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Plant and Soil

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RESEARCH ARTICLE

Soil mineralogical and nutrient characteristics of forest islands and surrounding ecosystem types in West Africa suggest anthropogenic soil improvement

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Abstract

Aims Ecosystem changes in the mesic savannas of West Africa are resulting in the formation of patches of 'forest islands' around local communities in an otherwise open savanna landscape. There have been conflicting reports on the origin of these forest islands with a very limited understanding of their biogeochemistry. This study evaluated the soil mineralogical and chemical characteristics of forest islands and their surrounding ecosystems comprising croplands and open savannas in Burkina Faso, Ghana, and Nigeria to provide information on the processes leading to the formation of forest islands.

Methods Soil mineralogy was determined using X-ray diffractometry (XRD) while the soil nutrients were analysed with ICP-OES and the other soil chemical properties were determined using standard conventional methodologies.

Results Overall, we found that quartz, kaolinite with significant quantities of 2:1 silicate minerals dominated the soil matrix irrespective of land use type. The minerals identified in most of the locations were independent of land use type. This suggests that the forest island formation is not directly related to soil mineralogy. Forest islands showed differences in soil nutrient contents, being richer in exchangeable potassium and dibasic cations than their surrounding

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savannas and agricultural fields. This superior fertility status of the soils could contribute to the luxuriant growth of the vegetation leading to the development of forest island. The soil nutrient characteristics of the ecosystem types reflect the land use practices with the forest island having higher nutrient and organic carbon contents.

Conclusions The study provided insight into how human-originated soil nutrient enhancement has induced forest island establishment in open savanna landscapes.

Keywords African dark earths · Ecosystem change · Forest-savanna interaction · Land use change · Land management · Terra preta

Introduction

In the West African savanna landscape, forest vegetation is often found surrounding or adjacent to local communities. They are often referred to as forest islands, kurmi, or anthropogenic forest (Morgan and Moss 1965; Fairhead and Leach 2009). Forest islands vary in size, age and tree species composition, and are found in the Sudan, Guinea savanna and forest-savanna transition agro-ecological zones. Early colonial botanists considered them as remnants of a once larger forest area destroyed by indiscriminate human action (see e.g. Hedberg and Hedbeg 1968, Sayer et al. 1992; FAO 1993) but later, they were discovered to have been created through deliberate human action (Fairhead et al. 1996). This finding has been supported by the palynological record as reported by Fairhead and Leach (1996).

Forest islands have been reported to increase in size and numbers in the savanna in recent times in West Africa and are shown to be strongly associated with human-induced changes to soil conditions (Hennenberg et al. 2005) and even after abandonment prove remarkably stable (Sobey 1978). They thus provide a unique example of how local knowledge and soil improvement practices may stimulate forest growth in what would otherwise be a savanna landscape (Frausin et al. 2014). Conversely, in different parts of Brazil, several authors have reported Cerrado (savanna) to have expanded, encroaching on the forest-savanna boundaries since the Holocene and during the Last Glacial Maximum primarily due to drier climates (Anhuf et al. 2006; Ledru et al. 2006) while in others there were cases of forest advancement against cerrado in forest – cerrado transitions in southern Amazonia (Marimon et al. 2014). They demonstrated this using soil carbon isotopes and indicated how the various carbon isotopic forms advanced or retreated in forest–savanna transects due to changes in vegetation covers over a timescale (Pessenda et al. 2001, 2004; Marimon et al. 2014). The present study on forest islands and those on forest–cerrado transition in Brazil essentially highlights the dynamic relationship between forest and savanna and focuses on the mechanisms underlying the advances and retreats of these different vegetation covers over time.

The mechanisms behind forest island formation include anthropogenic activities such as the addition of household wastes to land around homesteads, deposition of animal dungs and human faecal matter, selection and protection of important economic trees, fire exclusion, prohibition of tree felling around homesteads, shrine, and community relocation –leaving the former settlement sites to fall back to succession and eventually reaching secondary vegetation have been previously identified (Fairhead and Leach 1998; Fairhead and Leach 2009). The human influence on soil development in the tropics has been previously described e.g. Amazonian dark earth or Terra preta (Glaser and Birk 2012, Lima et al. 2002) with major consequences on soil properties especially soil organic carbon. Fairhead and Leach (2009) describe the soils of forest islands as “African Dark Earths”. However, these soils have been poorly studied and the underlying biogeochemistry behind this phenomenon remains to be elucidated. A better understanding of the role of soil factors and interactions that drive forest island creation could provide important lessons for forest creation in the area South of the Sahel, thus helping to achieve some of the objectives of the Great Green Wall project (Sacande et al 2021).

One aspect that has received little attention is forest islands’ mineralogy and nutrient characteristics (but see Bougma et al 2022). Soil mineralogy is a major determinant of soil physical and chemical properties, being a reflection of its parent material. Soil mineral compositions are key pedogenetic indicators of soil quality. For instance, iron (Fe) and aluminum (Al) are released during soil weathering and development and are precipitated as short-range-ordered or crystalline oxides, hydroxides, or oxhydroxides (Guertal 1994).

The forms as well as the abundance of Fe and Al oxides are contributing factors that influence nutrient retention and availability in soils (Onweremadu et al. 2007; Ajiboye et al. 2016).

In this study, therefore, we investigate whether the mineralogical characteristics of the underlying soils of the forest islands are different and how they compare with the surrounding land use types with the view of evaluating whether soil mineralogy was a driving factor in forest island formation or the process was rather anthropogenic. We also evaluate a number of soil chemical properties that relate to soil fertility enhancement and, compare land uses (forest island, farmland, and savanna) on some major chemical properties across a climatic gradient in Ghana, Nigeria, and Burkina Faso.

We aim to gain insight into what extent forest islands are the products of major soil differences or that human-originated soil nutrient enhancement may have induced their establishment. We, thus, provide an understanding of the mechanisms by which previously savannas areas can transform into a forest vegetation type through anthropogenic activities.

Materials and methods

Description of study area

The study was conducted across 11 locations in Burkina Faso, Ghana, and Nigeria between year 2015 and 2018 (Fig. 1). The region is characterized by uniformly high sunshine and high temperatures throughout the year with the mean annual temperature usually above 18 °C. Vegetation under uniformly high temperatures is largely determined to a large extent by rainfall (Couteron and Kokou 1997). Consequently, vegetation

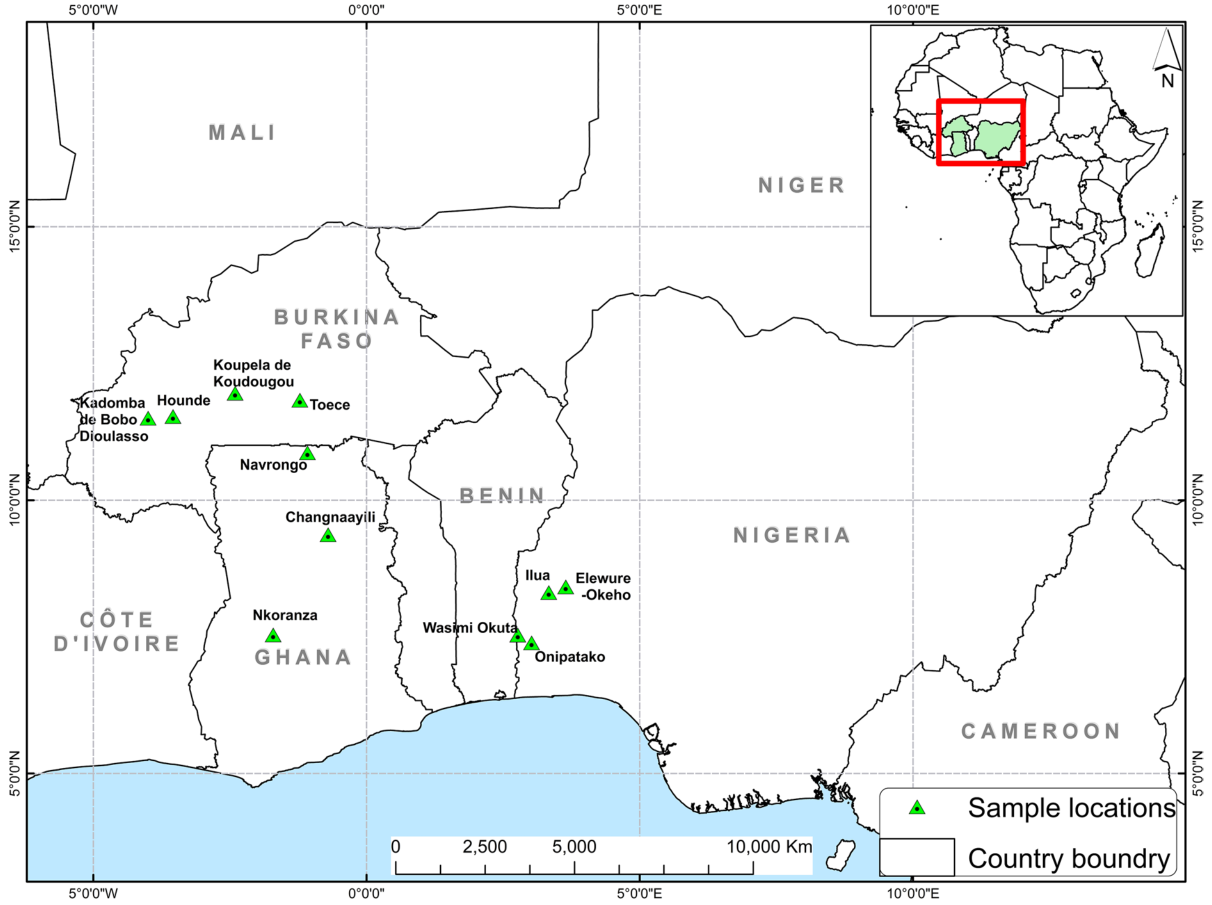


Fig. 1 Map of the study sites in West Africa

zones run parallel to each other from north to south and are related to rainfall amount with rainfall in the study locations ranging from 795 mm in Burkina Faso to 1266 mm in Ghana with a mean value of 1127 mm for locations in Nigeria. The weather condition is characterized by a dry season starting in October in Burkina Faso, December in Ghana and November in Nigeria to February or early March. As a result, in Burkina Faso, the study sites Toécé (TOE), Koupéla de Koudougou (KPL), Houndé (HOU), and Kadomba de Bobo Dioulasso (KAD), were in the Sudan and Sahelian ecological zones; in Ghana Navrongo (NAG) also in Sudan savanna with Changnayili (CHN) in Guinea savanna and Nkonranza (NKZ) in a forest-savanna transition. In Nigeria, the sites-Wasimi-Okuta (WSM), Ilua (ILU), Onipatako (ONP), and Elewure-Okeho (ELE) were all within the Guinea savanna agroecological zone. The geographic coordinates, rainfall amounts and the dominant vegetation of each of the locations are summarised in the supporting table, Table S1.

Proximity of the land-use systems at each location

In all locations (Fig. 1), three forms of land use were examined. The interspatial distribution of the land-use types is described in Bougma et al. (2022). In Nigeria, the three land-use systems at each location were within 0.13 to 0.60 km radius. In Ghana and Burkina Faso, the forest islands and agricultural plots at a location were within 0.10 to 0.70 km radius except for the Nkoranza cropland, which was about 3.1 km from the forest island. The savanna plots in Ghana were generally within 10 km radius from the forest islands whereas in Burkina Faso, they were a little bit further apart (Bougma et al. 2022).

West Africa is composed of ancient crystalline Basement Complex and sedimentary rocks. As a result, soils generally are highly weathered and of low inherent fertility (Sayer et al. 1992). The different soil types (FAO-WRB 2015) of the study sites are presented in Table 1. Further information on the identification and description of the soil profiles are presented in Table S2. The soils of the experimental sites were all developed on the basement complex rocks.

Soil Sampling technique and sample pretreatment

A 0.16 ha of each land use type was divided into four subplots, each of dimension 20 × 20 m from which soil samples were taken randomly at 4 locations within the subplots. Soil heterogeneity was considered in the selection of sampling sites. At each sampling points, soil samples were taken at the 0–5, 5–10, 10–20, 20–30, 30–50, and 50–100 cm soil depths using a set of standard augers (Eijkelkamp Agrisearch Equipment BV, Giesbeek, The Netherlands). Due to hard plinthite, rocky and stony nature of some sites,

Table 1 Soil types of forest islands and their adjacent ecosystems in the study areas

Location	Savanna	Farmland	Forest island
ELE	Eutric Cambisol (Arenic)	Plinthosol (Arenic)	Rhodic Luvisol (Clayic)
ILU	Ferric Lixisol	Plinthosol (Arenic, Eutric)	Plinthosol (Lixic)
ONP	Plinthosol (Clayic)	Lixisol (Arenic, Rhodic)	Lixisol (Arenic, Rhodic)
WSM	Rhodic Luvisol (Arenic)	Eutric Petroplinthic Cambisol	Eutric Arenosol (Humic)
HOU	Stagnic Lixisol (Loamic, Hypereutric)	Lixisol (Arenic)	Stagnic Plinthosol (Lixic, Clayic)
KAD	Stagnic Lixisol (Loamic Hypereutric)	Lixisol (Arenic, Loamic)	Ferric Lixisol
KPL	Eutric Plinthosol (Lixic, Loamic)	Eutric Plinthosol (Lixic)	Plinthosol (Arenic)
TOE	Stagnic Pisoplinthic Plinthosol (Lixic, Loamic)	Eutric Arenosol	Stagnic Pisoplinthic Plinthosol (Lixic)
CHN	Stagnic Petric Plinthosol (Eutric, Arenic)	Pisoplinthic Plinthosol (Loamic, Ochric)	Pisoplinthic Plinthosol (Abruptic, Loamic)
NAG	Stagnic Petric Plinthosol (Eutric, Arenic)	Stagnic Pisoplinthic Plinthosol (Lixic, Clayic)	Stagnic Pisoplinthic Plinthosol (Lixic, Clayic, Humic)
NKZ	Abruptic Chromic Lixisol (Loamic, Cutanic, Profondic)	Abruptic Chromic Lixisol (Loamic, Cutanic, Profondic)	Abruptic Chromic Lixisol (Loamic, Cutanic, Profondic)

Source: Mesele (2021)

samples could not be taken at greater depths. Samples collected at the various depths in each subplot were composited per depth and thoroughly mixed before a sub-sample was taken. The samples were air-dried and then passed through 2 mm sieve to obtain the fine earth fraction (Bougma et al. 2022).

Soil mineralogical analysis

To gain insight into the mineralogy of the parent materials underlying the soils of the various ecosystem types, soil samples from the deepest depth ($>$50 cm soil depth) in each of the sampling points were selected for X-ray diffraction (XRD) analysis. The XRD analyses were performed at the Natural History Museum, London on each dried fine earth fraction (2 mm sieved soil which was further fine ground to powder) at 25 °C using an Enraf–Nonius PSD 120, equipped with an INEL 120° curved position sensitive detector. The XRD analysis was performed on the bulk soil samples without fractional separation of the soil particles. No additional pretreatment was done apart from the fine-grinding. The powdered samples were placed in deep-well sample holders with sapphire substrates. Most samples were analysed using Cu $K_{\alpha 1}$ radiation (45 kV and 45 mV), however for those samples deemed to have significant Fe content, we used Co K_{α} radiation (45 kV and 45 mV) to minimise background noise due to fluorescence. Diffraction patterns were collected over 4 to 18 h.

The diffraction patterns were correlated with the d-spacing and peaks to identify the specific minerals. The abundance of the minerals was grouped into 4 categories based on their relative counts. Number of counts exceeding 20,000 were classified as 'Dominant', Counts between 6,000 and 20,000 are termed 'Abundant' while Counts less than 6,000 but $\geq$ 2,000 are classified 'few' and those mineral counts less than 2000 are termed 'trace'.

Analyses of soil physical and chemical properties

Soil particle size distribution was done using the pipette method (Day, 1965; Green, 1981). Soil pH and electrical conductivity (EC) were determined in a soil:water ratio of 1: 2 and read with a digital integrated pH & EC meter (Hanna Instruments). Soil total nitrogen and organic carbon were determined using Elementar CN analyzer (Vario MACRO Cube, Elementar, Germany). Carbon stock was calculated following the procedure described by Donovan (2013). The available phosphorus was extracted by the Bray-1 method (Bray and Kurtz 1945). The exchangeable cations (Ca^{2+}, Mg^{2+}, K^+, and Na^+) were extracted with 1.0 N NH_4OAc using a soil: solution volume ratio of 1:10. The extracts were read using an Inductively Coupled Plasma-Optical Emission Spectrometer (ICP-OES). Effective Cation Exchange Capacity was calculated as the sum of exchangeable cations (including Al^{3+} $+H^+$). The percentage Base Saturation was determined as the total exchangeable bases (TEB) divided by effective cation exchange capacity (ECEC) and multiplied by 100. The exchangeable cations are basically referred to as soil nutrients while pH, EC and SOC are not nutrients in themselves but influence soil nutrient availability. Extraction of free Fe and Al oxides was carried out using the dithionite-citrate-bicarbonate (DCB) extraction (Mehra and Jackson 1960) and the ammonium oxalate extraction (McKeague et al. 1971). Determination of Al and Fe in all the digests was done by the xylenol–orange colorimetric method (McKeague, 1971) while Fe was measured colorimetrically using ortho-phenathrolin method (Mehra and Jackson 1960).

The crystalline fraction was determined by subtracting the value of the Oxalate fraction from the DCB fraction. The oxides ratios were calculated by dividing the crystalline oxide by the short-range order (Oxalate) fraction. These fractions are important in evaluating the degree of pedogenesis and soil development of the forest islands and the adjacent ecosystems.

Statistical analyses

The data were subjected to exploratory statistics to identify the most suitable model for data analysis in R Studio. A comparative analysis of nutrients and mineralogy on the three ecosystem types was conducted using the principal coordinate analysis (PCoA) model. This technique works by first reducing the dimensionality of the data by identifying principal "axes" of differentiation among land use types, which represent distinct combinations of chemical and mineralogical data. The PCoA has the advantage of allowing the user to tune the similarity of the distance metric used for comparison; this fact yields a more flexible tool regarding the dynamics or range of the different variables (Chahouki 2011)1. A resemblance matrix is built by comparing each element of the data matrix to one another using the chosen comparison metric d:

$$\forall_i j \in \{1, \ldots, n\}, Dij = dx^{(i)}, x^{(j)}$$

This matrix is then squared and centered as follows:

$$Aij = D^2 ij$$

$$Bij = Aij - Ai^{-} - Aj^{-} + A^{-}$$

where Ai^{-}, $Aj^{-}$and A^{-} denote the means taken of each row, column and the whole matrix, respectively. This matrix transformation does not affect the distance relationships between the samples and hence keeps the structure of the data. This technique is fully described by König et al. (2023).

The Scientific Graphing Functions for Factorial Designs (Sciplot) package was used to generate the interaction graphs. Deming regression, which is an errors-in-variables model that fits a line describing the relationship between two variables, was used to fit the relationship between savanna and forest island, and savanna and farmlands for some of the soil nutrients.

Results

Mineralogical differences between locations

Quartz and kaolinite dominated the soils of CHN and NKZ in Ghana; ELE, ONP and TOE in Nigeria and, HOU, KAD, and KPL in Burkina Faso. Potassium-feldspar (orthoclase, sanidine, and microcline) though with a significant amount of quartz, dominated the soils of WSM and ILU in Nigeria, and NAG location in Ghana (Table 2).

Apart from the dominant minerals, mica (muscovite) and K-feldspar were particularly abundant in the ELE and TOE, respectively. Locations HOU, ILU, ONP, NKZ and TOE were rich in iron oxide minerals. Goethite is the most abundant Fe oxide at ILU although hematite is also present in quantities near the detection limit (~2%) but in HOU and ONP, hematite was the dominant iron oxide mineral. At NKZ, both hematite and goethite were present, with the most intense peaks assigned to hematite. For the TOE forest island, cronstedtite, Fe-rich member of the kaolinite-serpentine group was found. Zeolite was present in WSM, KAD and KPL soils.

Muscovites were detected at trace quantities in soils of CHN, ILU, and TOE while small amounts of feldspars were identified in KPL soil. Minor quantities of hornblende, and anatase were also observed in WSM and NKZ soils, respectively. Aluminum phosphate was present only in KPL soils (Table 2).

Mineralogical differences between land use types

There were no major mineralogical differences between the forest islands and the other ecosystem types (farmland and open savanna) at each location as the ecosystems showed very similar major mineralogical compositions (Table 2). However, there were minor differences in the mineralogical composition of the soils between the forest islands and the adjacent ecosystems and this varied with the geographic locations but there was no specific pattern across the agro-ecological zones. Quartz and kaolinite dominated the forest island soils of CHN, ELE, ONP, HOU, KAD NKZ, KPL, and TOE (Table 2). Over seventy percent (≥73%) of the forest islands was dominated by quartz and kaolinite while K-feldspar dominated the soils of WSM, ILU, and NAG forest islands. In most cases, these differences were in terms of the abundance of a particular mineral species in the forest island than in either the farmland or open savanna.

Variations of iron and aluminum oxides fractions between the locations

There were significant differences in the abundance of short-range order (SRO), Citrate bicarbonate-dithionite extractable (CBD) and crystalline fractions (CBD –SRO) of iron and aluminum oxides across the various locations (Fig. 2). Navrongo (NAG) of Ghana had the least SRO Fe oxide fraction (Fig. 2A) while ELE and WSM of Nigeria had the least concentrations of both CBD and crystalline Fe oxide fractions (Fig. 2B). Ilua (ILU), KPL and ONP had the highest SRO, CBD and crystalline fractions of Fe oxides among the other locations. There were little

Table 2 Soil mineralogical profile of forest islands, adjacent farmlands and open savannas

Country code	Sites	Quartz	Kaolinite	Feldspars	Mica/ Illite	Goethite	Hematite	Variscite/ Phosphosiderite	Chlorite/ Anatase	Smectites	Hornblende/ Boehmite/Zeolites
NGA	ELE 01	+++	++	-	++	+	-	-	-	-	-
NGA	ELE 02	+++	+++	+	t	t		t	-	-	-
NGA	ELE 03	+++	+++		++	+	-	-	t	-	-
NGA	ILU 01	+++	+++	+++	+	++	+	-	-	-	
NGA	ILU 02	+++	+++	+++	-	t	-	-	-	-	H+
NGA	ILU 03	+++	+++	+++	+	+	+	-	-	-	H+
NGA	ONP 01	+++	+++	-	-	-	++	t	Ct		
NGA	ONP 02	+++	+++	-	-	-	++	-	-	-	-
NGA	ONP 03	+++	+++	-	-	-	++	-	-	++	-
NGA	WSM 01	+++	T	+++	t	-	-	-	-	-	H+, Zt
NGA	WSM 02	+++	T	+++	t	-	-	-	-	-	H++
NGA	WSM 03	+++	-	++	-	-	-	-	-	++	Zt, Ht
BFA	HOU 01	+++	+++	-	-	-	++	-	At	-	-
BFA	HOU 02	+++	+++	-	t	t	++	-	At	-	-
BFA	HOU 03	+++	+++	-	-	-	++	-	At	-	-
BFA	KAD 01	+++	+++	-	-	+	-	-	-	-	Zt
BFA	KAD 02	+++	++	-	-	t	-	-	-	-	Zt
BFA	KAD 03	+++	+++	-	-	+	-	-	-	-	Zt
BFA	KPL 01	+++	+++	+	-	+	-	t		-	Z+
BFA	KPL 02	+++	+++	-	-	+	-	t	-	t	-
BFA	KPL 03	+++	+++	+	-	+	-	t	-	-	Zt
BFA	TOE 01	+++	+++	++	+	-	-	-	-	-	-
BFA	TOE 02	+++	+++	+	-	-	-	t	-	-	-
BFA	TOE 03	+++	+++	-	++	-	-	-	-	-	-
GHA	CHN 01	+++	+	-	+	+	-	-	-	t	B+
GHA	CHN 02	+++	+	-	t	t		t	-	-	Bt
GHA	CHN 03	+++	+++	-	+	+	-	-	-	-	Bt
GHA	NAG 01	+	t	+++	+++	-	-	-	-	+++	Ht
GHA	NAG 02	+++	+	-	-	+	-	-	-	+++	Ht
GHA	NAG 03	+++	+	-	-	+	-	-	-	+++	Ht
GHA	NKZ 01	+++	+++	-	-	++	++	-	A+	-	-
GHA	NKZ 02	+++	+++	-	-	-	++	-	-	-	-

Table 2 (continued)

Country code	Sites	Quartz	Kaolinite	Feldspars	Mica/ Illite	Goethite	Hematite	Variscite/ Phosphosiderite	Chlorite/ Anatase	Smectites	Hornblende/ Boehmite/Zeolites
GHA	NKZ 03	+++	+++	-	-	-	++	-	-	-	-

Sites -01 = forest island, -02 = farmland, -03 = savanna. +++ = Dominant, ++ = Abundant, + = some/few, t = trace, — = None, A = Anatase, B = Boehmite, C = Chlorite, H = Hornblende, Z = Zeolites; NGA = Nigeria, BFA = Burkina Faso; A+ = anatase in few quantities, At = anatase in trace quantities; B+ = Boehmite in few quantities, Bt = Boehmite in trace quantities, Ct = chlorite in trace quantities, Zt = Zeolites in trace quantities; — = Not detected

Sites -01 = forest island, -02 = farmland, -03 = savanna. +++ = Dominant, ++ = Abundant, + = some/few, t = trace, — = None (for class values see main text). A = Anatase, B = Boehmite, C = Chlorite, H = Hornblende, Z = Zeolites, GHA = Ghana, A+ = anatase in few quantities, B+ = Boehmite in few quantities, Bt = Boehmite in trace quantities

differences between the Fe oxide ratio though these were confounded by the large variation in the oxide ratios of KPL soils. Contrarily, NKZ had the lowest SRO Al oxides while TOE and KPL had the highest SRO Al (Fig. 2D - F). The lowest concentration of CBD Fe oxides occurred at WSM while the highest occurred at KPL, NKZ and TOE. The differences in the concentration of CBD Fe oxides among the other locations was very low. The highest and lowest concentrations of the crystalline iron oxides occurred at NKZ and WSM, respectively. Significant differences in crystalline Fe oxides were also found among other locations. The highest and the lowest Al oxides ratios were found at WSM and NKZ, respectively.

Variations of iron and aluminum oxides fractions between the land use types

There were clear differences in the short-range-ordered (SRO), citrate-bicarbonate-dithionite (CBD) and crystalline fractions of iron (Fe) and aluminum (Al) oxides (CBD—oxalate extractable form) in the soils as functions of land use types (Fig. 2). There were no significant differences between the farmland and forest island with respect to the SRO and CBD Fe oxide fractions while those of the open savanna differed significantly (p value <0.001, Fig. 2A-F). Further analysis shows that the short-range-order Fe fraction in the savanna varied directly proportional to those in the farmland and forest island while the total pedogenic Fe oxides in the savanna vary inversely proportional to those in the farmland and directly proportional to that of the forest island. The open savanna had the least SRO, the highest CBD and the highest crystalline Fe oxides among the other ecosystem types. Changes in the Al oxide fractions of the land use types follow a similar trend. The savanna had remarkably the lowest amounts of SRO and CBD Al oxides fractions (Fig. 2D -F).

Soil pH and electrical conductivity differences between locations

Soil pH and electrical conductivity varied considerably among the selected locations. The mean pH values ranged between 5.8 and 7.8 while EC ranged from 0.4 to 6.4 dS m^{-1}. Toece in Burkina Faso (TOE) had significantly the highest soil pH followed by NAG

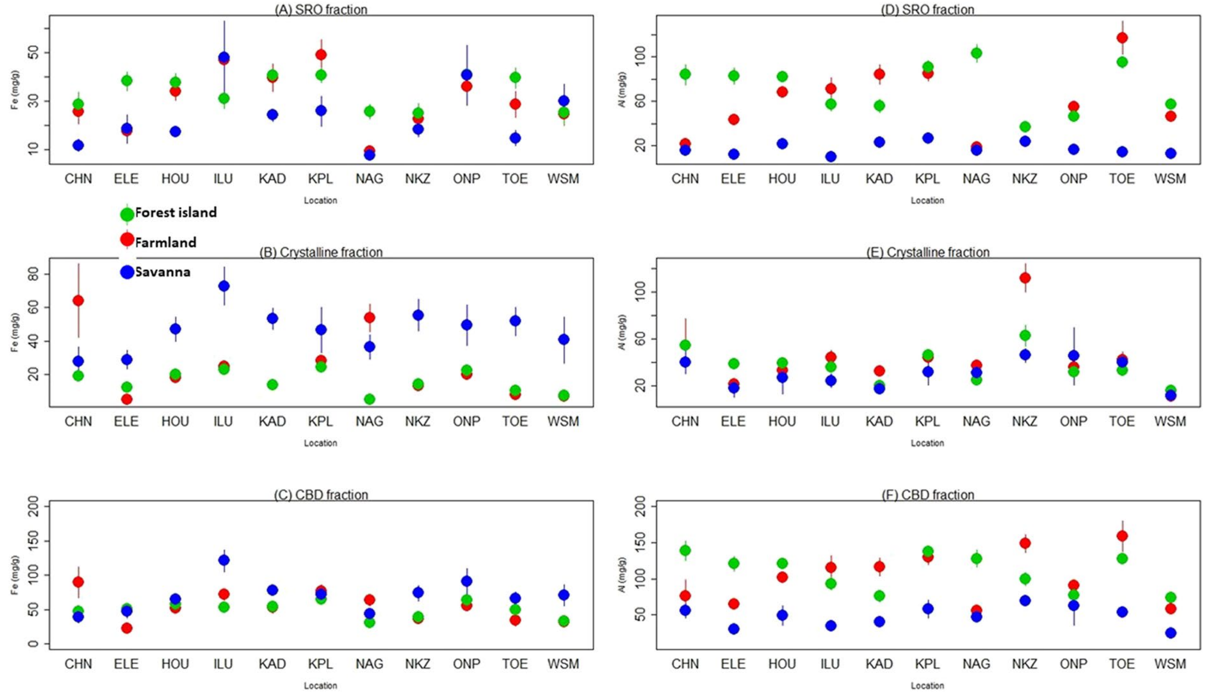


Fig. 2 The distribution of iron oxide fractions in the different locations SRO = short-range-order fraction = Oxalate extractible form; CBD = citrate-bicarbonate-dithionite fraction; Crystalline fraction = CBD – SRO

(Navrongo, Ghana) while the lowest mean values occurred at CHN, ELE, KPL, ONP, and WSM (Fig. 3). The highest and lowest mean EC were found at NAG and KAD, respectively (Fig. 3).

There were considerable differences in the EC values in the soils of the other locations. For instance, ELE clearly had a higher EC value than in locations such as HOU, ILU, NKZ and ONP.

The adjacent farmlands varied in their soil pH and EC between 4.0 and 9.2 with a standard deviation of 0.2, and 0.2 and 6.4 dS m^{-1}with a standard deviation of 0.3, respectively. Likewise, the soil pH and EC of the open savannas varied from 4.1–7.1 and from 0.2–14.0 dS m^{-1}, respectively. The forest islands had the highest soil pH and EC values. The farmland has the lowest EC while the adjacent open savanna has the lowest soil pH.

Soil organic carbon, total nitrogen and carbon stocks between locations and land use types

Soil organic carbon (SOC) among the forest island locations of West Africa showed significant differences between locations ($P < 0.05$, Fig. 4). The NAG soils had the highest SOC values, which ranged from 1.5 to 5.7% in the 0–20 cm topsoil (Fig. 4a). The KAD forest island in Burkina Faso had the lowest SOC values. The SOC values also varied significantly between the land use types. The forest island had the highest values while the least was observed in farmlands (Fig. 4b).

Soil total nitrogen differed among the locations (Fig. 4b) and land use types (Fig. 4d) and the differences followed a similar trend as SOC. Figure 5 shows the distribution of the soil organic carbon stocks in the various locations and under the 3 ecosystem types at 0—5 and 0 -30 cm depths. Carbon stocks in forest islands at 5 cm depth were twice that of savanna and four times that of farmland. Within the 0–30 cm depth, carbon stock in the forest island quadrupled that of savanna and farmland. The site at NAG has the highest carbon stocks; 38.7 Mg/ha at 0–5 cm and 200 Mg/ha at 0–30 cm depth.

The relationship between soil organic matter and soil nutrients (cations) under the ecosystems were tested with significant and high positive correlations between them (Table S3). Specifically, soil organic

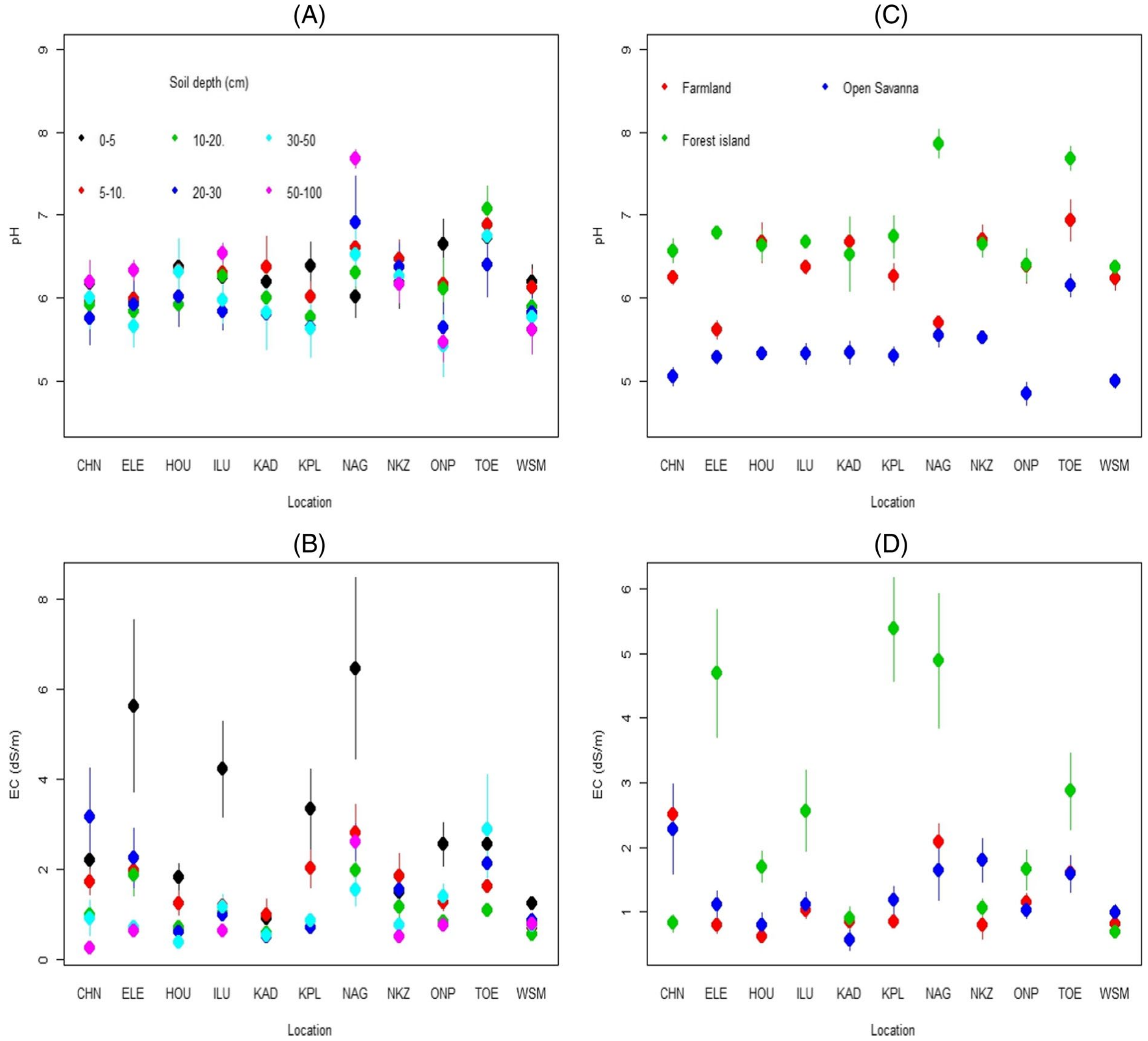


Fig. 3 Differences in soil pH and electrical conductivity across the study area

matter (SOM) had a positive and significant relationship with the exchangeable calcium (0.858**), exchangeable magnesium (0.891**), exchangeable potassium (0.849**) and the effective cation exchange capacity (0.877**).

Differences between locations in soil exchangeable cations and cation exchange capacity

Soil exchangeable cations and cation exchange capacity varied significantly among the selected locations. The highest mean concentrations of potassium (K), calcium (Ca) and magnesium (Mg) were found at NAG while the highest concentration of sodium occurred at TOE (Fig. 6). Onipatako (ONP) had the lowest K while most of the locations were low in Na^+. The KAD had the least concentrations of $Ca^{2+}$and Mg^{2+} as well as the lowest ECEC. The soils of NAG had significantly the highest ECEC among the locations (Fig. 7). There were little differences among the other locations in their exchangeable cations and effective cation exchange capacities.

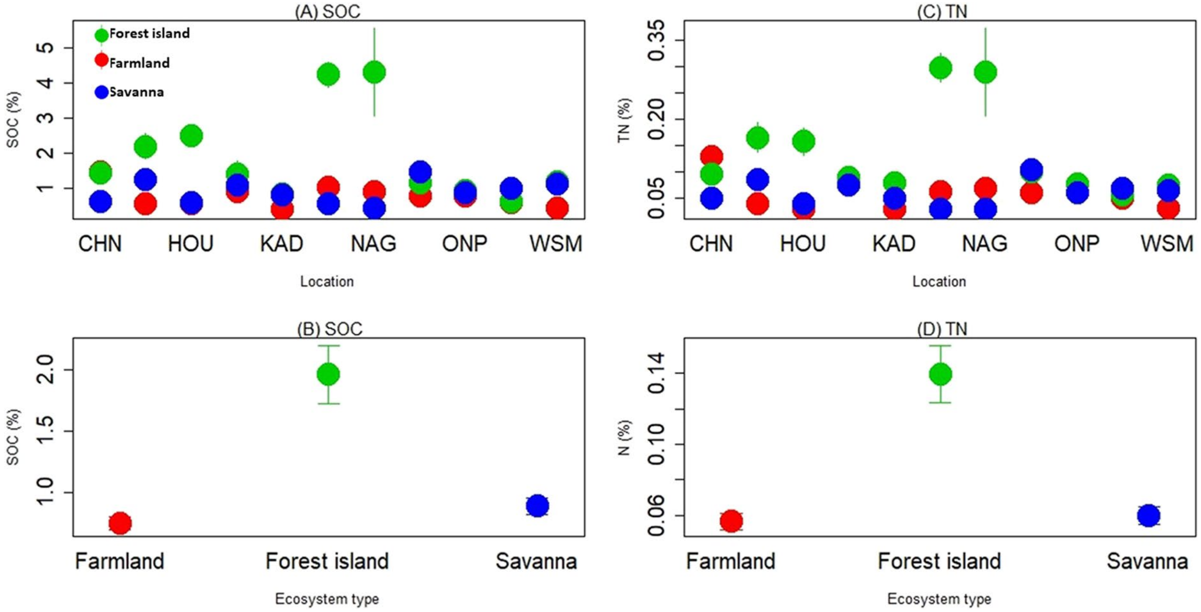


Fig. 4 Soil organic carbon and total nitrogen differences in location and land use types of West Africa at the 0–20 cm soil depth. SOC = OC = soil organic carbon, TN = total soil nitrogen

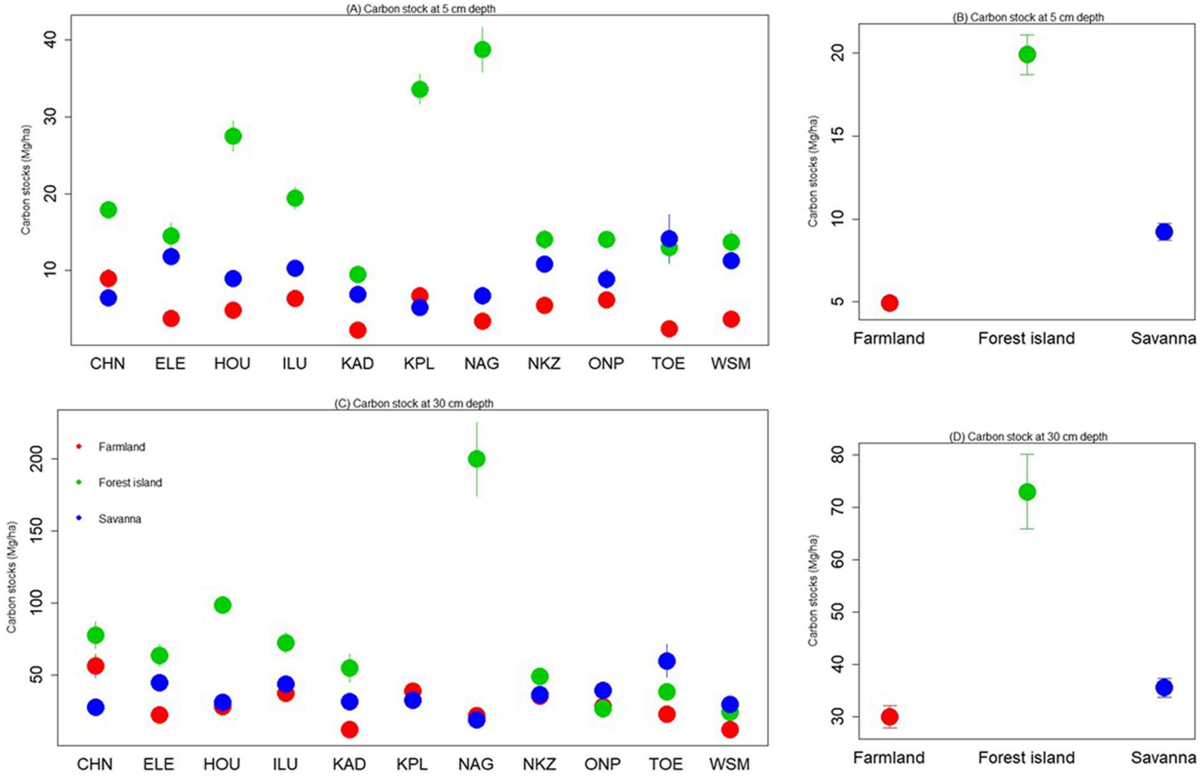


Fig. 5 Soil organic carbon stocks at 5 and 30 cm depth in the different land use types of West Africa

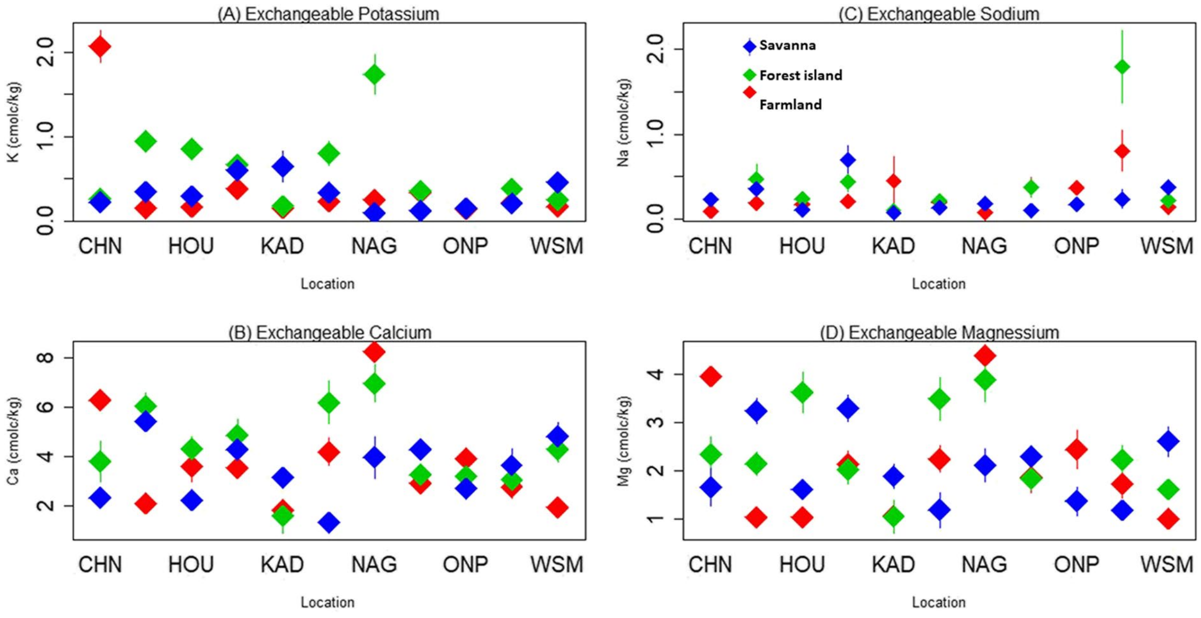


Fig. 6 Differences in soil exchangeable cations between locations

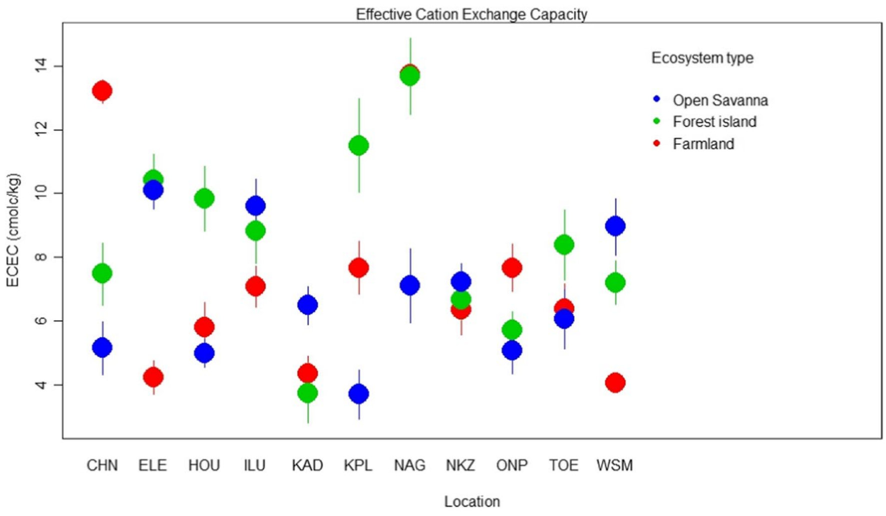
Differences in soil exchangeable cations and cation exchange capacity between land use types

The soil exchangeable cations varied significantly ($P < 0.05$) among the land use types (Fig. 8). Generally, the exchangeable cation (K, Na, Ca, Mg) concentrations, as well as the effective cation exchange capacity (ECEC) of forest island were considerably higher compared to either the farmland or the open savanna. There were no significant differences ($P > 0.05$) between the farmland and the open savanna in the concentrations of the exchangeable cations and the ECEC.

Co-variations of soil nutrients with the mineralogical compositions of the land use types at the different locations

Soil nutrients such as calcium, magnesium, and potassium were abundant in locations such as WSM

Fig. 7 Differences in soil effective cation exchange capacity between locations and ecosystems



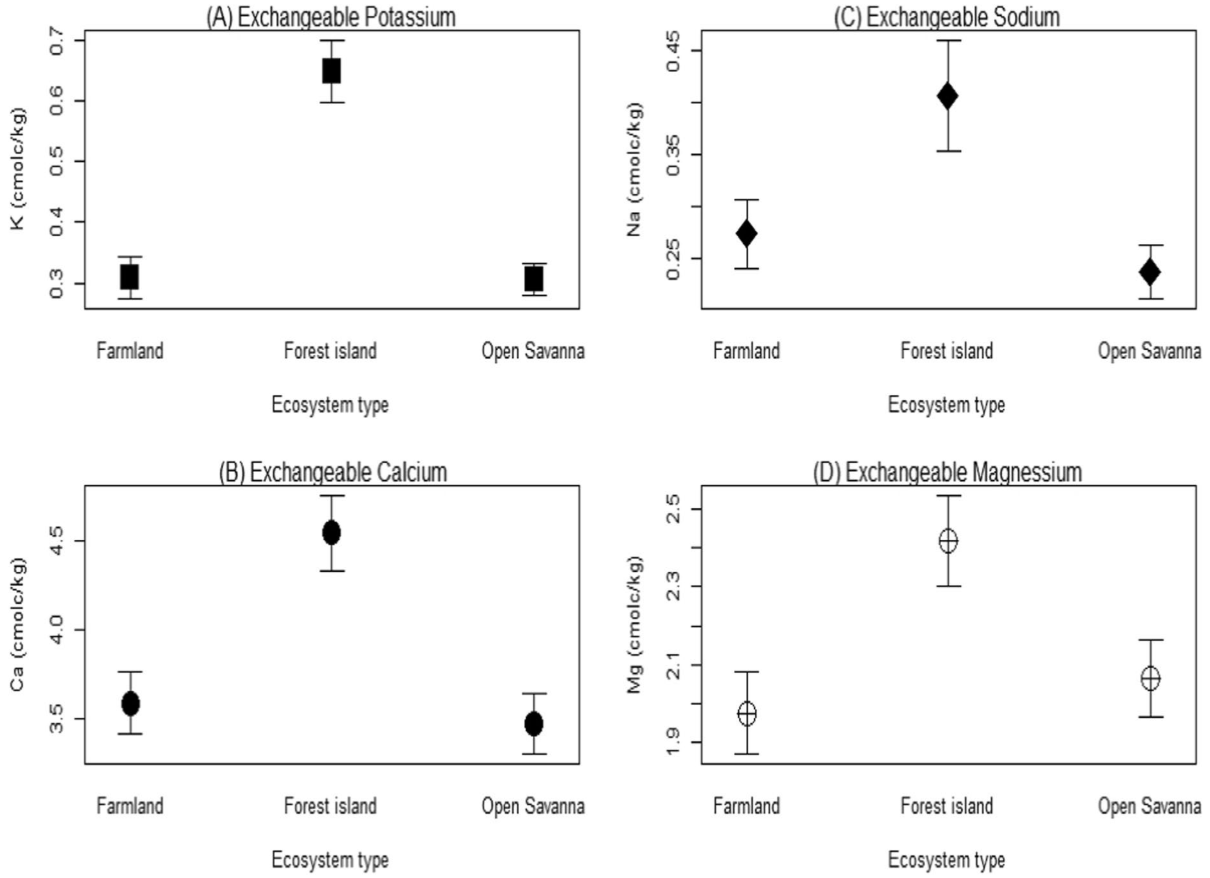


Fig. 8 Differences in soil exchangeable cations between the land use types irrespective of location

forest island, NAG and CHN farmlands where feldspars, hornblende, smectites and mica/illite were detected (Fig. 9). In the first quadrant, Short-range-order Fe oxide (Feo) which is the most reactive forms of iron oxides co-migrate with the exchangeable acidity mostly in the forest islands (TOE, HOU, KPL, ILU). Kaolinite, quartz, hematite, and anatase were predominant in farmlands. The scores of the principal component analysis also showed that there was a co-migration of short-range-order Fe and Al oxides with the pH, exchangeable aluminum, and variscite (aluminum phosphate) and this condition was prevalent at TOE farmland and forest islands at TOE, ELE, CHN, ILU and HOU (Fig. 9). In the second quadrant, the soil macronutrients were oriented within the same direction as illite, mica, smectites, and potassium feldspar, among others. This situation was prevalent at Navrongo and Wasimi-Okuta forest islands, Navrongo and Changnayili farmlands. Most of the savanna sites have chlorite and zeolites in their underlying soils as shown in the third quadrant. Quartz, kaolinite, hematite, and anatase which are very resistant non-weatherable minerals were detected in most of the farmlands. Hence, they were oriented in the 4th quadrant with Eigenvalues of 5.04 (Dim. 1) and 3.56 (Dim. 2).

Discussion

The major mineralogical compositions of the forest islands and the adjacent ecosystems (farmlands and the open savannas) were similar, which suggests that mineralogy of the soils had no direct effect on the processes leading to the development of the forest islands in West Africa. Corroborating the XRD findings, the inconsistent differences observed in the short-range order (oxalate extractable) and

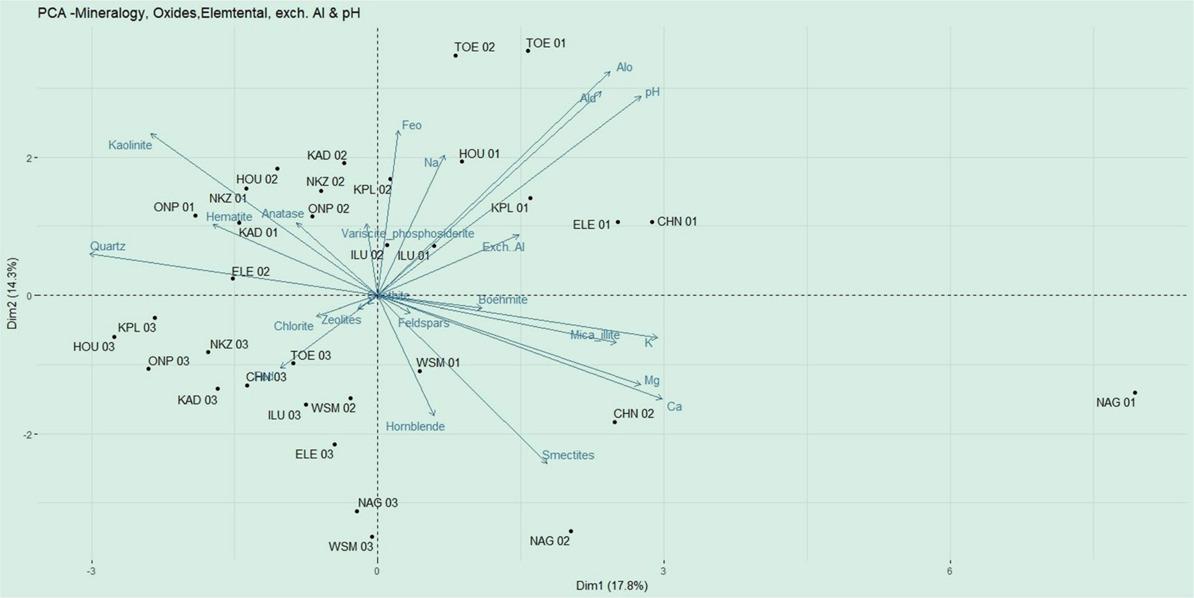


Fig. 9 Comparative analysis of the mineralogical and nutrient compositions with respect to their dominant sites

dithionite-citrate-bicarbonate extractable iron and aluminum oxides of the soils underlying the forest islands, farmlands, and the open savannas across the various landscapes and agro-ecologies also portend that the forest islands are more likely to be caused by anthropogenic rather than edaphic factors (Liu et al. 2009). The results suggested therefore that the soils of the forest islands and those of the adjacent land use types essentially originated from the same pedogenic processes.

Soil mineralogy by X-ray diffractometry and wet chemistry (iron and aluminum oxides) provided very useful information on the state of soil development and the associated pedogenic processes which have either taken place in the soil or are in progress (Barrera-Bassols and Zinck 2003; Ajiboye et al. 2018). These have implications for the use and management of such soils. For instance, the fractions of iron oxides have a direct impact on the formation of stable aggregates in the soil (Bougma et al. 2022). Recognizing the West African forest islands as products of human intervention on savanna soils implies that socio-cultural activities by the local communities represent viable tools for soil transformation from a less productive state to a productive soil capable of supporting forest growth under limited precipitation regimes. These activities, for example, include dumping of refuse or household wastes, animal excreta, etc. by the villagers with some sort of protection to the forest growth from encroachment and bushfire as some were considered culturally, as sacred groves or “place for the gods”. Fairhead and Leach (1998) reported cases of similar forest islands around villages at Kissidougou region, south-eastern Guinea; which were created and maintained by the villagers. The forest islands were of social, economic and cultural importance to the local communities. This lends plausibility to the maintenance and preservation of such forests around homesteads and exemplifies an age-long process of soil improvement in West Africa. Here we corroborate their suggestion with quantitative evidence from Nigeria, Ghana, and Burkina Faso.

In terms of mineralogical complexity, the forest islands are diverse and could be categorized into those rich in quartz and kaolinite, and those rich in feldspars. About 70% of the forest islands fall into the first category while the remaining 30% are in the latter category. The differences among the forest islands in the magnitude of oxalate extractable and dithionite-citrate-bicarbonate extractable iron oxides are not distinctive. A major missing link between these forests has been whether or not they are geochemically the same at least in some functional soil properties. The results of this study show that the forest islands are geochemically diverse. The trend of diversity does not follow the agroecological division but the geographic locations and the specific nutrient or soil property being considered. NAG (Ghana) and TOE (Burkina Faso) forest islands are for example, comparable in their pH values. The other 10 forest islands are very similar in their carbon, nitrogen, and phosphorus contents. Soil organic matter is a major source of nutrients (such as nitrogen, phosphorus, sulphur among others) in forest island ecosystem. This explains the coupling of SOC and total nitrogen (Mesele and Ajiboye 2020). The soil organic matter in the present study revealed significant and positive correlations with the effective cation exchange capacity of the soil, and the exchangeable cations such as Ca, Mg, and K.

Carbon stocks in the forest islands were twice those of the savanna and quadrupled those of the farmland within the 5 cm soil depth. At deeper depths (0 – 30 cm), carbon stocks in the savanna and farmland were similar and were four times lower than those in the forest islands. This remarkably higher soil organic carbon stock of the forest islands (Figs. 4, 5) relative to adjacent ecosystems shows that there has been a relative buildup of soil organic matter within the forest island ecosystem. The soil organic matter accumulation (through litter fall and human additions) may directly affect ecosystem carbon storage (Liu et al. 2016) and forest growth via improvement in soil quality through the release of nutrients such as N, P, K, Ca, Mg, and S after mineralization, and this is partly seen in the high and positive correlation between the soil organic matter and the exchangeable cations in this study. Adjunct to climatic conditions, cation availability has been directly linked to tropical forest formation in West Africa and elsewhere in the tropics (Veenendaal et al. 2015). More recently, Bougma et al. (2022) found that organic carbon and macroaggregates are closely linked in West African ecosystems and thus suggest that soil organic carbon improves soil aggregate stability of forest islands through key organo-mineral mechanisms. The maintenance of these forest islands in the West-African savanna landscapes, thus, provides insight into long-term indigenous innovative land management practices that could reduce the adverse effects of climate change on rural livelihoods.

The low level of SOC observed within the farmlands of West Africa is a cause of concern not only to agroecosystem sustainability but also to sustainable food production and food security within the region. The low soil organic matter content of the agricultural lands has been attributed to several factors including but not limited to inappropriate land management practices, impact of tillage, higher rate of decomposition, erosion, and lower vegetation cover (Bakker et al 2005; Blanco and La1 2008; Mesele et al. 2016). The latter also exaggerate the severity of soil erosion with a concomitant loss in soil organic carbon and a general decline in soil productive capacity (Mesele and Adigun 2017).

Many of the forest islands (> 55%) are rich in soil exchangeable potassium. Forest islands at ELE, ILU and NAG with high potassium concentrations have K-feldspar and muscovite mica as their parent materials. Potassium-feldspar is rich in potassium and these K ions are released through pedogenesis (Masood and Bano 2016). Some authors have reported that 98–99% of the potassium is found in the crystal structure of K-bearing minerals of K-feldspars and micas (Bakker et al. 2019; Brouder 2011; Mengel et al. 2001). This underscores the importance of mineralogy in soil nutrient availability and retention (Ajiboye et al. 2019). Potassium may play an important role in woody vegetation cover formation (Lloyd et al 2015; Ametsitsi et al. 2020). The observed high level of potassium in the forest islands are indeed consistent with the Combined Water and Potassium (CWAK) hypothesis of Lloyd et al (2015) which states that potassium is an important modulator of tropical vegetation structure and functions, particularly in water-limited environments where water content within the rooting zone is critical. Other studies have previously also pointed to the role of potassium availability in accounting for different ecosystem types (forest, savanna) over wide precipitation gradients (Egilla et al. 2005; Tripler et al. 2006; Rossatto et al. 2013;Viani et al. 2014). Other cations could as well play a role (Veenendaal et al. 2015) but the evidence for this is less pronounced. The forest islands are similar in their sodium concentrations with the exception of TOE, which has relatively high sodium ions. This high sodium concentration in the TOE forest island gave credence to the observed high EC values in this ecosystem (Richardson et al. 2017). There are a few differences between the forest islands in their calcium and magnesium concentrations in the soil. With the exception of the locations rich in potassium, calcium, and magnesium ions predominate the soil exchange sites of the forest islands.

As evidenced earlier by mineralogy, the forest islands and farmlands are products of anthropogenic influence on the natural ecosystem. Generally, there were changes in soil nutrient status due to ecosystem changes (Matias et al. 2011). Calcium decreased in the farmland over the savanna but increased in the forest island over the savanna (Fig. 8); consequence of relatively more weatherable minerals (rich in dibasic cations) in the forest island soils compared with the savanna (Table 2). Lloyd et al. (2015) concluded that savannas are found on soils of a consistently lower cation status and K in particular) than their forest counterparts. The capacity of the soil to hold cations (CEC) declined in the farmland relative to the savanna while it increased in the forest island over the savanna (Fig. 9) implying that as savannas are transformed into forest islands, the capacity of the soil to hold cations improves, stimulating forest formation (see e.g. Lloyd et al 2015 and Ametsitsi et al. 2020). As observed in this study, the higher organic carbon and dibasic cation-rich minerals led to higher nutrients in the forest islands than in the other land use types. This is because the soil organic matter (SOC is a measurable component of the soil organic matter) and the clay content (minerals) are key determinants of the soil CEC. These observations are in alignment with the recent works of Arthur et al. (2020), Ramos et al. (2018), Sulieman et al. (2018), and Wood et al. (2018). The establishment and development of forest type vegetation on savanna landscapes of Wenwuta in the North-West of Liberia as reported by Frausin et al. (2014) led to soil enrichment. Similar to the observations in this study, Frausin et al. (2014) found nutrient-enriched dark soils under forest islands in Pujehun, Kenema and Bo districts of South-East Sierra Leone. It was perceived that several household and agricultural practices contributed to the creation of the enriched soils (Fairhead et al. 1996; Altieri et al. 2012). The decomposition of the waste materials over time enriches the soil. This process is comparable to the phenomenon of Terra preta in the Amazon. The Amazonian dark earths has many important similarities with most of the soils of forest islands in West Africa; both sharing similar socio-cultural history, pedogenic processes, and fertility status (Fairhead and Leach 2009; Glaser and Birk 2012; Lima et al 2002).

Thus, this study provides scientific evidence to the aphoriss of the people of Guinea Republic of West Africa that God made the soil while the people made it fertile (Frausin et al. 2014; Fairhead and Leach 2009). The ability of these soils to support forest formations under low precipitation regimes provides opportunities for sustainable wood and forest products production and accentuates the significance of indigenous innovations in soil management.

Conclusions

The study highlighted the limited mineralogical diversities between the ecosystem types (forest island, savanna, and farmland) of West Africa and showed that the forest islands themselves are mineralogically diverse from one location to another. These suggest that in each of the locations studied, the soils underlying them, all originated from a similar parent material and that the soil mineralogy itself plays a little role in the forest island formation.

We also evaluated a matrix of soil chemical properties that relate to soil fertility enhancement, compare land uses on some major chemical properties across a climatic gradient in West Africa and conclude that irrespective of location or agro-ecological zone, the forest islands have higher soil nutrient status or nutrient holding capacity than their surrounding land use types. The soil organic carbon, exchangeable calcium, and potassium are the main edaphic factors improved through forest island establishment. Hence, soil fertility improvement created a favourable condition that changed the vegetation composition, microclimate leading to the formation and sustenance of forest islands. We conclude that soil organic carbon and soil exchangeable potassium play a leading role in the West-African forest island phenomenon.

Our findings also confirm that forest islands are not the products of major soil differences but that human-originated soil nutrient enhancement has induced their establishment. The cultural and socio-economic practices of the local communities underpinned the creation of such forests around homesteads. Overall, the study provided insights into how human-originated soil nutrient enhancement has induced forest island establishment in open savanna landscapes and the mineralogical attributes of such anthropogenic ecosystems.

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Data Availability Data is available upon request.

Declarations

Conflict of interest The authors declare that there are no conflicts of interest.

References

Ajiboye GA, Ogunwale JA, Talbot J, Mesele SA (2016) Effect of iron and aluminum oxides fractions and clay type on phosphorus sorption in some Alfisols in the Guinea savanna ecology of Nigeria. Nigerian J Soil Environ Res 14:57–67

Ajiboye GA, Ogunwale JA, Talbot J, Mesele SA (2018) Wrong pedogenetic assumptions: a case study of the soils developed over talc in Southern Guinea Savanna of Nigeria using clay mineralogy. South Afr J Plant Soil 35(1):61–69. https://doi.org/10.1080/02571862.2017.1333637

Ajiboye GA, Oyetunji CA, Mesele SA, Talbot J (2019) The Role of Soil Mineralogical Characteristics in Sustainable Soil Fertility Management: A Case Study of Some Tropical Alfisols in Nigeria. Commun Soil Sci Plant Anal 50(3):333–349. https://doi.org/10.1080/00103624.2018.1563100

Altieri MA, Funes-Monzote FR, Petersen P (2012) Agroecologically efficient agricultural systems for smallholder farmers: contributions to food sovereignty. Agron Sustain Dev 32(1):1–13

Ametsitsi GKD, Langevelde FV, Logah V, Janssen T, Medina-Vega JA, Issifu H, Ollivier L, Hartogh KD, Adjei-Gyapong T, Adu-Bredu S, Lloyd J, Veenendaal EM (2020) Fixed or mixed? Variation in tree functional types and vegetation structure in a forest-savanna ecotone in West Africa. J Trop Ecol. https://doi.org/10.1017/S0266467420000085

Anhuf D, Ledru MP, Behling H, Da Cruz Jr FW, Cordeiro RC, Van der Hammen T, Karmann I, Marengo JA, De Oliveira PE, Pessenda L, Siffedine A (2006) Paleo-environmental change in Amazonian and African rainforest during the LGM. Palaeogeogr Palaeoclimatol Palaeoecol 239(3–4):510–527

Arthur E, Tuller M, Moldrup P, de Jonge LW (2020) Clay content and mineralogy, organic carbon and cation exchange capacity affect water vapour sorption hysteresis of soil. Eur J Soil Sci 71(2):204–214

Bakker MM, Govers G, Jones R, Rounsevell M (2005) The effect of soil erosion on agricultural productivity. Geophys Res Abstr 7:00695

Bakker E, Lanson B, Findling N, Wander MM, Hubert F (2019) Mineralogical differences in a temperate cultivated soil arising from different agronomic processes and plant K-uptake. Geoderma 347:210–219

Barrera-Bassols N, Zinck JA (2003) Ethnopedology: a worldwide view on the soil knowledge of local people. Geoderma 111(3–4):171–195

Blanco H and Lal R (2008) Principles of soil conservation and management (Vol. 167169). New York: Springer.

Bougma AB, Ouattara K, Compaore H, Nacro HB, Melenya C, Mesele SA, Logah V, Azeez JO, Veenendaal E, Lloyd J (2022) Soil aggregate stability of forest islands and adjacent ecosystems in West Africa. Plant and Soil 1–14. https://doi.org/10.1007/s11104-022-05302-x

Bray and Kurtz (1945) Determination of total, organic and available forms of phosphorus in soils. Soil Sci 5(1945):39-45

Brouder S (2011) Potassium cycling. In: Hatfield JL, Sauer TJ (eds) Soil Management: Building a Stable Base for Agriculture. Soil Science Society of America, Madison, WI, pp 79–102

Chahouki MAZ (2011) Multivariate analysis techniques in environmental science. In Earth and Environmental Sciences. 2011 Dec 7 IntechOpen

Couteron P, Kokou K (1997) Woody vegetation spatial patterns in a semi-arid savanna of Burkina Faso. West Africa Plant Ecology 132(2):211–227

Donovan P (2013) Measuring soil carbon change: a flexible, practical, local method. Retrieved on November 5:2014

Egilla JN, Davies FTJ, Boutton TW (2005) Drought stress influences leaf water content, photosynthesis, and water-use efficiency of Hibiscus rosa-sinensis at three potassium concentrations. Photosynthetica 43:135–140. https://doi.org/10.1007/s11099-005-5140-2

Fairhead J, Leach M, Mearns R (1996) Rethinking the forest-savanna mosaic: colonial science and its relics in West Africa (pp. 105–121). James Currey Ltd

Fairhead J, Leach M (1998) Reframing deforestation. Global analyses and local realities: studies in West Africa. Routledge, London and New York

Fairhead J, Leach M (2009) Amazonian Dark Earths in Africa? In Amazonian Dark Earths: WimSombroek's Vision. Springer, Netherlands, pp 265–278

FAO (1993) Forest resources assessment 1990: Tropical countries. FAO forestry paper 112.

Frausin V, Fraser JA, Narmah W, Morrison KL, Thomas RW, Fairhead J, Leach M (2014) God Made the Soil, but We Made It Fertile": Gender, Knowledge, and Practice in the Formation and Use of African Dark Earths in Liberia and Sierra Leone. Hum Ecolology. https://doi.org/10.1007/s10745-014-9686-0

Glaser B, Birk JJ (2012) State of the scientific knowledge on properties and genesis of Anthropogenic Dark Earths in Central Amazonia (terra preta de Índio). Geochim Cosmochim Acta 82(2012):39–51

Guertal WR (1994) The pedologic nature of weathered rock. Whole Regolith Pedology, SSSA, Madison, 21–40.

Hedberg I, Hedbeg O (eds) (1968) Conservation of vegetation in Africa South of the Sahara. Proceedings of a symposium held at the 6th plenary meeting of the Association pour l'Etude Taxonomique de la flore d'Africque Tropicale in Uppsala, spte 12–16, 1966

Hennenberg KJ, Goetze D, Minden V, Traoré D, Porembski S (2005) Size-class distribution of *Anogeissus leiocarpus* (Combretaceae) along forest–savanna ecotones in northern Ivory Coast. J Trop Ecol 21:273–281. https://doi.org/10.1017/S0266467404002160

IUSS Working Group WRB (2015) World Reference Base for Soil Resources 2014, update 2015. International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Reports No. 106. FAO, Rome

König LA, Medina-Vega JA, Longo RM, Zuidema PA, Jakovac CC (2023) Restoration success in former Amazonian mines is driven by soil amendment and forest proximity. Philos Trans R Soc B 378(1867):20210086

Ledru MP, Ceccantini G, Gouveia SE, López-Sáez JA, Pessenda LC, Ribeiro AS (2006) Millenial-scale climatic and vegetation changes in a northern Cerrado (Northeast, Brazil) since the Last Glacial Maximum. Quatern Sci Rev 25(9–10):1110–1126

Lima HN et al (2002) Pedogenesis and pre-Colombian land use of “Terra Preta Anthrosols”(“Indian black earth”) of Western Amazonia. Geoderma 110.1–2(2002):1–17

Liu X, Zhang W, Zhang M, Ficklin DL, Wang F (2009) Spatio-temporal variations of soil nutrients influenced by an altered land tenure system in China. Geoderma 152(2009):23–34

Liu Y, Li S, Sun X et al (2016) Variations of forest soil organic carbon and its influencing factors in east China. Ann Forest Sci 73:501–511

Lloyd J, Domingues TF, Schrodt F, Ishida FY, Feldpausch TR, Saiz G, Quesada CA, Schwarz M, Torello-Raventos M, Gilpin M, Marimon BS (2015) Edaphic, structural and physiological contrasts across Amazon Basin forest–savanna ecotones suggest a role for potassium as a key modulator of tropical woody vegetation structure and function. Biogeosciences 12(22):6529–6571

Marimon BS, Marimon-Junior BH, Feldpausch TR, Oliveira-Santos C, Mews HA, Lopez-Gonzalez G, Lloyd J, Franczak DD, de Oliveira EA, Maracahipes L, Miguel A (2014) Disequilibrium and hyperdynamic tree turnover at the forest–cerrado transition zone in southern Amazonia. Plant Ecolog Divers 7(1–2):281–292

Masood S, Bano A (2016) Mechanism of potassium solubilization in the agricultural soils by the help of soil microorganisms. Potassium solubilizing microorganisms for sustainable agriculture. Springer, New Delhi, pp 137–147

Matias L, Castro J, Zamora R (2011) Soil-nutrient availability under a global-change scenario in a Mediterranean mountain ecosystem. Glob Change Biol 17(4):1646–1657

McKeague JA, Brydon JE, Miles NM (1971) Differentiation of forms of extractable iron and aluminum in soils. Soil Sci Am Proc 35:303–306

Mehra O, Jackson M (1960) Iron Oxide removal from soil and clay by a dithionite – citrate system buffered with sodium bicarbonate. Clay Clay Min 7:317–327

Mengel K, Kirkby EA, Kosegarten H, Appel T (2001) Principles of Plant Nutrition. Springer, Dordrecht, p 849

Mesele SA, Adigun JK (2017) Temporal variations in soil organic matter content of different land use types in south west Nigeria. Global symposium on soil organic carbon, Rome, Italy, 21–23

Mesele SA, Ajiboye GA (2020) Pedo-Transfer Functions for Predicting Total Soil Nitrogen in Different Land Use Types under Some Tropical Environments. Ghana J Sci 61(2):45–56

Mesele SA, Amegashie BF, Quansah C, Adigun JK (2016) (2016) Soil and nutrients losses under different management practices in Ghana. Acta Agrophys 23(4):631–645

Mesele SA (2021) Chemical, mineralogical characterization and quality potentials of soils of forest islands in selected savanna ecologies of West Africa. An Unpublished Ph.D. thesis submitted to the Department of Soil Science and Land Management, Federal University of Agriculture Abeokuta Ogun State Nigeria. pp83 –91

Morgan WB, Moss RP (1965) Savanna and Forest in Western Nigeria. J Int Afr Inst 35(3):286–294

Onweremadu EU, Omeke J, Onyia VN, Aguand CM, Onwubiko NC (2007) Inter-Horizon Variability in Phosphorus-Sorption Capability of Sesquioxide-Rich Soils Southeastern Nigeria. J Am Sci 3:43–48

Pessenda LC, Boulet R, Aravena R, Rosolen V, Gouveia SEM, Ribeiro AS, Lamotte M (2001) Origin and dynamics of soil organic matter and vegetation changes during the Holocene in a forest-savanna transition zone, Brazilian Amazon Region. Holocene 11(2):250–254

Pessenda LCR, Gouveia SEM, Aravena R, Boulet R, Valencia EPE (2004) Holocene fire and vegetation changes in southeastern Brazil as deduced from fossil charcoal and soil carbon isotopes. Quatern Int 114(1):35–43

Ramos FT, Dores EFDC, Weber OLDS, Beber DC, Campelo JH Jr, Maia JCDS (2018) Soil organic matter doubles the cation exchange capacity of tropical soil under no-till farming in Brazil. J Sci Food Agric 98(9):3595–3602

Richardson M, Sentlinger G, Moore RD, Zimmermann A (2017) Quantifying the relation between electrical conductivity and salt concentration for dilution gauging via dry salt injection. Confluence: J Watershed Sci Manage 1(2)

Rossatto D, Hoffmann W, de Carvalho Ramos Silva L, Haridasan M, Sternberg LL, Franco A (2013) Seasonal variation in leaf traits between congeneric savanna and forest trees in Central Brazil: implications for forest expansion into savanna. Trees 27:1139–1150. https://doi.org/10.1007/s00468-013-0864-2

Sacande, M., Parfondry, M., Cicatiello, C., Scarascia-Mugnozza, G., Garba, A., Olorunfemi, P.S., Diagne, M. and Martucci, A., 2021. Socio-economic impacts derived from large scale restoration in three Great Green Wall countries. Journal of Rural Studies, 87, pp.160–168.

Sayer J, Harcourt CS, Collins NM (1992) The conservation atlas of tropical forests: Africa. Macmillan, London

Sobey DG (1978) Anogeissus groves on abandoned settlement sites in the Mole National Park, Ghana, Biotropia, 87–99.

Sulieman M, Saeed I, Hassaballa A, Rodrigo-Comino J (2018) Modeling cation exchange capacity in multi geochronological-derived alluvium soils: An approach based on soil depth intervals. CATENA 167:327–339

Tripler CE, Kaushal SS, Likens GE, Todd Walter M (2006) Patterns in potassium dynamics in forest ecosystems. Ecology Letters 9:451–466

Veenendaal EM, Torello-Raventos M, Feldpausch T, Domingues TF, Gerard FF, Schrodt F, Saiz G, Quesada CA, Djagbletey G, Ford A, Kemp J, Marimon BS, Marimon Junior BH, Lenza E, Ratter JA, Maracahipes L, Sasaki D, Sonké B, Zapfack L, Villarroel D, Schwarz M, Ishida FY, Gilpin M, Nardoto GB, Affum-Baffoe K, Arroyo L, Bloomfield K, Gjeca G, Compaore H, Davies K, Diallo A, Fyllas NM, Gignoux J, Hien F, Johnson M, Mougin E, Hiernaux P, Killeen TJ, Metcalfe D, Miranda HS, Steininger M, Sykora K, Bird MI, Grace J, Sl L, Ol P, Lloyd J (2015) Structural, physiognomic and aboveground biomass variation in savanna-forest transition zones on three continents. How different are co-occurring savanna and forest formations? Biogeosciences 12:2927–2951

Viani RAG, Rodrigues RR, Dawson TE, Lambers H, Oliveira RS (2014) Soil pH accounts for differences in species distribution and leaf nutrient concentrations of Brazilian woodland savannah and seasonally dry forest species. Perspect Plant Ecol 16(64–74):2014. https://doi.org/10.1016/j.ppees.2014.02.001

Wood SA, Tirfessa D, Baudron F (2018) Soil organic matter underlies crop nutritional quality and productivity in smallholder agriculture. Agric Ecosyst Environ 266:100–108