele et al. 2024; Logah et al. 2024). Our results showed that the effects of land use change vary in magnitude and have mixed effects (both positive and negative) on soil quality including the soil organic matter. These effects are dependent on the type of land use change (savanna to forest island [ms-forest] or savanna to arable land [ms-farm]) and the specific soil quality indicator of interest as well as the cultural and agronomic management being practiced after land use conversion. This is supported by the work of Frausin et al. (2014) who observed soil enrichment under land management operations leading to the development of forest-type vegetation in northwest Liberia.

Our findings showed that when natural savannas are converted to arable lands, there is a general decline in soil organic matter in both the topsoil and

subsoil layers with the decline in the topsoil being most pronounced. The decline in soil organic matter in the soil varies from slight to severe across the location while there was only one location with an increase in soil organic matter after savanna conversion to arable land. Crop replacement and fertilization-related changes to the root system architecture and litter quality could affect how SOM decomposes and stabilizes in soil (Sanderman et al. 2017). Studies have shown that the conversion of savannas to arable lands is often accompanied by a significant loss in soil organic carbon as observed in West Africa (Lal 2006). The loss in soil organic carbon has deleterious effects on soil quality predominantly in the soil's ability to deliver its ecosystem functions (Lorenz et al. 2019). A loss in soil organic matter implies a reduction in the productive capacity of the soil, reduced crop yield in low-input agriculture (Maseko et al. 2022), increased rate of soil erosion (Mesele et al. 2016), poor soil aggregation (Bougma et al. 2022), and reduced activity of soil organisms (Liang et al. 2019). According to Anokye et al. (2021), the pace of organic matter decomposition is accelerated on lands with insufficient canopy cover because they are more susceptible to high temperatures. While savanna conversion to arable lands could not be halted in the region due to the increased need for food production to feed the teeming population, the need to improve

the farming systems and the land management practices is of utmost importance to ensure sustainable food systems.

Conversely, when savannas are transformed into forests, our results showed a general increase in the soil organic matter in both the topsoil and subsoil layers owing to the favourable conditions provided by the forest ecosystem. The high soil organic carbon content in turn contributes to ecosystem sustainability, acting often as nutrient reservoir for plant growth and development (Ametsitsi et al. 2020; Lloyd et al. 2015; Logah et al. 2020). Across all areas, soil organic matter increased on average by 279% in the topsoil and by 70% in the subsoil (Figs. 1 and 2). These results suggest that savanna conversion to forest can appreciably raise the organic matter content of the soil. These findings were supported by reports of Pessenda et al. (2004) who showed how different carbon isotopic forms advanced or retreated in forest-savanna transects in Brazil. In the present study, the four-fold level of soil organic matter in the topsoil compared to the subsoil may be due to the large amount of above-ground biomass produced by the forest islands (Mesele and Adigun 2017) coupled with dense canopy cover leading to reduced solar irradiation and increased humidity favourable for organic matter accumulation (Anokye et al. 2021; Boakye et al. 2016; De Feudis et al. 2022; Liu et al. 2020). In a similar context, Bougma et al. (2022) showed that soil aggregate sizes and precipitation affect soil organic carbon accumulation and stabilization.

The positive and significant correlation of soil organic carbon with soil nutrients (total nitrogen, available phosphorus, and calcium content), electrical conductivity, and CEC (Fig. 4) underscores the importance of forest islands maintenance and improvement for ecosystem sustainability owing to their pivotal role in nutrient cycling and climate regulation (Wiesmeier et al. 2019; Ajiboye et al. 2019a; Baveye et al. 2020). Our results further demonstrated that changes in land use have a considerable positive influence on soil macronutrients. Potassium, calcium, and magnesium increased by $\geq 12\%$, $\geq 15\%$ and 27% , respectively, while increases in Mn and Zn were 37% and $\geq 250\%$ in the forests over the savannas pointing to the compounding effect of anthropogenic soil improvement in the forest island. This nutrient enrichment primarily resulted from the accumulation and

decomposition of organic matter which came from both the above and below-ground biomass of the forest islands. Another reason for the nutrient-enriched soils could be the ability of some of the trees to fix atmospheric nitrogen through symbiotic associations with nitrogen-fixing bacteria in their root systems. Additionally, the leaf litter and organic matter decomposition in forest island release various nutrients, including phosphorus, potassium, and micronutrients, further enhancing soil fertility. Thus, land use change from savanna to forest islands leads to considerable enhancements in both the soil macro- and micronutrients. Our findings support other studies reporting anthropogenic soil amelioration for instance, Asare (2022) reviewed the distribution of anthropogenic dark earths in some tropical and temperate regions, and Frausin et al. (2014) observed nutrient-enriched black soils beneath forest islands in Sierra Leone. The process of transforming savannas to forests simultaneously transforms the soils, making them comparable to the well-known anthropogenic Amazonia Dark Earths (ADE) in South America but in contrast to South America, where the processes that produced these anthropogenic soils were mostly stopped following European colonization (Erickson 2003), our research demonstrates that similar Africa Dark Earth (AfDE) are still being formed in West Africa, as shown in Nigeria, Ghana and Burkina Faso (Mesele et al. 2024).

It was observed that the accumulation of metals varied considerably as a product of ecosystem type and geographic locations (Fig. 3). Manganese varied substantially and accumulated in the topsoil. The concentration of Fe was significantly low in the forest islands relative to the arable land and the savanna. There were major differences in lead concentrations across the ecosystems and locations. Generally, forest islands had the highest Mn and Zn while savannas had the highest Fe and Pb contents. In most cases, these metals were accumulated within the topsoil and were below the toxic levels. The forest, however, was more vulnerable to manganese and zinc toxicities than iron and lead. Copper and chromium could not be detected in the study areas. These findings confirm and suggest that the soils are suitable for agricultural food production (Solomon et al. 2016) with no evidence of contamination and that the forest islands themselves are ecologically safe. Thus, the practice of forest island creation could be incorporated in

agroforestry initiatives in the region as part of efforts towards African food systems transformation.

Our results further showed that soil quality is a function of land use type and geographic location, and this is independent of a particular soil quality indicator. The pattern of variation is however erratic, not following a specific identifiable biophysical parameter probably owing to the inherent spatial heterogeneity of the study sites. For instance, At CHN, SQI % was in the order of arable land > forest island > savanna. During the field survey in 2016, it was observed that the CHN arable land was intensively managed with a special focus on nutrient management in addition to the soil being rich in mica and zeolites which might have also contributed to the soil fertility of CHN (Ajiboye et al. 2018, 2019b; Mesele et al. 2024). This provides probable reason the soil quality in CHN farmland was better than other ecosystems. As expected, the SQI % was in the order of forest island > savanna > arable land in locations such as ELE, ILU, NKZ and WSM. A threshold of SQI % ≥ 50 was set as the baseline below which soil is severely affected and unable to perform its ecosystem functions. About 63% of the forest islands are above this threshold, while 18% and 9% of the arable lands and savannas are above the threshold. This shows a general level of improvement in soil quality indicators translating into improved soil health conditions in the forest island as compared to the other ecosystems.

Conclusions

In West Africa, the effects of land use conversion are manifold and dependent on the type of land use change, soil depth, and soil quality indicator. Land conversion to forest islands has several positive influences on the soil quality indicators compared to land conversion to arable lands. Our results reveal a significant increase in soil organic matter and soil nutrients when savannas are converted to forests. There is a general decline in soil organic carbon and soil nutrients when savannas were converted to arable lands. Trace elements increased significantly but remained below toxicity and contamination thresholds under the land use change. In marginal lands, land use conversion to forest islands may presents great potential for improving soil fertility and overall ecosystem

health. Thus, our findings provide scientific credence to the West African saying that the settlement, which includes people and animals, is responsible for the creation of the African dark earth, transforming originally infertile soils to fertile and productive soils.

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Data Availability Data available upon request.

Declarations

Ethical Approval Not Applicable.

Consent to Participate Not Applicable.

Consent to Publish All authors read and approve the work.

Competing Interests The authors declare that they have no known conflicts of interest.

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