



Natural Built Social Environment Health

ISSN 3085-461X

www.nbseh.org



Geological and Pedoclimatic Controls on Soil Evolution and Degradation in the Humid Tropical Gabon: Insights from Ferralitic and Coastal Sedimentary Terrains

Rolf Gäel Mabicka Obame ^{1a}, Elie Fosso Menkem ^{2b}, Neil-Yohan Musadji ^{3c*}, Maurice Ognalaga ^{3d}, Lydie-Stella Koutika ^{4e}, Jean Aubin Ondo ^{5f}, Graham Oroedjogo Nouhando ^{3g}, Jeremy Soumaho ^{6h}, Eric Raivire ⁷ⁱ, Warren Mayobe ^{8j}, Hervé Patrick Opiangah ^{8k}

¹ University of Science and Technology of Masuku ^{ROR}, National Institute of Agronomy and Biotechnology, Department of Phytotechnology, Soil and Environmental Analysis Laboratory, PO Box 941 Franceville, Gabon;

² Department of Geology, University of Buea, Buea, Cameroon ^{ROR},

³ University of Science and Technology of Masuku ^{ROR}, National Institute of Agronomy and Biotechnology, Department of Fundamental Engineering Sciences, Soil and Environmental Analysis Laboratory, Laboratory of Chemistry, Environments and Inorganic Materials, PO Box 941 Franceville, Gabon;

⁴ Centre de Recherche sur la Productivité et la Durabilité des Plantations Industrielles ^{ROR}, Pointe Noire, Republic of Congo.

⁵ Laboratoire Pluridisciplinaire Des Sciences, Ecole Normale Supérieure, Libreville, Gabon ^{ROR}.

⁶ Esri France, 38 avenue du Château, 92195, Meudon ^{ROR}, France

⁷ Sucaf Gabon Somdiaa, Franceville ^{ROR}, Gabon.

⁸ Gabonese Agricultural Development Company of Gabon PO Box 7543 Libreville ^{ROR}, Gabon

^a **ORCID:** 0000-0002-8519-1170; **Email:** rolfgaelmabickaobame@gmail.com

^b **ORCID:** 0000-0003-4550-1856; **Email:** fosso.menkem@gmail.com

^c **ORCID:** 0000-0003-4911-0289; **Email:** neil.yohan.musadji@gmail.com

^d **ORCID:** 0000-0001-8223-3032 ; **Email:** ognalagam59@gmail.com

^e **ORCID:** 0000-0003-1020-8908; **Email:** ls_koutika@yahoo.com

^f **ORCID:** 0009-0006-0280-9788; **Email:** ondo.jean-aubin@laplus-ens.ga

^g **ORCID:** 0009-0007-5228-055X; **Email:** oroedjogonouhandograham@gmail.com

^h **ORCID:** 0009-0005-6103-3409; **Email:** jeremysoumaho@gmail.com

ⁱ **ORCID:** 0009-0005-4557-3974; **Email:** eraivire@groupe-somdia.com

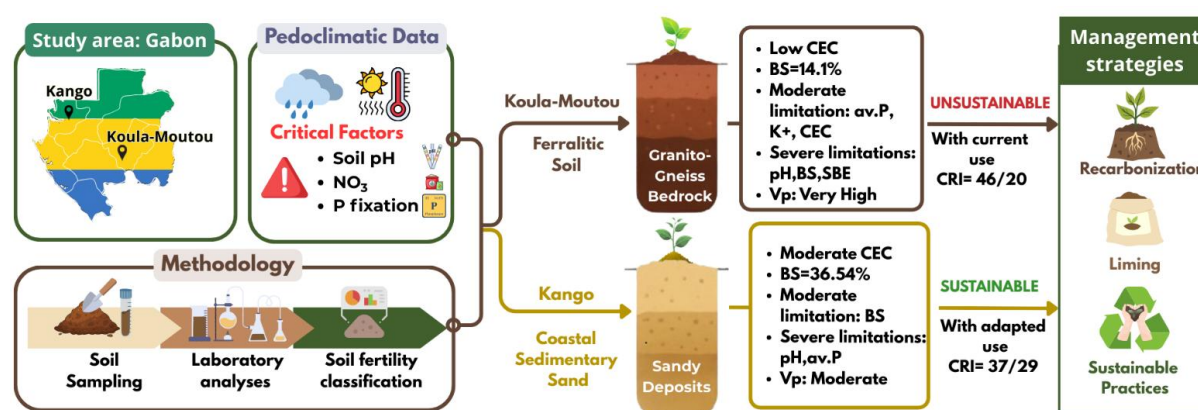
^j **ORCID:** 0009-0004-9983-8555; **Email:** mayobe1997@gmail.com

^k **ORCID:** 0009-0002-3851-0535; **Email:** hervepatrick@hotmail.com

* Corresponding author: **Neil-Yohan Musadji** ^{id}; neil.yohan.musadji@gmail.com

Graphical abstract

This study examines how lithology and pedoclimate govern soil evolution and degradation in humid tropical Gabon by comparing ferralitic soils developed on ancient granito-gneissic basement at Koula-Moutou to younger coastal sedimentary sands at Kango. Ferralitic soils display extreme acidity (pH < 4.5), low cation exchange capacity, and severe base depletion, reflecting advanced degradation but lower vulnerability, whereas coastal sands retain nutrients more moderately yet remain more prone to nutrient loss, highlighting the need for site-specific management such as liming and organic inputs.



DOI: [10.63095/NBSEH.26.7451298](https://doi.org/10.63095/NBSEH.26.7451298)

Received: 06 January 2026

Revised: 03 March 2026

Accepted: 29 May 2026

Published online: 07 June 2026

Citation: Mabicka Obame, R. G., Fosso Menkem, E., Musadji, N.-Y., Ognalaga, M., Koutika, L.-S., Ondo, J. A., Oroedjogo Nouhano, G., Soumaho, J., Raivire, E., Mayobe, W., & Opiangah, H. P., 2026, Geological and pedoclimatic controls on soil evolution and degradation in humid tropical Gabon: Insights from ferralitic and coastal sedimentary terrains. *Natural Built Social Environment Health* 2(3), 77-111. <https://doi.org/10.63095/NBSEH.26.7451298>

Abstract: This study investigates how lithology and pedoclimate control soil evolution and degradation across two contrasting systems in humid tropical Gabon. The research compares ferralitic soils formed on ancient granito-gneissic basement at Koula-Moutou to younger coastal sedimentary sands at Kango. Physicochemical analyses revealed divergent trajectories: ferralitic soils exhibited extreme acidity (pH < 4.5), low cation exchange capacity, and severe base depletion, rendering them highly degraded but less vulnerable through persistent weathering. Conversely, coastal sands showed moderate nutrient retention but greater vulnerability to nutrient loss. These findings highlight the fact that lithological inheritance governs fertility dynamics. There is a need for site-specific management, such as liming and organic inputs, to restore Congo Basin soils.

Keywords : Lithological inheritance, Tropical soil degradation, Sustainable soil management.

1. Introduction

Soils link the lithosphere, biosphere, and climate systems. Soils are fundamental in regulating ecosystem processes such as nutrient cycling, water retention, carbon sequestration, and primary productivity [1,2]. Many soils, particularly tropical soils, are considered to be degraded [3], and these functions are increasingly compromised by abiotic and biotic factors, including climate variability, parent material, and anthropogenic activities [4]. Covering approximately 40% of the Earth's terrestrial surface [5,6] and exhibiting heightened sensitivity to degradation, tropical soils are a frontier for global sustainability initiatives [7,8]. Central to the "4 per 1000" Initiative, these soils are critical to promote a transition toward productive, resilient, and climate-smart agriculture rooted in sustainable land and soil resource management [9]. Tropical soils also play a strategic role in advancing several interlinked United Nations Sustainable Development Goals (SDGs), including food security (SDG 2), sustainable land use (SDG 12), climate action (SDG 13), and biodiversity conservation (SDG 15) [10].

In Central Africa, particularly in Gabon, the interplay between complex bedrock geology and high rainfall regimes has produced a striking geopedological mosaic. Soils derived from contrasting parent materials such as highly weathered ferralitic soils formed on the Precambrian crystalline basement and relatively younger coastal sedimentary sands developed on Cretaceous–Tertiary formations exhibit divergent physical and chemical behaviours [11]. These lithological differences influence not only the mineralogical and structural properties of soils but also their fertility potential and degradation pathways under increasing anthropogenic pressure [12].

The functional differentiation of soils reflects their underlying geological heritage and their response to climatic drivers, both critical to landscape evolution and long-term soil sustainability. Fertility is governed by interrelated variables such as texture, organic carbon content, base saturation, and nutrient retention—all shaped by the mineralogy of the parent material, the intensity of weathering, and the input of organic matter associated with vegetation cover [13–16]. Moreover, these parameters influence the vulnerability of soils to degradation, particularly in agricultural landscapes and areas affected by deforestation [17,18].

The study areas, Koula-Moutou in southeastern Gabon and Kango in the western coastal belt, offer contrasting litho-climatic contexts. Koula-Moutou is located in the Chaillu Massif, a mountainous region straddling the border between southern Gabon and the western Republic of the Congo [19]. This massif is a segment of the ancient Archean basement dominated by

tonalites, granodiorites, and mafic intrusions, indicative of a complex polyphase magmatic and metamorphic history [11,20]. Kango, in contrast, is situated within Gabon's coastal sedimentary basin [21], a geomorphic unit formed during the Early Cretaceous rifting of the South Atlantic. This basin records a complex fluviomarine depositional history, comprising stratigraphic sequences such as the Agoula, Madiela, and Sibang formations [10,11]. These formations, dominated by unconsolidated sands, marls, and occasional carbonates, underpin a landscape of inherently fragile, quartz-rich soils [22]. The coastal sedimentary sands extend far beyond Gabon, forming a continuous belt along the Atlantic margins of Central Africa, notably in Cameroon and the Democratic Republic of the Congo [23]. This transboundary distribution emphasizes that they are a shared geopedological resource—and a common vulnerability—within the Congo Basin's coastal fringe [24,25].

These lithostratigraphic contrasts condition the processes of soil formation, mineral weathering, and nutrient availability. By linking soil processes to their geological substrates and climatic regimes, this research contributes to understanding lithology–soil–climate interactions in the context of tropical landscape evolution and long-term ecosystem resilience. This study investigates how lithological inheritance and pedoclimatic conditions influence the development, degradation, and sustainability of tropical soils in these two divergent settings. The aim is to: (1) characterize the physicochemical properties of ferralitic and coastal sedimentary soils across vertical soil profiles; (2) evaluate fertility levels using a structured classification approach based on integrated soil indicators; (3) assess the soil degradation rate (SDR) and vulnerability potential (Vp) through composite indices to quantify susceptibility to nutrient loss and functional decline; and (4) propose site-specific soil management strategies for each geopedological context.

Given the differences in the geological substrate—which govern not only structural development but, more critically, nutrient bioavailability— we hypothesize that coastal sedimentary sands, despite structural fragility, will show higher nutrient responsiveness and more favourable sustainability indices under improved management conditions, whereas ferralitic soils formed on the crystalline basement will exhibit lower resilience. This hypothesis is tested by comparing soil properties across contrasting geopedological contexts in Gabon.

2. Materials and methods

2.1 Study area and sampling design

Field investigations were conducted during two separate campaigns (December 2023 and February 2024) at two ecologically and geologically distinct sites in Gabon: Koula-Moutou, located in the southeast, and Kango, in the western coastal region (Fig. 1a). Both locations are characterized by secondary forest cover but differ in climatic regimes, floristic composition, and underlying lithology.

The Koula-Moutou site (01°14.686' S, 12°54.743' E) lies within the fully humid equatorial zone and receives a mean annual rainfall of ~2,000 mm, with an average temperature of 26 °C. The vegetation comprises mainly dense tropical forests, gradually transitioning into disturbed secondary growth near human settlements. Dominant species include *Aucoumea klaineana* (Okoumé), *Desbordesia insignis* (Alep), *Pachylobus butettneri* (Ozigo), and *Irvingia gabonensis* (bush mango). Montane zones are frequently colonized by heliophilous pioneers such as *Musanga cecropioides* (parasol tree) and *Aucoumea klaineana*.

In contrast, Kango (00°06.977' N, 10°11.264' E) experiences a transitional equatorial climate, with a similar mean temperature but higher rainfall (~2,566 mm/year). The site has been historically influenced by anthropogenic activity, particularly selective logging and settlement expansion, resulting in floristic compositions dominated by species similar to those of Koula-Moutou but in varied successional stages.

Geologically, Koula-Moutou is part of the Chaillu Massif, underlain by Archean-aged granitoid complexes (e.g., tonalites, granodiorites, and monzogranites) and mafic intrusions, indicative of a polyphase magmatic evolution within the Congo Craton [11,26,27]. This lithostructural setting has promoted the formation of deeply weathered ferralitic soils. In contrast, Kango lies within the coastal sedimentary basin, an Atlantic margin basin formed during the Early Cretaceous, characterized by interbedded continental, lacustrine, and marine formations. The dominant surficial material here is coastal alluvium and sandy sediments, derived from the Agoula, Madiela, Cocobeach, and Sibang sequences [10,27] (Fig. 1b–c).

At each site, composite soil samples were collected at three depth intervals (0–10 cm, 10–20 cm, 20–30 cm), with three replicates per depth, following a randomized spatial layout. A total of 22 soil profiles were surveyed in Kango and 18 in Koula-Moutou, resulting in 120 individual samples from 40 profiles. All samples were air-dried, sieved (2 mm), and stored for physicochemical analysis.

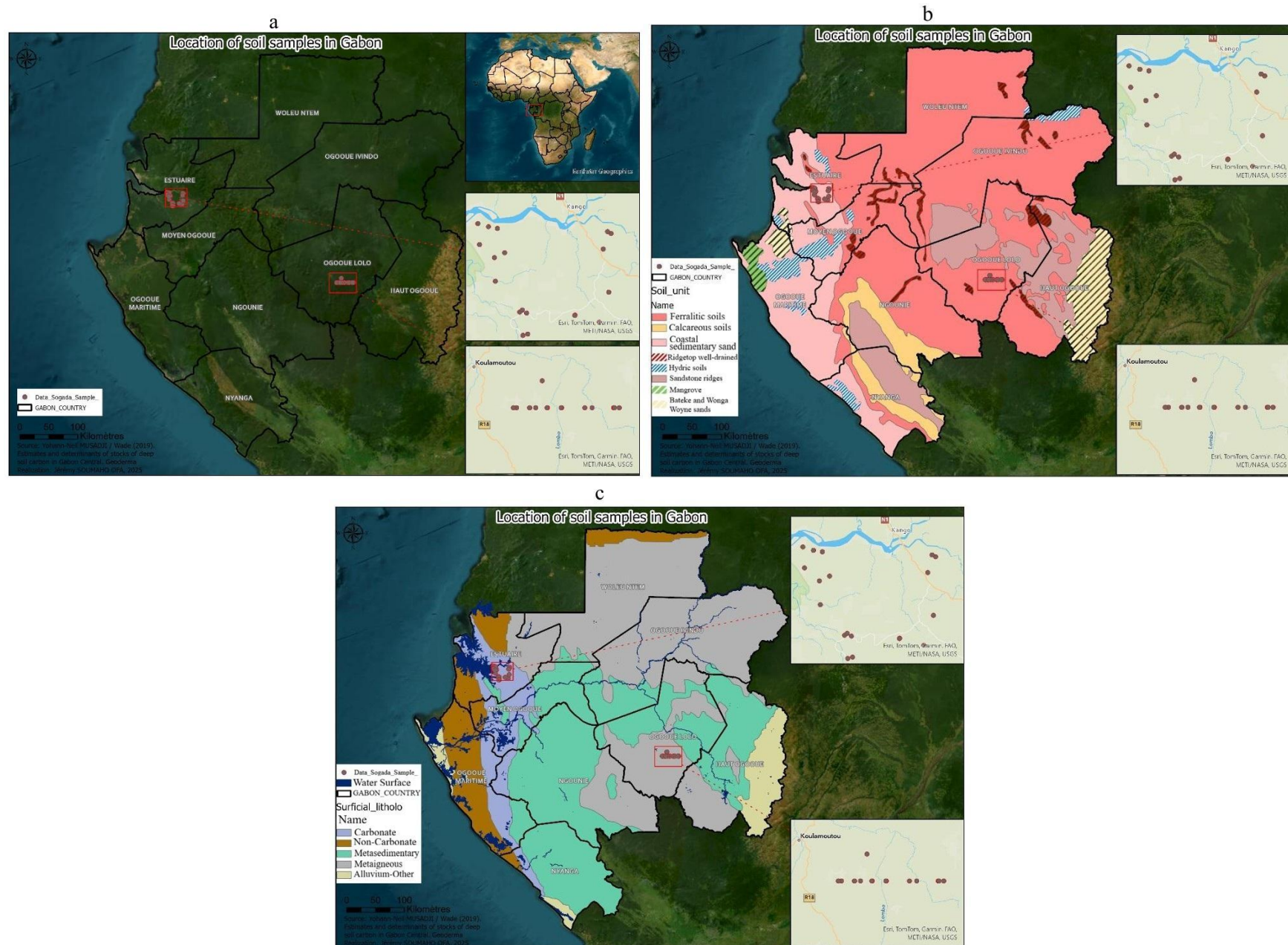


Figure 1. Sampling sites maps showing: (a) vegetation cover, (b) lithology, and (c) soil units. Maps adapted from Wade *et al.* [27]

2.2 Laboratory analyses of soil Properties

Soil pH was measured in a 1:2.5 soil-to-water suspension using a calibrated pH meter. Soil organic carbon (SOC) was quantified using the Walkley-Black dichromate oxidation method [28]. Total nitrogen (TN) was determined via Kjeldahl digestion [29]. Ammonium (NH_4^+) and nitrate (NO_3^-) concentrations were determined spectrophotometrically, following [30].

Available phosphorus was extracted using 0.5 M NaHCO_3 and analysed colorimetrically [31]. Exchangeable base cations (Ca^{2+} , Mg^{2+} , K^+ and Na^+) were extracted using a 1 M ammonium acetate solution (pH 7.0). Ca^{2+} and Mg^{2+} were quantified using EDTA titration, whereas K^+ and Na^+ were determined via flame photometry [32]. The cation exchange capacity (CEC) was determined using the 1 M ammonium acetate method (pH 7.0) [33].

Soil particle size distribution was assessed using the pipette method. Bulk density (Bd) was estimated using pedotransfer functions [34]. Soil water content (WC), total porosity (TP), and air porosity (AP) were calculated following [35]. Soil structural stability was evaluated using the Index of Soil Structural Stability (ISS) [36]:

$$ISS (\%) = \frac{1.724 \times OC}{\text{Silt} + \text{Clay}} \times 100$$

Where OC represents the organic carbon content. Interpretation thresholds were defined as follows: $ISS > 9\%$: high structural stability; 7–9%: moderate stability, low risk; 5–7%: high degradation risk; $\leq 5\%$: structurally degraded soils [36].

2.3 Soil fertility classification and degradation assessment

To assess current fertility status, soils were classified using the framework of [Quemada and Cabrera [37], refined by Nguemezi et al. [38]. Soils were assigned to one of four fertility classes based on the severity and number of physicochemical limitations: Class I (no or minimal limitations), Class II (up to three moderate limitations with low severity), Class III (more than three moderate limitations and at least one severe limitation), Class IV (multiple severe limitations).

The following parameters were included in the assessment: soil texture, SOC, TN, C/N ratio, available P, exchangeable bases (Ca^{2+} , Mg^{2+} , K^+ , Na^+), base saturation (BS), CEC, and pH.

Degradation dynamics were evaluated using two metrics: soil degradation rate (SDR) and vulnerability potential (Vp). SDR scores ranged from 1 (none) to 5 (extreme degradation), whereas Vp scores ranged from 5 (very low vulnerability) to 1 (very high vulnerability).

The Cumulative Rating Index (CRI) (Table 1) was derived by summing the SDR and Vp weighting values, providing an integrated proxy for soil quality and functional stability [39].

Table 1. Interpretation of Cumulative Rating Index

	Cumulative Rating Index	
	SDR	SVP
Sustainability		
Highly Sustainable	<20	>40
Sustainable	20-30	35-40
Sustainable with high input	30-35	30-35
Sustainable with another land use	35-40	20-30
Unsustainable	>40	<20

2.4 Statistical analyses

All data were tested for normality using the Shapiro–Wilk test. When the assumptions of normality were met, one-way ANOVA was applied; in other cases, non-parametric Kruskal–Wallis tests were employed. Post hoc comparisons were performed when required. Relationships among soil properties were explored using Pearson’s correlation and linear regression analyses. All statistical analyses were conducted at a 95% confidence level ($\alpha = 0.05$) using Python (Spyder IDE).

3. Results

3.1 Soil physical properties and profile structure

The particle size distribution and structural properties of soils varied significantly between the two geologically distinct sites (Table 2; Fig. 2). At Kango, coastal sedimentary sands exhibited a loamy texture, whereas Koula-Moutou’s ferrallitic soils were classified as sandy clay. In both soils, sand was the dominant fraction; the overall distribution of sand, silt, and clay showed contrasting depth trends (Fig. 2a–c).

Clay content increased with depth at both sites, reaching higher proportions in Koula-Moutou, where it constituted the second most abundant fraction. By contrast, silt was more abundant in surface horizons and declined with depth, particularly in the Kango profiles. These opposing trends were reflected in the silt/clay ratio, which was significantly higher in the coastal sedimentary sands (Kango) than in the ferrallitic soils (Koula-Moutou; $p < 0.05$). Quantitatively, the arable layer (0–30 cm) at Koula-Moutou contained 85% more clay and 65% more silt than its counterpart in Kango ($p = 1.5 \times 10^{-12}$).

Bulk density (Bd) was significantly lower across all depths in Kango soils compared to Koula-Moutou ($p = 2.0 \times 10^{-9}$, Table S1), consistent with a looser, coarser sediment structure (Fig. 2d). Conversely, the Index of Soil Structural Stability (ISS) was significantly higher in the surface horizons of the ferrallitic soils ($p = 1.2 \times 10^{-3}$), but declined with depth at both sites (Fig. 3a). Although water content (WC) and air porosity (AP) did not differ significantly between sites ($p > 0.05$), total porosity (TP) was notably greater in Kango soils ($p = 2.0 \times 10^{-9}$), especially in the upper 10 cm, consistent with their lower compaction and higher sand fraction (Fig. 3b–d).

Table 2. Mean soil physical properties of studied soil types: Coastal sedimentary sands (Kango site) and Ferralitic soils (Koula-Moutou site)

Soil types	<i>n</i>	Depth(cm)	Clay (%)	Sand (%)	Silt (%)	Silt:Clay	Texture	Bd (g/cm)	ISS (%)	WC (%)	AP (%)	TP (%)
Coastal sedimentary sands	21	0-30	14.22 ± 6.44 ^a	52.15 ± 8.58 ^a	33.63 ± 7.69 ^a	2.84 ± 1.45 ^a	Loam	1.44 ± 0.01 ^a	9.03 ± 3.69 ^a	22.19 ± 3.16 ^a	21.89 ± 3.01 ^a	45.61 ± 0.40 ^a
Ferralitic soils	18	0-30	26.29 ± 8.36 ^b	61.90 ± 8.50 ^b	11.81 ± 4.79 ^b	0.59 ± 0.54 ^b	Sandy clay loam	1.48 ± 0.02 ^b	14.46 ± 7.53 ^b	14.22 ± 4.36 ^a	21.85 ± 4.29 ^a	44.06 ± 0.79 ^b

n : Number of samples ; Bd: Bulk density ; ISS : Soil aggregate stability index ; WC : Water content ; AP : Air porosity ; TP : Total porosity, Subscript letters following the data denote statistical similarities and differences among groups. Identical letters indicate that the compared groups are not significantly different. Distinct subscripts represent statistically significant differences in mean values, as determined by Tukey's multiple comparison test at the 5% significance level.

Table 3. Mean soil chemical properties of studied soil types: Coastal sedimentary sands (Kango site) and Ferralitic soils (Koula-Moutou site)

Soil types	<i>n</i>	Depth (cm)	pH	SOM (%)	SOC (%)	TN (%)	C/N	NO_3^- (ppm)	NH_4^+ (ppm)
Coastal sedimentary sands	21	0-30	4.61 ± 0.23 ^a	3.84 ± 0.98 ^a	2.22 ± 0.57 ^a	0.24 ± 0.6 ^a	9.57 ± 1.84 ^a	16.12 ± 5.76 ^a	32.63 ± 9.85 ^a
Ferralitic soils	18	0-30	3.76 ± 0.42 ^b	4.64 ± 1.28 ^b	2.69 ± 0.74 ^b	0.23 ± 0.08 ^a	11.87 ± 1.61 ^b	14.58 ± 4.75 ^a	30.32 ± 11.40 ^a

Table 4. Mean soil fertility properties of studied soil types: Coastal sedimentary sands (Kango site) and Ferralitic soils (Koula-Moutou site)

Soil types	<i>n</i>	Depth (cm)	av.P (ppm)	Ca ²⁺ (cmol/kg)	Mg ²⁺ (cmol/kg)	K ⁺ (cmol/kg)	Na ⁺ (cmol/kg)	CEC (cmol/kg)	SBE (cmol/kg)
Coastal sedimentary sands	21	0-30	4.74 ± 1.63 ^a	3.80 ± 1.53 ^a	1.34 ± 0.59 ^a	0.32 ± 0.1 ^a	0.07 ± 0.05 ^a	16.73 ± 4.30 ^a	6.10 ± 3.17 ^a
Ferralitic soils	18	0-30	8.17 ± 2.51 ^b	0.64 ± 0.40 ^b	0.24 ± 0.16 ^b	0.11 ± 0.04 ^b	0.04 ± 0.04 ^a	8.73 ± 3.12 ^b	1.05 ± 0.57 ^b

n: Number of samples ; av.P : Available phosphorus; Ca²⁺ : Exchangeable calcium; Mg²⁺ : Exchangeable magnesium; K⁺ : Exchangeable potassium; Na⁺ : Exchangeable sodium; CEC: Cationic exchangeable capacity; SBE : Sum exchangeable bases. Subscript letters following the data denote statistical similarities and differences among groups. Identical letters indicate that the compared groups are not significantly different. Distinct subscripts represent statistically significant differences in mean values, as determined by Tukey's multiple comparison test at the 5% significance level.

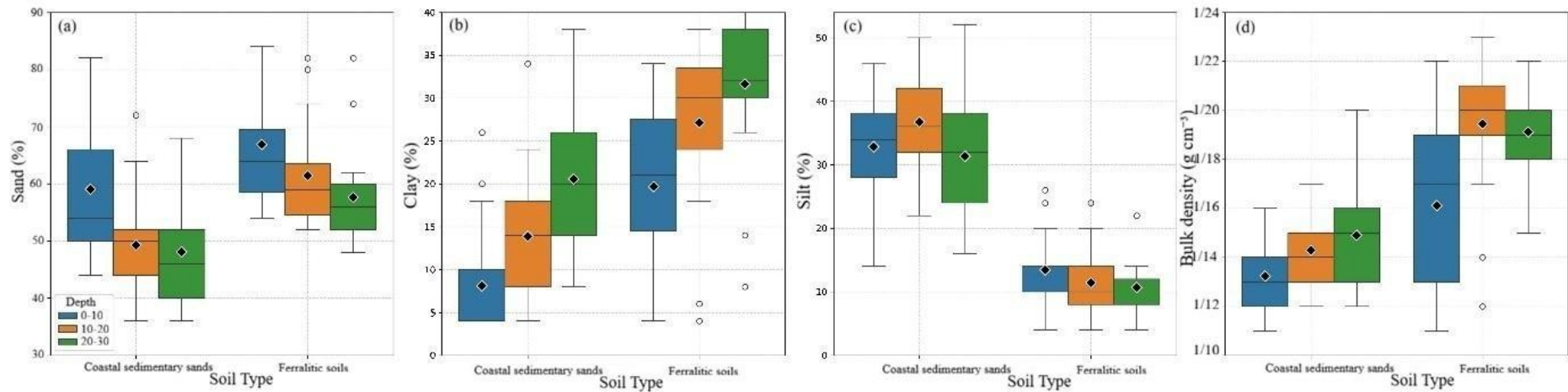


Figure 2. Distribution of physical soil quality indicators by soil type: (a) Sand, (b) Clay, (c) Silt, and (d) Texture. Box plots show the interquartile range (25th–75th percentiles), with the median (solid line), mean (diamond), and outliers (dots).

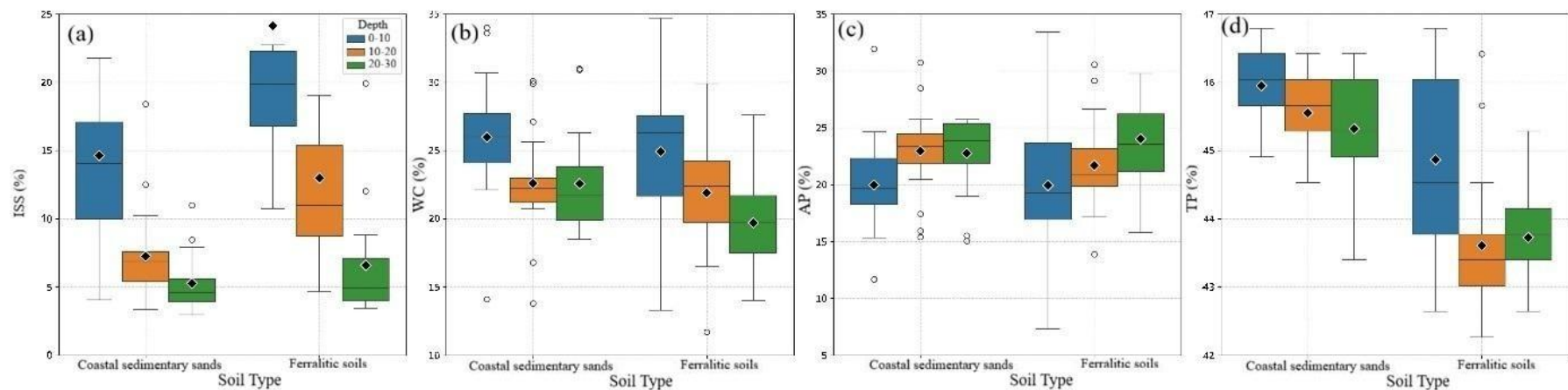


Figure 3. Distribution of structural and porosity-related indicators: (a) ISS (Soil Structural Stability Index), (b) WC (Water Content), (c) AP (Air Porosity), and (d) TP (Total Porosity). Box plot elements as in Figure 2.

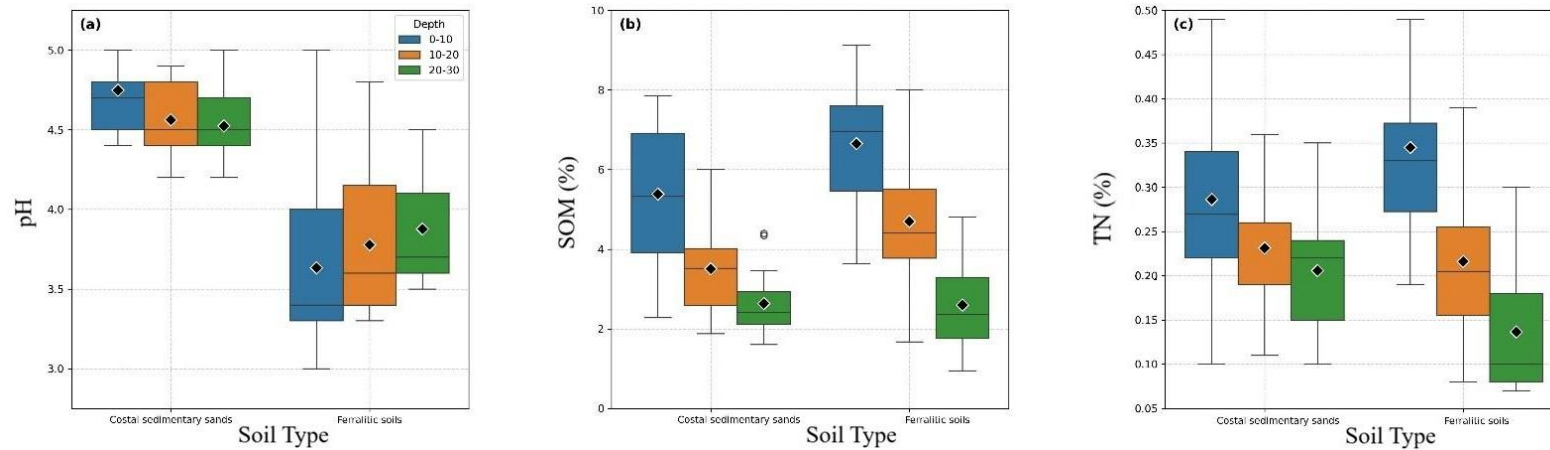


Figure 4. Distribution of chemical soil indicators: (a) pH, (b) SOM (Soil Organic Matter), (c) TN (Total Nitrogen). Box plot elements as in Figure 2.

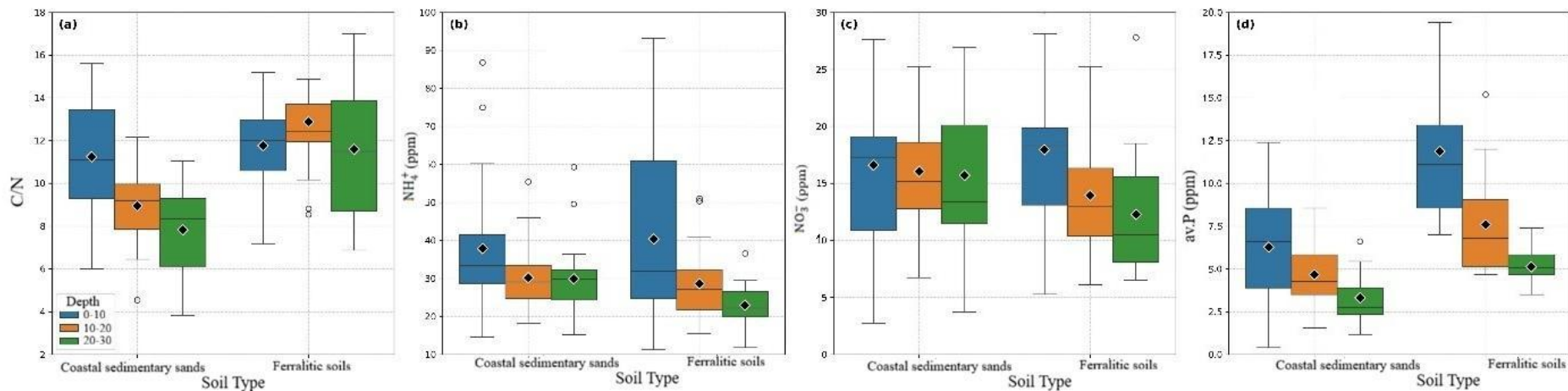


Figure 5. Distribution of nitrogen and phosphorus indicators: (a) C/N ratio, (b) Ammonium (NH_4^+), (c) Nitrate (NO_3^-), (d) av.P (Available Phosphorus). Box plot elements as in Fig. 2.

3.2 Chemical characteristics of soil horizons

The chemical fertility of the soils showed sharp contrasts between the two lithologically distinct systems (Table 3; Fig. 4). Mean pH values were significantly higher in the coastal sedimentary sands (+0.85 unit, $p = 1.4 \times 10^{-6}$), with declining acidity in surface layers and increased acidification with depth in Kango. By contrast, Koula-Moutou soils exhibited an upward trend in pH with depth (Fig. 4a).

Soil organic matter (SOM) content was significantly enriched in the arable layers of ferralitic soils (+21%, $p < 0.05$), although both sites displayed a general decrease in SOM with depth (Fig. 4b, Table S2). Total nitrogen (TN) levels were similar across soil types with no significant difference ($p > 0.05$); a steeper vertical decline in TN was observed in Koula-Moutou (−60%) than in Kango (−38%; Fig. 4c).

C/N ratios were significantly higher in Kango soils, indicative of slower organic matter mineralization ($p = 2.5 \times 10^{-5}$, Fig. 5a). This ratio declined with depth in Kango but remained relatively stable in Koula-Moutou. In coastal sands, these differences were not statistically significant. Although both nitrate (NO_3^-) and ammonium (NH_4^+) concentrations were slightly elevated in coastal sedimentary sands (+8% and +11%, respectively), these differences were not statistically significant (Fig. 5b–c).

3.3 Nutrient distribution and soil fertility indices

The spatial distribution of macronutrients and cation exchange capacity (CEC) revealed divergent nutrient retention strategies (Table 4, Figs. 5d, 6, and 7).

Available phosphorus (available P) was significantly higher in the ferralitic soils (+72%, $p = 1.3 \times 10^{-5}$, Table S3), despite the overall nutrient impoverishment typical of highly weathered profiles. In both soils, available P declined with increasing depth (Fig. 5d).

Exchangeable base cations followed a consistent hierarchy: $\text{Ca}^{2+} > \text{Mg}^{2+} > \text{K}^+ > \text{Na}^+$. Their absolute concentrations were markedly higher in Kango soils: Ca^{2+} (+484%), Mg^{2+} (+452%), K^+ (+179%) and Na^+ (+68%). These differences were reflected in the significantly higher CEC (+92%, $p = 1.1 \times 10^{-7}$) and sum of exchangeable base cations (SEB) in Kango soils (+475%, Table S3). CEC remained relatively stable with depth in Kango, whereas in Koula-Moutou it declined sharply (−57.5%). Notably, the exchangeable base cations in Kango decreased with depth ($p = 1.4 \times 10^{-7}$), whereas Koula-Moutou soils showed minimal depth variation (Fig. 7a–b). Base saturation (BS) was also higher in coastal sedimentary sands ($p = 8.5 \times 10^{-6}$) and declined moderately with depth at Kango (−36%), but remained nearly unchanged in Koula-Moutou (Fig. 7c, Table S4).

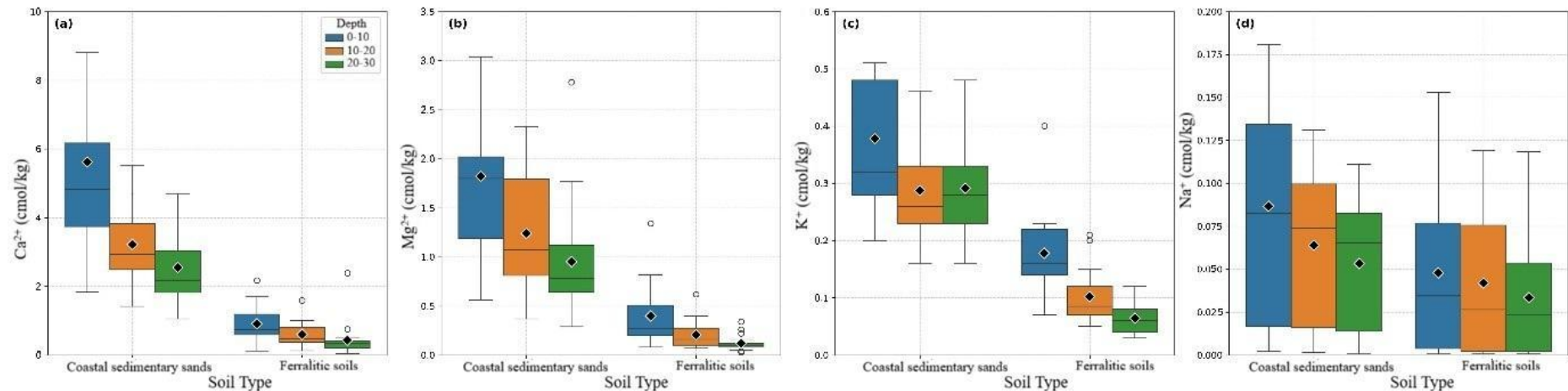


Figure 6. Distribution of exchangeable base cations: (a) Ca^{2+} (Calcium), (b) Mg^{2+} (Magnesium), (c) K^+ (Potassium), (d) Na^+ (Sodium). Box plot elements as in Figure 2.

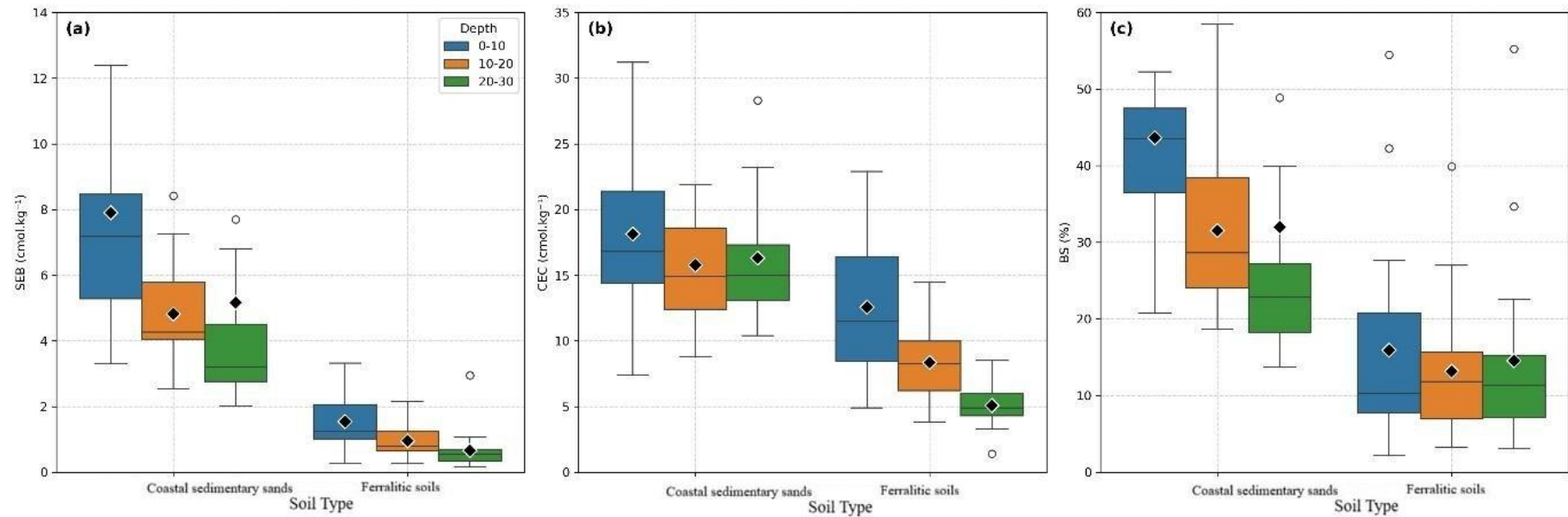


Figure 7. Distribution of nutrient capacity indicators: (a) SEB (Sum of Exchangeable Bases), (b) CEC (Cation Exchange Capacity), (c) BS (Base Saturation). Box plot elements as in Figure 2.

The $\text{Ca}^{2+}/\text{Mg}^{2+}$ ratio was stable in Kango but increased slightly with depth in Koula-Moutou. The $\text{Mg}^{2+}/\text{K}^+$ ratio, in contrast, showed a significant decline in Kango and remained unchanged in Koula-Moutou. Differences in $\text{Mg}^{2+}/\text{K}^+$ ratios between the two soil types were highly significant ($p = 9.7 \times 10^{-6}$, Table 5).

Table 5. Mean soil chemical fertility indicators (BS, $\text{Ca}^{2+}/\text{Mg}^{2+}$, $\text{Mg}^{2+}/\text{K}^+$) for the studied soil types: Coastal sedimentary sands (Kango site) and Ferralitic soils (Koula-Moutou site)

Soil types	<i>n</i>	BS (%)	$\text{Ca}^{2+}/\text{Mg}^{2+}$	$\text{Mg}^{2+}/\text{K}^+$
Coastal sedimentary sands	21	36.54 ± 17.09^a	2.96 ± 0.77^a	4.18 ± 1.16^a
Ferralitic soils	18	14.15 ± 11.17^b	2.83 ± 0.77^a	2.11 ± 1.03^b

n: Number of samples; BS: Base saturation; $\text{Ca}^{2+}/\text{Mg}^{2+}$: Calcium-to-Magnesium ratio; $\text{Mg}^{2+}/\text{K}^+$: Magnesium –to–Potassium ratio. Subscript letters following the data denote statistical similarities and differences among groups. Identical letters indicate that the compared groups are not significantly different. Distinct subscripts represent statistically significant differences in mean values, as determined by Tukey’s multiple comparison test at the 5% significance level.

3.2 Multivariate structure of soil properties

The Pearson correlation matrix (Fig. 8) revealed key functional linkages among soil indicators. Clay content was negatively correlated with nutrient pools (exchangeable cations, NO_3^-), CEC, pH, and TP, but positively correlated with Bd ($p < 0.0001$). Silt content was positively associated with TP, C/N, and CEC. Sand fraction exhibited positive correlations with ISS and Bd.

Soil pH emerged as a central integrator, positively correlated with exchangeable nutrients, CEC, and SEB, but negatively with SOM and available P. TP exhibited strong correlations with multiple fertility indicators, highlighting its diagnostic value for soil quality.

Principal Component Analysis (PCA) explained 94.03% of the total variance (Fig. 9a; Table 6). The first component (PC1, 59.12%) was dominated by variables indicative of parent material influence (texture, Bd, CEC, exchangeable bases).

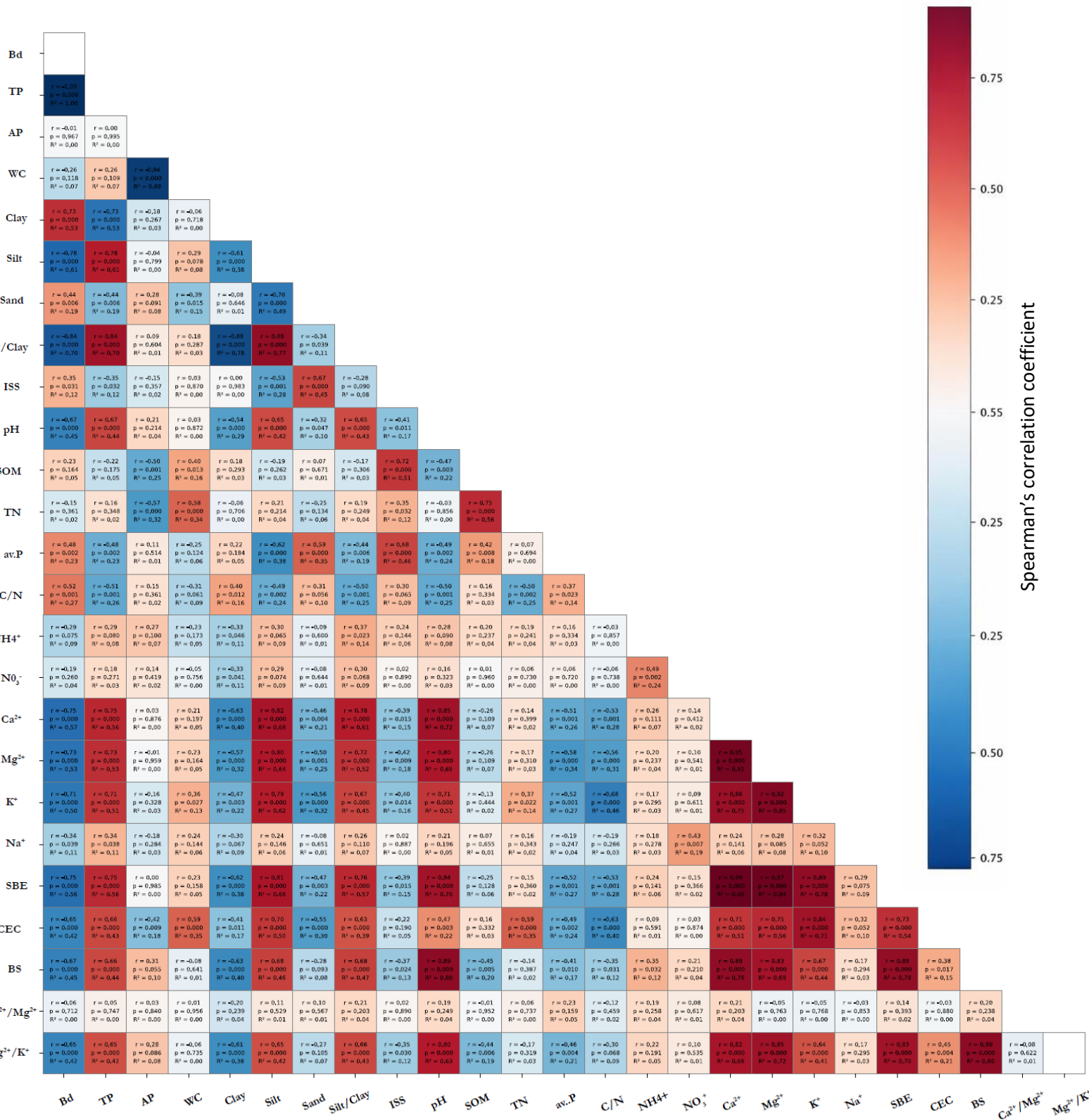


Table 6. Correlation between principal components (PC) and soil quality indicators of the studied soil

SQI	PC1	PC2	p-value
Bd	-0.97	-0.15	0.00005
TP	0.97	-0.15	0.00005
AP	-0.64	-0.75	0.03349
WC	0.87	0.49	0.00521
Clay	-0.98	-0.04	0.00001
Sand	-0.16	0.95	0.00030
Silt	0.82	-0.54	0.01209
ISS	0.22-	0.97	0.00005
pH	0.76	-0.63	0.02900
SOM	0.37	0.92	0.00109
TN	0.60	0.76	0.02748
C/N	-0.41	0.67	> 0.05
NH_4^+	0.66	0.73	0.03967
NO_3^-	0.78	0.49	0.02360
av.P	-0.05	0.99	0.00000
Ca^{2+}	0.91	-0.24	0.00146
Mg^{2+}	0.94	-0.26	0.00052
K^+	0.97	-0.21	0.00004
Na^+	0.96	-0.02	0.00013
CEC	0.97	-0.11	0.00005
BS	0.91	-0.37	0.00195
Eigenvalue	12.24	7.33	
Variance (%)	59.12	34.91	
Cumulative (%)	59.12	94.03	

SQI : Soil quality indicators ; Bd: Bulk density ; ISS : Soil aggregate stability index ; WC : Water content ; AP : Air porosity ; TP : Total porosity ; SOM: Soil organic matter ; TN : Total nitrogen ; C/N : Carbon-to-nitrogen ratio ; NO_3^- : Nitrate ; NH_4^+ : Ammonium ; av.P : Available phosphorus; Ca^{2+} : Exchangeable calcium; Mg^{2+} : Exchangeable magnesium; K^+ : Exchangeable potassium; Na^+ : Exchangeable sodium; CEC: Cationic exchangeable capacity; BS : Base saturation

The second component (PC2, 34.91%) concerned fertility attributes (SOM, TN, ISS, NH_4^+ , available P). PC1 was closely associated with coastal sediments (Kango), whereas PC2 differentiated ferrallitic soils (Koula-Moutou), reflecting divergent pedogenetic and nutrient retention pathways (Fig. 9b).

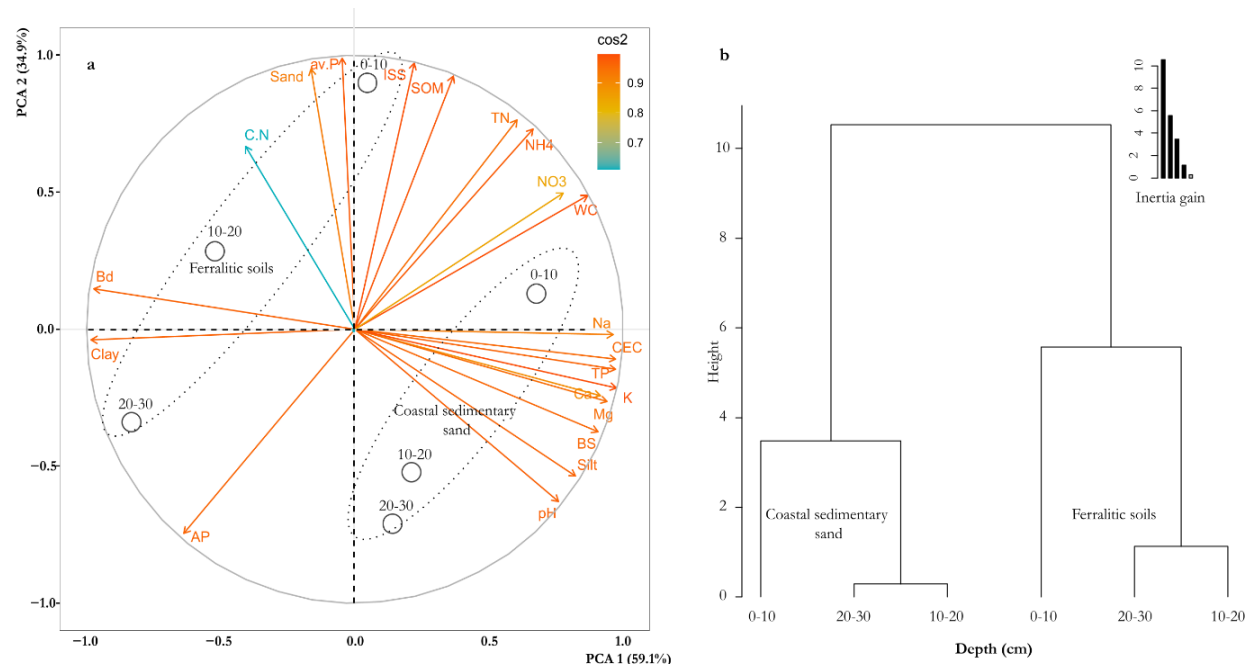


Figure 9. Principal Component Analysis (PCA) of soil quality indicators: **(a)** PCA biplot, **(b)** Hierarchical clustering of soil types based on PCA results.

3.5 Soil fertility classification and degradation assessment

Using the fertility classification, both soils were assigned to Fertility Class IV, indicating severe to moderate limitations. For Kango soils, constraints included low pH and available P, as well as moderate BS deficiency. In Koula-Moutou, limitations were linked to low K^+ and CEC, together with severe deficits in BS, SEB, and pH.

Table 7. Soil types fertility assessment: Coastal sedimentary sands (Kango site) and Ferralitic soils (Koula-Moutou site).

SQI	Coastal sedimentary sands	Ferralitic soils
SOM (%)	I	I
TN (%)	I	I
av.P (ppm)	IV	III
K^+ (cmol/kg)	II	III
SEB (cmol/kg)	II	IV
BS (%)	III	IV
CEC (cmol/kg)	II	III
pH	IV	IV
ISS (%)	I	I
Fertility level	Poor	Poor
Limiting factors	pH, av.P, BS,	pH, SEB, BS, CEC, K^+ and av.P
Class	IV	IV

SQI : Soil quality indicators ; SOM: Soil organic matter ; TN : Total nitrogen ; av.P : Available phosphorus; K^+ : Exchangeable potassium; SEB : Sum of exchangeable bases; BS : Base saturation ; CEC: Cationic exchangeable capacity

Degradation metrics further clarified these differences (Table 7). For both soil types, SDR/Vp scores indicated high degradation susceptibility in pH and TN (scores of 5/1), moderate degradation in Bd (3/3), and varying patterns in base cations. Ferralitic soils consistently scored high SDR (5) and low Vp (1) for all cations, whereas coastal sands displayed more moderate degradation potential (e.g., Ca^{2+} : 4/2; Mg^{2+} : 3/3).

The Cumulative Rating Index (CRI) revealed contrasting degradation dynamics: ferralitic soils exhibited higher degradation rates but lower vulnerability (CRI: 46/20), whereas coastal sands showed a lower degradation profile but higher susceptibility (CRI: 37/29). These findings underscore the distinct geopedological constraints and resilience characteristics embedded in each soil system (Table 8).

Table 8. Assessment of soil degradation rate and vulnerability potential of selected soil quality indicators in the soil types.

SQI	Coastal sedimentary sands		Ferralitic soils	
	SDR	Vp	SDR	Vp
Texture	1	5	2	4
Bd	3	3	3	3
pH	5	1	5	1
SOC	3	3	3	3
TN	5	1	5	1
BS	4	2	5	1
av.P	4	2	3	3
CEC	3	3	4	2
Ca^{2+}	4	2	5	1
Mg^{2+}	3	3	5	1
K^{+}	3	3	5	1
CRI	38	28	45	21

SQI : Soil quality indicators ; SDR : Soil degradation rate ; Vp : Vulnerability potential ; SOC: Soil organic carbon ; TN : Total nitrogen ; BS : Base saturation ; av.P : Available phosphorus; CEC: Cationic exchangeable capacity ; Ca^{2+} : Exchangeable calcium; Mg^{2+} : Exchangeable magnesium; K^{+} : Exchangeable potassium; Na^{+} : Exchangeable sodium ; CRI : Cumulative Rating Index.

4. Discussion

4.1 Lithological control on soil texture, structure, and physical properties

The contrasting physical properties observed between Kango and Koula-Moutou reflect the foundational influence of their parent material, which governs particle size distribution, structural organization, and hydrological behaviour. At both sites, sand dominates the arable layer (>50%), a hallmark of regional pedogenic patterns across Gabon [23,27]. The ferralitic soils at Koula-Moutou, derived from intensely weathered metaigneous substrates of the Chaillu

Massif, exhibit a markedly higher clay content than the coastal sedimentary sands at Kango, which developed on less altered marls and sandstones [10,11]. This contrast underscores the role of geological inheritance in shaping long-term pedogenesis.

The lower silt/clay ratio in Koula-Moutou soils signals an advanced weathering stage, characteristic of mature tropical Ferralsols. This process is marked by silt eluviation and in situ clay accumulation [40,41]. This interpretation is quantitatively supported by a strong negative correlation between silt and clay ($r = -0.61$, $p < 0.0001$), pointing to systematic mineralogical differentiation over time [42].

Texture and mineralogy also shaped the mechanical integrity of the soil matrix. The higher ISS in the finer-textured ferrallitic profiles suggests enhanced aggregation and resistance to erosive forces, a crucial asset under intense tropical rainfall [36]. Conversely, coastal sands, though more porous and aerated, exhibited lower ISS and Bd, rendering them more vulnerable to physical breakdown, rapid infiltration, and nutrient leaching—especially under unsustainable land use [42].

Lithological control extended to Bd and TP. Koula-Moutou soils exhibited higher compaction and reduced moisture retention, probably associated with clay-dominated matrices and sesquioxide enrichment [41–43]. The observed perfect inverse relationship between Bd and TP ($r = -1.00$, $R^2 = 1.00$, $p < 0.0001$; Fig. 8) underscores the tight coupling between mineralogical composition, structural properties, and hydrological functioning in tropical soils. These insights carry critical implications for erosion risk, water availability, and land-use suitability, reinforcing the need for pedologically informed management strategies in contrasting tropical ecosystems [44].

4.2 Lithological control on soil acidity, nitrogen dynamics, and organic matter stabilization

The chemical differentiation of soils across the study sites strongly reflected their lithological heritage (Table 3). Both soil types exhibited acidic conditions, but the contrast in intensity was striking: ferrallitic soils at Koula-Moutou displayed extreme acidity ($\text{pH} < 4.5$), a hallmark of deep tropical weathering and prolonged leaching. By contrast, the coastal sedimentary sands at Kango maintained very strong acidity ($4.5 < \text{pH} < 5.5$), consistent with their carbonate-depleted, quartz-dominated provenance [27,45]. These pH regimes not only differentiated

geochemical signatures but also exerted a profound influence on nutrient dynamics and organic matter stabilization [46].

Although SOM levels were significantly higher in the ferralitic soils (+21%), the mechanisms underlying SOM persistence differed between the two sites. At Koula-Moutou, where extreme acidity and high Fe/Al sesquioxides co-occur, SOM stabilization is probably mediated by organo-mineral associations, including ligand exchange and surface complexation on oxide mineral surfaces [47]. This interpretation is reinforced by negative pH–SOM ($r = -0.47$, $R^2 = 0.22$, $p = 0.003$) and pH–clay ($r = -0.54$, $R^2 = 0.29$, $p < 0.0001$; Fig. 8) correlations, suggesting that mineral surface chemistry plays a critical role in organic carbon retention under low-pH, high-clay conditions [48].

Yet, the acidic environment also imposes biochemical constraints, particularly on nitrogen cycling. Microbial nitrification is suppressed under low pH, leading to an accumulation of ammonium (NH_4^+) at the expense of nitrate (NO_3^-) —a pattern observed at both sites but especially pronounced in the ferralitic profiles, where acidity and clay jointly inhibit nitrifier populations [49]. By contrast, the coarser texture and better-aerated conditions of the coastal sands appear to support greater NO_3^- availability, hinting at more efficient SOM mineralization and improved microbial activity despite their lower SOM stocks [50].

Together, these findings illustrate how geology-mediated pH regimes modulate nutrient retention, microbial function, and organic matter dynamics, emphasizing the need for context-sensitive soil fertility interventions. In ferralitic soils, efforts must focus on pH correction and enhancement of bioavailable nitrogen, whereas in coastal sands, maintaining organic inputs and buffering against acidification will sustain nutrient cycling and productivity [51].

4.3 Phosphorus limitation and nutrient retention patterns

Although phosphorus (P) concentrations appeared elevated in the ferralitic soils of Koula-Moutou relative to the coastal sedimentary sands of Kango, this trend reflects analytical bias rather than agronomic reality. The commonly employed Olsen method—designed for neutral to alkaline soils—tends to overestimate P availability under acidic conditions, a flaw particularly pronounced in tropical weathered soils dominated by Fe and Al sesquioxides [52]. These sesquioxides exhibit strong sorptive affinities for phosphate, effectively sequestering it into insoluble forms that are quantified chemically but inaccessible biologically [53].

In this study, the extremely low pH values recorded in the ferralitic soils ($\text{pH} < 4.5$; Fig. 5d) further exacerbate P sorption, masking an underlying phosphorus deficiency beneath seemingly adequate concentrations. Hence, the observed P enrichment in ferralitic profiles likely represents a fixation artefact—not a reservoir of plant-available nutrients. This insight reinforces a central paradigm in tropical pedology: phosphorus availability must be interpreted through the lens of soil mineralogy, not merely extraction values [54].

From a management standpoint, this underscores the critical need for integrated diagnostic frameworks that consider pH buffering capacity, sesquioxide dominance, and P retention dynamics. Reliance on conventional extraction methods in isolation risks overlooking latent P constraints and misleading fertilization regimes. Instead, targeted interventions—such as slow-release phosphate formulations, organo-mineral amendments, or enhanced organic inputs—should be prioritized to circumvent P fixation bottlenecks and boost nutrient-use efficiency in acidic, highly weathered environments [54].

By contrast, the coastal sedimentary soils, though chemically less complex, exhibited higher CEC and BS—a reflection of their lower weathering intensity and quartz-dominated lithology [55,56]. This fertility advantage was largely confined to the upper horizon, where nutrient stocks are concentrated and vulnerable to leaching. Sodium levels remained uniformly low, consistent with expectations for tropical rainforest soils under high rainfall regimes [57], further highlighting the need for site-specific nutrient budgeting even in relatively resilient soil systems.

Together, these findings offer a scientifically grounded framework for rethinking nutrient diagnostics and fertilization strategies across lithologically diverse tropical soils, with direct implications for yield stability, ecological resilience, and sustainable land-use planning under changing climatic and socioeconomic pressures [58].

4.4 Fertility classes, degradation rates, and site-specific vulnerabilities

Both soil types evaluated in this study—coastal sedimentary sands at Kango and ferralitic soils at Koula-Moutou—were classified as Fertility Class IV, a category denoting multiple severe agronomic constraints, particularly in pH, base saturation, and available phosphorus [37]. At Kango, very strong soil acidity and critically low phosphorus availability emerged as dominant fertility barriers. By contrast, Koula-Moutou's deeply weathered ferralitic soils exhibited

pronounced deficiencies in exchangeable potassium (K^+) and cation exchange capacity (CEC), compounding their intrinsic nutrient limitations.

Among all variables assessed, pH stood out as a central geochemical control, exerting strong positive correlations with both CEC and Mg^{2+}/K^+ ratios ($p < 0.0001$). This relationship reinforces the role of acid–base equilibria in regulating nutrient retention and availability in tropical soils—a dynamic particularly sensitive to both parent material and land-use intensity [59–60].

The dual-index framework of Soil Degradation Rates (SDR) and Vulnerability Potential (Vp) provided deeper insight into the degradation–resilience continuum of these soils [61]. Ferralitic soils, despite registering a higher Cumulative Rating Index (CRI = 46/20), displayed greater degradation but lower vulnerability, associated with their already impoverished baseline and structural robustness. By contrast, coastal sands, though moderately degraded (CRI: 37/29), exhibited greater vulnerability to further fertility loss, underlining their tenuous nutrient balance and elevated sensitivity to anthropogenic disturbance.

These findings resemble broader pedological observations from humid tropical soils in Central Africa, where ferralitic soils are often described as chemically exhausted but physically resilient, whereas sedimentary soils are more chemically responsive yet structurally fragile under unsustainable land use [62–63]. Such distinctions carry tangible implications for regional land-use planning: ferralitic systems demand nutrient rehabilitation and pH correction, whereas coastal sands require immediate protection from accelerated degradation through conservation-based practices. In both cases, failure to act could precipitate irreversible losses in soil function and landscape productivity, compromising long-term sustainability in the Congo Basin [58,63].

4.5 Agroecological implications and sustainable soil use

The contrasting genesis and mineralogical composition of ferralitic and coastal sedimentary soils point to divergent agroecological pathways, each demanding distinct strategies for sustainable land management [7]. Ferralitic soils, enriched in sesquioxides and kaolinite clays, are chemically constrained—they exhibit low CEC, poor nutrient retention, and intense phosphorus fixation, all of which limit their agricultural potential [13, 27, 64]. By contrast, coastal sedimentary sands, though structurally fragile, remain more pedogenically dynamic and

responsive to well-targeted interventions, making them more amenable to sustainable intensification [15,65,66].

As for land-use planning, these findings carry critical implications for resource allocation, restoration priorities, and climate-smart agriculture in humid tropical systems. In ferrallitic soils, fertility restoration must begin with acid amelioration (liming) to improve nutrient availability, coupled with site-specific phosphorus supplementation and organic carbon enhancement through agroforestry, mulching, or legume-based rotations. Without such targeted efforts, these soils are unlikely to support long-term productivity under conventional cropping systems.

In coastal sand zones, the moderate inherent fertility, greater porosity, and higher management responsiveness offer a strategic entry point for sustainable agricultural intensification. Approaches that combine nutrient inputs with water conservation techniques can enhance productivity while mitigating risks of nutrient leaching and structural decline.

The divergent biogeochemical constraints and opportunities presented by these soils call for a lithologically informed, precision-based approach to soil governance—one that recognizes the legacy of Earth surface processes while designing future-facing agricultural systems adapted to local realities.

4.6 Pedoclimatic constraints and soil governance in humid tropical Central Africa

The intense equatorial rainfall [67,68], lithological heterogeneity [69], complex vegetation mosaics [70], and inherently fragile tropical soils [71] make Central Africa a key degradation hotspot within the Congo Basin's dynamic geosphere–biosphere interface. This biophysical fragility is increased by unsustainable land-use trajectories, notably slash-and-burn cultivation, abbreviated fallow periods, and unregulated deforestation—all of which disrupt soil–vegetation feedbacks, destabilize aggregate structure, and impair pedogenetic function [72].

The impacts are acute in landscapes where human disturbance has already reshaped forest architecture and floristic composition, resulting in declining aboveground biomass inputs, accelerated nutrient loss, and functional degradation of soil biota and structure [73]. These coupled anthropogenic–pedoclimatic pressures require geologically informed and spatially differentiated soil governance frameworks, capable of maintaining ecosystem services and enhancing resilience across humid tropical regions [74].

The present findings demonstrate that soil resilience is co-regulated by pedoclimatic context and land cover dynamics, highlighting the integrated influence of climate, parent material, and vegetation on soil system stability [75].

Three recommendations can be offered:

- i. Recarbonize soils using organic amendments, cover crops, and agroforestry to improve structure, biodiversity, and SOM stocks [76];
- ii. Apply lime judiciously to correct soil acidity, improve nutrient availability, and reduce Al toxicity [76-78];
- iii. Implement Conservation Agriculture: minimal tillage, crop rotation, and residue management to reduce physical and chemical degradation [78].

These actions fall within broader land governance frameworks integrating soil health and national climate strategies [7,9], such as the Congo Basin's Nationally Determined Contributions (NDCs) under the Paris Agreement. Technical solutions to local systems and socio-economic realities need participatory monitoring systems and farmer-led soil management initiatives. Geological, pedological, and ecological data enhance our understanding of soil system evolution in humid tropical Africa. Our study provides a geoscientific foundation for sustainable land-use planning in nutrient-poor yet biodiversity-rich landscapes such as the Congo Basin. The study seeks to model Earth surface processes, support agroecological resilience, and inform policy.

5. Strengths and limitations of the study

A central strength of this work is its juxtaposition of two geopedologically contrasting systems within the humid tropics of Central Africa: the highly weathered ferralitic soils of the Chaillu Massif and the quartz-rich coastal sedimentary sands of the Atlantic basin. This approach describes a natural experiment in which lithological heritage and pedoclimatic context can be distinguished in regard to soil fertility, structural stability, and degradation. By integrating physical, chemical, and functional soil metrics—including composite indices such as SDR, Vp, and CRI—the study is a multidimensional view of soil system performance and resilience. The use of high-resolution vertical profiling, with replicated samples across depth intervals, further strengthens the analysis by revealing depth-dependent patterns in nutrient distribution, acidity buffering, and structural stability that are critical for sustainable management interventions.

The process-based interpretation frames observed differences not merely as site-specific attributes but as expressions of deep-time geological inheritance interacting with contemporary climatic forcing. Accordingly, the findings are transferable to broader questions of Earth surface process modelling, agroecological planning, and land-use governance in other lithologically diverse tropical landscapes. The direct policy relevance of the results—particularly their applicability to climate-smart agriculture, national soil restoration strategies, and biodiversity conservation in the Congo Basin—underscores the value of such an approach.

Nonetheless, there are limitations. The temporal scope of the study is two discrete sampling campaigns within a single climatic year. Although mineralogical interpretations are grounded in geological mapping and prior regional studies, the absence of direct mineral phase analyses (e.g., X-ray diffraction or spectroscopic techniques) restricts the precision with which sesquioxide dominance, clay mineral assemblages, and phosphorus-binding phases can be quantified. Furthermore, the land-use context examined—predominantly secondary forest—does not encompass the full range of agricultural or degraded states in which these soils function, limiting the generalizability of the management recommendations.

Methodologically, the reliance on Olsen extraction for available phosphorus under strongly acidic conditions introduces the risk of overestimating plant-available P in ferralitic soils, given the known fixation effects of Fe and Al sesquioxides. Finally, although the two sites capture a sharp litho-climatic contrast, they do not represent the entire pedological spectrum of Gabon or the Congo Basin; extrapolating the findings to other geopedological zones requires additional site-specific validation.

By recognizing these limitations as well as the strengths, the work maintains both scientific rigour and transparency, providing a robust framework for future research aimed at refining lithology-informed soil governance in the humid tropics.

6. Conclusion

This study reveals that the fertility and degradation of tropical soils in humid Gabon are not merely products of climate or land use alone, but are fundamentally affected by the deep-time imprint of lithological inheritance and its interaction with pedoclimatic regimes. Through a comparative analysis of two contrasting geopedological systems—the quartz-rich coastal sedimentary sands at Kango and the highly weathered ferralitic soils over crystalline basement

at Koula-Moutou—we demonstrate that soil mineralogy, particle-size distribution, and acidity buffering capacity are key regulators of nutrient availability, structural stability, and resilience to degradation.

Ferralitic soils, shaped by prolonged weathering of Archean granito-gneissic substrates, exhibit severe chemical constraints, including extreme acidity, very low cation exchange capacity, and strong phosphorus fixation driven by sesquioxide dominance. These properties reinforce their low intrinsic fertility and limited responsiveness to conventional inputs, but also confer a certain structural stability that tempers their vulnerability under low-input systems.

By contrast, coastal sedimentary sands—derived from younger, less weathered sedimentary formations—are more chemically responsive, with moderate organic carbon content, higher base saturation, and greater nutrient mobility. Yet, their fragile structure and reduced water-holding capacity render them highly susceptible to nutrient leaching and degradation, particularly under intensified or poorly managed land use.

These findings validate our central hypothesis: that geologically inherited mineral and structural properties are the main drivers of soil fertility outcomes and degradation susceptibility in tropical environments. The divergent degradation indices—with higher degradation but lower vulnerability in ferralitic soils, and lower degradation but higher vulnerability in coastal sands—highlight the need for geologically contextualised soil governance.

More broadly, this work underscores the critical role of parent material in shaping Earth surface processes, including nutrient cycling, carbon sequestration, and soil structural evolution. It advances our understanding of how tropical landscapes function—and fail—under anthropogenic pressure, with direct implications for land-use policy, climate adaptation, and sustainable development.

In future, soil management strategies in Gabon and across the Congo Basin must transition from generic interventions to lithology-informed and site-specific frameworks. In ferralitic zones, restoration efforts should prioritize soil recarbonization (e.g. through agroforestry or legume rotations), pH correction via liming, and strategic phosphorus amendments adapted to high fixation environments. For coastal sandy systems, the focus should shift toward integrated nutrient and water management, alongside erosion control and organic matter stabilization.

These recommendations, if they are accepted for national land-use planning and climate adaptation strategies, can ensure that soil stewardship aligns with agroecological resilience, biodiversity conservation, and regional sustainability goals. In the context of accelerating climate change, it is clear that strengthening soil system resilience will require strategies that address both the inherited geological constraints and the evolving pedoclimatic pressures shaping tropical landscapes. Soil management strategies in Gabon and across the Congo Basin must transition from generic to integrated, lithology-informed frameworks that combine adaptive nutrient management, organic matter restoration, and structural conservation measures for each soil system's vulnerabilities and strengths.

Credit Author Statement

R.G. Mabicka Obame: Writing–review & editing, Writing–original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

E. Fosso Menkem: Writing–review & editing, Writing–original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

N.Y. Musadji: Writing–review & editing, Writing–original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

M. Ognalaga: Writing–review & editing, Validation, Supervision, Resources, Project administration, Methodology, Conceptualization.

L.S. Koutika: Writing–review & editing, Visualization, Validation, Supervision, Methodology, Formal analysis, Conceptualization.

J.A. Ondo: Writing–review & editing, Validation, Supervision, Resources, Project administration, Methodology, Conceptualization.

G. Oroedjogo Nouhando: Investigation, Formal analysis, Data curation.

J. Soumaho: Visualization, Conceptualization, Software, Resources.

E. Raivire: Writing–review & editing.

W. Mayobe: Investigation, Formal analysis, Data curation.

H. P. Opiangah: Writing–review & editing, Validation, Supervision, Funding acquisition.

Acknowledgments

The authors are most grateful for the collaborative efforts of the CSIR–Soil Research Institute (Kumasi, Ghana) and the Rwanda Agriculture and Animal Resources Development Board (RAB), whose technical expertise and analytical facilities were instrumental in this study. We particularly thank Mr Adams Sadick for his dedicated participation in laboratory analyses. We also extend our sincere appreciation to the anonymous reviewers for their constructive feedback, which greatly enhanced the manuscript.

References

- [1] Luo, P., Sun, Y., Wang, S., Wang, S., Lyu, J., Zhou, M., Nakagami, K., Takara, K., & Nover, D., 2020, Historical assessment and future sustainability challenges of Egyptian water resources management. *Journal of Cleaner Production* **263**, 121154. <https://doi.org/10.1016/j.jclepro.2020.121154>
- [2] Zhang, Y., Luo, P., Zhao, S., Kang, S., Wang, P., Zhou, M., & Lyu, J., 2020, Control and remediation methods for eutrophic lakes in the past 30 years. *Water Science and Technology* **81**(6), 1099–1113. <https://doi.org/10.2166/wst.2020.218>
- [3] Stahr, K., & Herrmann, L., 2023, Soils of the humid and sub-humid tropics. In M. J. Goss & M. Oliver (Eds.), *Encyclopedia of soils in the environment* (2nd ed., pp. 353–367). (San Diego: Academic Press). <https://doi.org/10.1016/B978-0-12-822974-3.00246-9>
- [4] Borrelli, P., Robinson, D. A., Panagos, P., Lugato, E., Yang, J. E., Alewell, C., Wuepper, D., Montanarella, L., & Ballabio, C., 2020, Land use and climate change impacts on global soil erosion by water (2015–2070). *Proceedings of the National Academy of Sciences of the United States of America* **117**(36), 21994–22001. <https://doi.org/10.1073/pnas.2001403117>
- [5] Pal, D. K., Wani, S. P., Sahrawat, K. L., & Srivastava, P., 2014, Red ferruginous soils of tropical Indian environments: A review of the pedogenic processes and its implications for edaphology. *CATENA* **121**, 260–278. <https://doi.org/10.1016/j.catena.2014.05.023>
- [6] Comar Pinhotti Aguiar, M., 2022, Tropical Soils: Considerations on Occurrence and Characteristics and Studies in Brazil. In *New Approaches in Foundation Engineering*. (London: IntechOpen). <https://doi.org/10.5772/intechopen.103947>
- [7] Koutika, L.-S., 2025, Sharing soil knowledge of the Congolese coastal plains within international research partnerships. *Soil Advances* **3**, 100037. <https://doi.org/10.1016/j.soilad.2025.100037>
- [8] Ladha, J.K., Chakraborty, D., Henry, B., Minasny, B., 2025, Carbon and Nitrogen Management for Climate-Resilient Agriculture: Toward the 4p1000 Target and Sustainable Development Goals. *Soil Advances* **4**, 100073. <https://doi.org/10.1016/j.soilad.2025.100073>
- [9] Koutika, L.-S., Henry, B., Schepp, C., Olaleye, A., Amiraslani, F., Minasny, B., 2025, Enhancing “4 per 1000” initiative implementation through region-specific agricultural and forestry practices. *Soil Advances* **4**, 100057. <https://doi.org/10.1016/j.soilad.2025.100057>
- [10] United Nations. (2015). *Transforming our world: The 2030 Agenda for Sustainable Development*. United Nations Department of Economic and Social Affairs. <https://sdgs.un.org/goals>
- [11] Thiéblemont, D., Castaing, C., Billa, M., & Bouton, P., 2009, Notice explicative de la Carte géologique et des Ressources minérales de la République gabonaise à 1/1 000 000.

- Editions DGMG – Ministère des Mines, du Pétrole, des Hydrocarbures*, Libreville, 381 p.
- [12] Lal, R., 2015, Restoring Soil Quality to Mitigate Soil Degradation. *Sustainability* 7(5), 5875–5895. <https://doi.org/10.3390/su7055875>
 - [13] Sanchez, P.A., 2019, Properties and management of soils in the tropics (2nd ed.). (Cambridge: Cambridge University Press). <https://doi.org/10.1017/9781316809785>
 - [14] Lal, R., 2020, Soil organic matter and water retention. *Agronomy Journal* 112(5), 3265–3277. <https://doi.org/10.1002/agj2.20282>
 - [15] Ciric, V., Prekop, N., Seremesic, S., Vojnov, B., Pejic, B., & Radovanovic, D., 2023, The implication of exchange capacity (CEC) assessment for soil quality management and improvement. *Journal of Agriculture and Forestry* 69(4). <https://doi.org/10.17707/AgricultForest.69.4.08>
 - [16] Franzluebbers, A.J., 2024, Texture and organic matter associations with soil functional properties in crop and conservation land uses in North Carolina. *Soil Science Society of America Journal* 88(2), 449–464. <https://doi.org/10.1002/saj2.20620>
 - [17] Eggel, D., & Galvin, M., 2019, Soil degradation at the core of the Anthropocene's intricate fragility. *Global Challenges*. <https://globalchallenges.ch/issue/6/soil-degradation-at-the-core-of-the-anthropocenes-intricate-fragility/>
 - [18] Bekele, B., Wei, W., Tsegaye, L., Tilahun, M., Girma, T., & Ketema, H., 2025, Urban expansion-induced land use land cover changes and the subsequent changes in ecosystem service and land surface temperature in the central highland of Ethiopia. *Environmental Sustainability Indicators* 26, 100626. <https://doi.org/10.1016/j.indic.2025.100626>
 - [19] Thiéblemont, D., Callec, Y., Fernandez-Alonso, M., & Chène, F., 2018, A geological and isotopic framework of Precambrian terrains in Western Central Africa: An introduction. In: Siegesmund, S., Basei, M.A.S., Oyhançabal, P., & Oriolo, S. (eds.), *Geology of Southwest Gondwana*, Springer, Cham, 107–132. https://doi.org/10.1007/978-3-319-68920-3_5
 - [20] Prian, J.P., Couëffé, R., Thiéblemont, D., Goujou, J.C., Ekogha, H., & Boulingui, S., 2009, Notice explicative de la Carte géologique de la République du Gabon à 1/200 000, feuille Lambaréné. *Editions DGMG – Ministère des Mines, du Pétrole, des Hydrocarbures*, Libreville.
 - [21] Brownfield, M.E., & Charpentier, R.R., 2002, Geology and total petroleum systems of the West-Central Coastal Province (7203). *U.S. Geological Survey Bulletin* 2207-B, 52 p. <http://www.usgs.gov/bul/2207/B/>
 - [22] Garzanti, E., Vermeesch, P., Vezzoli, G., Andò, S., Botti, E., & Limonta, M., 2019, Congo River sand and the equatorial quartz factory. *Earth-Science Reviews* 197. <https://doi.org/10.1016/j.earscirev.2019.102918>
 - [23] Ambassa Bela, V., Ekoa Bessa, A.Z., Nguetchoua, G., Aonsi Kamani, F., Abioui, M., & Kwewouo Janpou, A., 2022, Petrography and geochemistry of beach sediments along the central coast of Cameroon: Constraints on paleoweathering, provenance, and tectonic setting. *Arabian Journal of Geosciences* 15(9), 855. <https://doi.org/10.1007/s12517-022-10114-5>
 - [24] Dada, O.A., Almar, R., & Morand, P., 2024, Coastal vulnerability assessment of the West African coast to flooding and erosion. *Scientific Reports* 14(1), 890. <https://doi.org/10.1038/s41598-023-48612-5>
 - [25] Tchindjang, M., Mbevo Fendoung, P., & Kamgho, C., 2025, Coastal hazard and vulnerability assessment in Cameroon. *Journal of Marine Science and Engineering* 13(1), 65. <https://doi.org/10.3390/jmse13010065>

- [26] Sayre, R. G., Comer, P., Hak, J., Josse, C., Bow, J., Warner, H., Larwanou, M., Kelbessa, E., Bekele, T., Kehl, H., Amena, R., Andriamasimanana, R., Ba, T., Benson, L., Boucher, T., Brown, M., Cress, J. J., Dassering, O., Friesen, B. A., Gachathi, F., Houcine, S., Keita, M., Khamala, E., Marangu, D., Mokua, F., Morou, B., Mucina, L., Mugisha, S., Mwavu, E., Rutherford, M., Sanou, P., Syampungani, S., Tomor, B., Vall, A. O. M., Vande Weghe, J. P., Wangui, E., Waruingi, L. (2013). A new map of standardized terrestrial ecosystems of Africa. *African Geographical Review*. (Washington, D.C.: Association of American Geographers). <https://pubs.usgs.gov/publication/70045097>
- [27] Wade, A.M., Richter, D.D., Medjibe, V.P., Bacon, A.R., Heine, P.R., & White, L.J.T., 2019, Estimates and determinants of stocks of deep soil carbon in Gabon, Central Africa. *Geoderma* **341**, 236–248. <https://doi.org/10.1016/j.geoderma.2019.01.004>
- [28] Nelson, D.W., & Sommers, L.E., 1983. Total carbon, organic carbon, and organic matter. In: Page, A.L., Miller, R.H., Keeney, D.R. (Eds.), *Methods of Soil Analysis, Part 2: Chemical and Microbiological Properties*. (Madison, WI: American Society of Agronomy and Soil Science Society of America). <https://doi.org/10.2134/agronmonogr9.2.2ed.c29>
- [29] Bremner, J.M., 1996, Nitrogen-total. In: *Methods of Soil Analysis*. John Wiley & Sons, 1085–1121. <https://doi.org/10.2136/sssabookser5.3.c37>
- [30] Allende-Montalbán, R., San-Juan-Heras, R., Martín-Lammerding, D., Delgado, M.M., Albarrán, M.M., & Gabriel, J.L., 2024, The soil sample conservation method and its potential impact on ammonium, nitrate and total mineral nitrogen measurements. *Geoderma* **448**, 116963. <https://doi.org/10.1016/j.geoderma.2024.116963>
- [31] Olsen, S.R., 1954. *Estimation of Available Phosphorus in Soils by Extraction with Sodium Bicarbonate*. (Washington, DC: U.S. Department of Agriculture), Circular No. 939.
- [32] Page, A.L., Miller, R.H., & Keeney, D.R., 1982, Methods of soil analysis. Part II: Chemical and microbiological properties. *American Society of Agronomy*, Madison, USA.
- [33] Schollenberger, C.J., & Simon, R.H., 1945, Determination of exchange capacity and exchangeable bases in soil – Ammonium acetate method. *Soil Science* **59**(1), 13–24. <https://doi.org/10.1097/00010694-194501000-00004>
- [34] Mabicka Obame, R.G., Musadji, N.Y., Ndongo, A., Soumaho, J., Mouha Edou, D.L., & Abaker, M.G., 2021, Carbon and nitrogen stocks under various land cover in Gabon. *Geoderma Regional* **25**, e00363. <https://doi.org/10.1016/j.geodrs.2021.e00363>
- [35] Hazelton, P., & Murphy, B., 2016. *Interpreting Soil Test Results: What Do All the Numbers Mean?* (Collingwood: CSIRO Publishing). <https://doi.org/10.1071/9781486319374>
- [36] Pieri, C.J.M.G., 2012. *Fertility of Soils: A Future for Farming in the West African Savannah*. (Berlin: Springer). <https://doi.org/10.1007/978-3-642-84320-4>
- [37] Quemada, M., & Cabrera, M.L., 1995, CERES-N model predictions of nitrogen mineralized from cover crop residues. *Soil Science Society of America Journal* **59**(4), 1059–1065. <https://doi.org/10.2136/sssaj1995.03615995005900040015x>
- [38] Nguemezi, C., Tematio, P., Yemefack, M., Tsozue, D., & Silatsa, T. B. F. (2020). Soil quality and soil fertility status in major soil groups at the Tombel area, South-West Cameroon. *Heliyon*, 6(2). <https://doi.org/10.1016/j.heliyon.2020.e03432>
- [39] Musadji, N.Y., Mabicka Obame, R.G., Mbina MOUNGUENGUI, M., Ondo, J.A., Koutika, L.S., Ravire, E., & Geffroy, C., 2024, Multivariate approach to characterizing soil quality of Gabonese ferrallitic soils. *Open Journal of Soil Science* **14**(4). <https://doi.org/10.4236/ojss.2024.144014>

- [40] Pelletier, B.R., 1973, A re-examination of the use of the silt/clay ratios as indicators of sedimentary environments: A study for students. *Atlantic Geoscience* **9**(1), 1. <https://doi.org/10.4138/1422>
- [41] Onwudike, S.U., 2015, Effect of land use types on vulnerability potential and degradation rate of soils of similar lithology in a tropical soil of Owerri, Southeastern Nigeria. *International Journal of Soil Science* **10**, 177–185. <https://doi.org/10.3923/ijss.2015.177.185>
- [42] Rahayu, R., Supriyadi, S., Herdiansyah, G., Herawati, A., & Erdaswin, F., 2023, The influence of geological formations on soil characteristics and quality in the southeast region of Pacitan Regency, Indonesia. *Soil Science Annual* **74**(3), 1–13. <https://doi.org/10.37501/soilsa/175383>
- [43] Oguike, P. C., & Mbagwu, J. S. C., 2009, Variations in some physical properties and organic matter content of soils of coastal plain sand under different land use types. *World Journal of Agricultural Sciences* **5**(1), 63–69.
- [44] Di Prima, S., Castellini, M., Pirastru, M., & Keesstra, S., 2018, Soil water conservation: dynamics and impact. *Water* **10**(7), 952. <https://doi.org/10.3390/w10070952>
- [45] King, J., Duke, U., Moutsinga, J. B., & Doufoulon, G., 1997, Conversion of anthropogenic savanna to production forest through fire-protection of the forest–savanna edge in Gabon, Central Africa. *Forest Ecology and Management*. <https://agris.fao.org/agris-search/search.do?recordID=NL1998003033>
- [46] Valtera, M., & Godbold, D., 2024, Soil properties and nutrient cycling. In: *Basics of Forest Ecology and Management to Sustainable Forest Management in Mongolia*, pp. 64–72.
- [47] Kuzyakov, Y., & Domanski, G., 2000, Carbon input by plants into the soil: review. *Journal of Plant Nutrition and Soil Science* **163**, 421–431.
- [48] Zhou, W., Han, G., Liu, M., Zeng, J., Liang, B., Liu, J., et al., 2020, Determining the distribution and interaction of soil organic carbon, nitrogen, pH and texture in soil profiles: A case study in the Lancangjiang River Basin, Southwest China. *Forests* **11**(5), 532. <https://doi.org/10.3390/f11050532>
- [49] Sierra, J., & Desfontaines, L., 2018, La dynamique de l’azote biodisponible dans les sols acides de Guadeloupe. *Ce que Nous Savons Sur*, 26 p. <https://hal.inrae.fr/hal-02790782>
- [50] Guo, Z., Han, J., & Li, J., 2020, Response of organic carbon mineralization and bacterial communities to soft rock additions in sandy soils. *PeerJ* **8**, e8948. <https://doi.org/10.7717/peerj.8948>
- [51] Azlan Halmi, M. F., Hasenan, S. N., Simarani, K., & Abdullah, R., 2018, Linking soil microbial properties with plant performance in acidic tropical soil amended with biochar. *Agronomy* **8**(11), 255. <https://doi.org/10.3390/agronomy8110255>
- [52] Nishigaki, T., Sugihara, S., Kobayashi, K., Hashimoto, Y., Kilasara, M., Tanaka, H., et al., 2018, Fractionation of phosphorus in soils with different geological and soil physicochemical properties in southern Tanzania. *Soil Science and Plant Nutrition* **64**(3), 291–299. <https://doi.org/10.1080/00380768.2018.1436406>
- [53] Merino, C., Nannipieri, P., & Matus, F., 2015, Soil carbon controlled by plant, microorganism and mineralogy interactions. *Journal of Soil Science and Plant Nutrition* **15**(2), 321–332. <https://doi.org/10.4067/S0718-95162015005000030>
- [54] Kiflu, A., Beyene, S., Jeff, S., 2017, Fractionation and availability of phosphorus in acid soils of Hageresalam, Southern Ethiopia under different rates of lime. *Chemical and Biological Technologies in Agriculture* **4**(1), 21. <https://doi.org/10.1186/s40538-017-0105-9>

- [55] Ch'ng, H. Y., Ahmed, O. H., & Majid, N. M. A., 2014, Improving phosphorus availability in an acid soil using organic amendments produced from agroindustrial wastes. *Scientific World Journal* **2014**, 506356. <https://doi.org/10.1155/2014/506356>
- [56] Ferreira, E. P., Coelho, R. M., Valladares, G. S., Dias, L. M. da S., Assis, A. C. C. de, Silva, R. C. da, et al., 2018, Mineralogy and concentration of potentially toxic elements in soils of the São Francisco Sedimentary Basin. *Revista Brasileira de Ciência do Solo* **42**, e0170088. <https://doi.org/10.1590/18069657rbcs20170088>
- [57] Kaspari, M., Yanoviak, S. P., Dudley, R., Yuan, M., & Clay, N. A., 2009, Sodium shortage as a constraint on the carbon cycle in an inland tropical rainforest. *Proceedings of the National Academy of Sciences* **106**(46), 19405–19409. <https://doi.org/10.1073/pnas.0906448106>
- [58] Agegnehu, G., & Amede, T., 2017, Integrated soil fertility and plant nutrient management in tropical agro-ecosystems: A review. *Pedosphere* **27**(4), 662–680. [https://doi.org/10.1016/S1002-0160\(17\)60382-5](https://doi.org/10.1016/S1002-0160(17)60382-5)
- [59] Solly, E. F., Weber, V., Zimmermann, S., Walthert, L., Hagedorn, F., & Schmidt, M. W. I., 2020, A critical evaluation of the relationship between the effective cation exchange capacity and soil organic carbon content in Swiss forest soils. *Frontiers in Forests and Global Change* **3**, 98. <https://doi.org/10.3389/ffgc.2020.0009>
- [60] Sainju, U. M., Liptzin, D., 2022, Relating soil chemical properties to other soil properties and dryland crop production. *Frontiers in Environmental Science* **10**, 1005114. <https://doi.org/10.3389/fenvs.2022.1005114>
- [61] Lal, R., 2016, Soil health and carbon management. *Food and Energy Security* **5**(4), 212–222. <https://doi.org/10.1002/fes3.96>
- [62] Neumann-Cosel, L., Zimmermann, B., Hall, J. S., van Breugel, M., & Elsenbeer, H., 2011, Soil carbon dynamics under young tropical secondary forests on former pastures—A case study from Panama. *Forest Ecology and Management* **261**(10), 1625–1633. <https://doi.org/10.1016/j.foreco.2010.07.023>
- [63] Koutika, L. S., Obame, R. M., Nkouamoussou, C. K., Musadji, N. Y., 2022, Research priorities for sandy soils in Central Africa. *Geoderma Regional* **29**, e00519. <https://doi.org/10.1016/j.geodrs.2022.e00519>
- [64] Gérard, F., 2016, Clay minerals, iron/aluminum oxides, and their contribution to phosphate sorption in soils—A myth revisited. *Geoderma* **262**, 213–226. <https://doi.org/10.1016/j.geoderma.2015.08.036>
- [65] Bationo, A., Waswa, B., Kihara, J., & Kimetu, J. (eds.), 2007, *Advances in Integrated Soil Fertility Management in Sub-Saharan Africa: Challenges and Opportunities*. (Dordrecht: Springer Netherlands). <https://doi.org/10.1007/978-1-4020-5760-1>
- [66] Chen, Y., Liu, K., Hu, N., Lou, Y., Wang, F., & Wang, Y., 2023, Biochemical composition of soil organic matter physical fractions under 32-year fertilization in Ferralic Cambisol. *Carbon Research* **2**(1), 1. <https://doi.org/10.1007/s44246-022-00034-0>
- [67] Baumgartner, S., Barthel, M., Drake, T. W., Bauters, M., Makelele, I. A., Mugula, J. K., 2020, Seasonality, drivers, and isotopic composition of soil CO₂ fluxes from tropical forests of the Congo Basin. *Biogeosciences* **17**(23), 6207–6218. <https://doi.org/10.5194/bg-17-6207-2020>
- [68] Sonwa, D. J., Oumarou Farikou, M., Martial, G., Félix, F. L., 2020, Living under a fluctuating climate and a drying Congo Basin. *Sustainability* **12**(7), 2936. <https://doi.org/10.3390/su12072936>
- [69] Moquet, J. S., Bouchez, J., Braun, J. J., Bogning, S., Mbonda, A. P., Carretier, S., et al., 2021, Contrasted chemical weathering rates in cratonic basins: The Ogooué and Mbei

- Rivers, Western Central Africa. *Frontiers in Water* **2**, 589070. <https://doi.org/10.3389/frwa.2020.589070>
- [70] Besisa Nguba, T., Bogaert, J., Makana, J. R., Mate Mweru, J. P., Sambieni, K. R., Bwazani Balandi, J., et al., 2025, Assessing forest degradation in the Congo Basin: The need to broaden the focus from logging to small-scale agriculture (a systematic review). *Forests* **16**(6), 953. <https://doi.org/10.3390/f16060953>
- [71] Meunier, F., Verbruggen, W., Verbeeck, H., Peaucelle, M., 2022, Low sensitivity of three terrestrial biosphere models to soil texture over the South American tropics. *Geoscientific Model Development* **15**(20), 7573–7591. <https://doi.org/10.5194/gmd-15-7573-2022>
- [72] Abrell, T., Naudin, K., Bianchi, F.J.J.A., Aragao, D.V., Tiftonell, P., Corbeels, M., 2024, Shifting cultivation in decline: An analysis of soil fertility and weed pressure in intensified cropping systems in Eastern Amazon. *Agriculture, Ecosystems & Environment* **360**, 108793. <https://doi.org/10.1016/j.agee.2023.108793>
- [73] Qin, Y., Xiao, X., Wigneron, J.P., Ciais, P., Brandt, M., Fan, L., 2022, Carbon loss from forest degradation exceeds that from deforestation in the Brazilian Amazon. *arXiv*. <https://doi.org/10.48550/arXiv.2206.07363>
- [74] Weigelt, J., Müller, A., Janetschek, H., Töpfer, K., 2015, Land and soil governance towards a transformational post-2015 development agenda: An overview. *Current Opinion in Environmental Sustainability* **15**, 57–65. <https://doi.org/10.1016/j.cosust.2015.08.005>
- [75] Feng, M., Liu, P., Cai, X., Wallington, K., Shi, L., Li, Y., 2019, Understanding the resilience of soil moisture regimes. *Water Resources Research* **55**(9), 7541–7563. <https://doi.org/10.1029/2018WR024495>
- [76] Paul, E.A., 2016, The nature and dynamics of soil organic matter: Plant inputs, microbial transformations, and organic matter stabilization. *Soil Biology and Biochemistry* **98**, 109–126. <https://doi.org/10.1016/j.soilbio.2016.04.001>
- [77] Filho, A.A.R., Adams, C., Manfredini, S., Aguilar, R., Neves, W.A., 2015, Dynamics of soil chemical properties in shifting cultivation systems in the tropics: A meta-analysis. *Soil Use and Management* **31**(4), 474–482. <https://doi.org/10.1111/sum.12224>
- [78] Mabicka Obame, R.G., Musadji, N.-Y., Ntoma Obone, R., Koutika, L.-S., Fosso Menkem, E., Mbina Mounguengui, M., 2025. On-farm carbon capturing strategies to reduce carbon footprint. In: Kumar, S., Meena, R.S. (Eds.), *Agriculture Toward Net Zero Emissions*. (London: Academic Press). <https://doi.org/10.1016/B978-0-443-13985-7.00008-7>

Supplementary material

Supplementary Table 1. Mean soil physical properties of studied soil types: Coastal sedimentary sands (Kango site) and Ferralitic soils (Koula-Moutou site)

Soil types	n	Depth (cm)	Clay (%)	Sand (%)	Silt (%)	Silt/Clay	Texture	Bd (g/cm)	ISS (%)	WC (%)	AP (%)	TP (%)
Coastal sedimentary sands	21	0-10	8.09 ± 6.27 ^a	59.04 ± 11.70 ^a	32.86 ± 9.32 ^a	5.78 ± 3.35 ^a	Sandy loam	1.43 ± 0.01 ^a	14.62 ± 7.82 ^a	25.98 ± 4.31 ^a	19.97 ± 4.50 ^a	45.95 ± 0.48 ^a
		10-20	13.90 ± 7.96 ^{ab}	49.33 ± 8.70 ^{bc}	36.76 ± 9.53 ^a	4.23 ± 3.73 ^a	Loam	1.44 ± 0.01 ^{ab}	7.27 ± 3.32 ^{bc}	22.60 ± 3.65 ^{ab}	22.96 ± 3.61 ^a	45.55 ± 0.56 ^{ab}
		20-30	20.57 ± 7.82 ^{bc}	48.10 ± 10.51 ^b	31.33 ± 9.84 ^a	1.84 ± 1.15 ^b	Loam	1.45 ± 0.02 ^{ab}	5.28 ± 1.95 ^b	22.57 ± 3.57 ^{ab}	22.75 ± 3.18 ^a	45.32 ± 0.86 ^{ab}
Ferralitic soils	18	0-10	19.67 ± 9.39 ^{bc}	66.89 ± 10.87 ^a	13.44 ± 5.81 ^b	0.98 ± 0.83 ^b	Sandy loam	1.46 ± 0.04 ^b	24.15 ± 16.07 ^d	24.93 ± 6.72 ^a	19.94 ± 6.78 ^a	44.86 ± 1.39 ^b
		10-20	27.11 ± 9.51 ^{cd}	61.44 ± 8.97 ^a	11.44 ± 5.22 ^b	0.68 ± 0.87 ^b	Sandy clay loam	1.49 ± 0.03 ^c	13.00 ± 7.39 ^{ac}	21.90 ± 4.22 ^{ab}	21.71 ± 4.22 ^a	43.61 ± 1.07 ^c
		20-30	31.89 ± 8.64 ^d	57.56 ± 8.5 ^{ac}	10.56 ± 4.38 ^b	0.40 ± 0.29 ^b	Sandy clay loam	1.49 ± 0.02 ^c	6.56 ± 3.96 ^{bc}	19.79 ± 3.56 ^{ab}	23.91 ± 3.57 ^a	43.71 ± 0.76 ^c

n : Number of samples ; Bd: Bulk density ; ISS : Soil aggregate stability index ; WC : Water content ; AP : Air porosity ; TP : Total porosity. Subscript letters following the data denote statistical similarities and differences among groups. Identical letters indicate that the compared groups are not significantly different. Distinct subscripts represent statistically significant differences in mean values, as determined by Tukey's multiple comparison test at the 5% significance level.

Supplementary Table 2. Mean soil chemical properties of studied soil types: Coastal sedimentary sands (Kango site) and Ferralitic soils (Koula-Moutou site)

Soil types	n	Depth (cm)	pH	SOM (%)	SOC (%)	TN (%)	C/N	NO_3^- (ppm)	NH_4^+ (ppm)
Coastal sedimentary sands	21	0-10	4.75 ± 0.33 ^a	5.38 ± 1.71 ^a	3.12 ± 1.00 ^a	0.29 ± 0.10 ^{ab}	11.24 ± 2.66 ^a	16.60 ± 7.70 ^a	37.84 ± 18.65 ^a
		10-20	4.56 ± 0.21 ^a	3.51 ± 1.06 ^{bc}	2.03 ± 0.62 ^{bc}	0.23 ± 0.06 ^{bc}	8.95 ± 1.80 ^b	16.06 ± 6.19 ^a	30.21 ± 9.02 ^{ab}
		20-30	4.52 ± 0.20 ^a	2.63 ± 0.76 ^c	1.53 ± 0.44 ^c	0.21 ± 0.07 ^{cd}	7.82 ± 1.94 ^b	15.72 ± 6.38 ^a	29.87 ± 9.95 ^{ab}
Ferralitic soils	18	0-10	3.63 ± 0.52 ^b	6.65 ± 1.51 ^d	3.86 ± 0.87 ^d	0.35 ± 0.13 ^a	11.77 ± 2.23 ^a	17.94 ± 7.35 ^a	40.33 ± 23.64 ^a
		10-20	3.78 ± 0.46 ^b	4.70 ± 1.76 ^{ab}	2.72 ± 1.03 ^{ab}	0.22 ± 0.1 ^{bd}	12.89 ± 3.15 ^a	13.97 ± 5.24 ^a	28.55 ± 10.33 ^{ab}
		20-30	3.86 ± 0.33 ^b	2.60 ± 1.02 ^c	1.51 ± 0.60 ^c	0.14 ± 0.06 ^d	11.57 ± 2.90 ^a	11.90 ± 5.56 ^a	22.34 ± 6.00 ^b

n : Number of samples ; SOM: Soil organic matter ; TN : Total nitrogen ; C/N : Carbon-to-nitrogen ratio ; NO_3^- : Nitrate ; NH_4^+ : Ammonium. Subscript letters following the data denote statistical similarities and differences among groups. Identical letters indicate that the compared groups are not significantly different. Distinct subscripts represent statistically significant differences in mean values, as determined by Tukey's multiple comparison test at the 5% significance level.

Supplementary Table 3. Mean soil fertility properties of studied soil types: Coastal sedimentary sands (Kango site) and Ferralitic soils (Koula-Moutou site)

Soil types	n	Depth (cm)	av.P (ppm)	Ca ²⁺ (cmol/kg)	Mg ²⁺ (cmol/kg)	K ⁺ (cmol/kg)	Na ⁺ (cmol/kg)	CEC (cmol/kg)	SBE (cmol/kg)
Coastal sedimentary sands	21	0-10	6.27 ± 3.08 ^{ab}	5.62 ± 3.48 ^a	1.82 ± 0.88 ^a	0.37 ± 0.15 ^a	0.09 ± 0.06 ^a	18.12 ± 6.28 ^a	7.91 ± 4.17 ^a
		10-20	4.66 ± 1.80 ^{ac}	3.23 ± 1.17 ^b	1.24 ± 0.53 ^b	0.29 ± 0.08 ^b	0.06 ± 0.04 ^{ab}	15.77 ± 4.20 ^{ab}	4.82 ± 1.55 ^b
		20-30	3.31 ± 1.38 ^c	2.55 ± 1.02 ^b	0.95 ± 0.55 ^b	0.29 ± 0.09 ^b	0.05 ± 0.04 ^{ab}	16.31 ± 4.58 ^{ab}	5.17 ± 6.64 ^{ab}
Ferralitic soils	18	0-10	11.87 ± 4.66 ^d	0.92 ± 0.53 ^c	0.40 ± 0.32 ^c	0.18 ± 0.07 ^c	0.05 ± 0.05 ^{ab}	12.57 ± 5.38 ^{bc}	1.54 ± 0.84 ^c
		10-20	7.60 ± 2.89 ^b	0.60 ± 0.36 ^c	0.21 ± 0.14 ^c	0.10 ± 0.05 ^{cd}	0.04 ± 0.04 ^b	8.35 ± 3.00 ^{cd}	0.95 ± 0.50 ^c
		20-30	5.11 ± 0.93 ^{bc}	0.43 ± 0.52 ^c	0.12 ± 0.08 ^c	0.06 ± 0.03 ^d	0.03 ± 0.04 ^b	5.34 ± 2.00 ^d	0.65 ± 0.61 ^c

n : Number of samples ; av.P : Available phosphorus; Ca²⁺ : Exchangeable calcium; Mg²⁺ : Exchangeable magnesium; K⁺ : Exchangeable potassium; Na⁺ : Exchangeable sodium; CEC: Cationic exchangeable capacity; SBE : Sum exchangeable bases. Subscript letters following the data denote statistical similarities and differences among groups. Identical letters indicate that the compared groups are not significantly different. Distinct subscripts represent statistically significant differences in mean values, as determined by Tukey's multiple comparison test at the 5% significance level.

Supplementary Table 4. Mean soil fertility proxies of studied soil types: Coastal sedimentary sands (Kango site) and Ferralitic soils (Koula-Moutou site)

Soil types	n	Depth (cm)	BS (%)	Ca ²⁺ :Mg ²⁺	Mg ²⁺ :K ⁺
Coastal sedimentary sands	21	0-10	43.66 ± 14.32 ^a	3.16 ± 1.13 ^a	4.87 ± 1.62 ^a
		10-20	31.55 ± 10.03 ^{ab}	2.98 ± 1.77 ^a	4.32 ± 1.49 ^a
		20-30	32.00 ± 38.95 ^{ac}	3.01 ± 1.17 ^a	2.97 ± 1.34 ^b
Ferralitic soils	18	0-10	15.91 ± 14.00 ^{bc}	2.65 ± 1.11 ^a	2.22 ± 1.40 ^b
		10-20	13.17 ± 9.07 ^b	3.20 ± 1.29 ^a	2.04 ± 0.95 ^b
		20-30	14.02 ± 12.88 ^{bc}	3.10 ± 1.31 ^a	2.00 ± 1.17 ^b

n: Number of samples ; BS : Base saturation; Ca²⁺/Mg²⁺ : Calcium-to-Magnesium ratio; Mg²⁺/K⁺ : Magnesium –to-Potassium ratio. Subscript letters following the data denote statistical similarities and differences among groups. Identical letters indicate that the compared groups are not significantly different. Distinct subscripts represent statistically significant differences in mean values, as determined by Tukey's multiple comparison test at the 5% significance level.