



Non-linear soil health trajectories in smectitic Vertisols: Coupling sedimentary inheritance to long-term intensive cultivation in Am-Timan, Southeastern Chad

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ABSTRACT

Long-term cultivation can substantially reorganize soil physicochemical functioning in semi-arid agroecosystems, particularly in smectitic Vertisols developed from fine-grained alluvial deposits. This study assessed depth-dependent soil quality trajectories and the influence of sedimentary inheritance along a cultivation chronosequence in Southeastern Chad, comprising an uncultivated reference and fields cultivated for approximately 25, 35, and 50 years under continuous flood-recession sorghum production with glyphosate-based weed management. Soil samples were collected at 0–20, 20–40, and 40–60 cm depths and analysed for bulk density, electrical conductivity, particle-size distribution, soil organic matter and total nitrogen, available phosphorus, exchangeable base cations, cation exchange capacity, and derived soil quality indicators. Multivariate analyses, including principal component analysis and hierarchical clustering, revealed non-linear, vertically structured soil quality trajectories rather than a monotonic degradation gradient. The 25-year stage represented an early adjustment phase, characterized by profile-wide compaction, elevated pH, and incomplete structural recovery. The intermediate 35-year stage appeared to correspond to a transient phase exhibiting the strongest coupling between soil structure, base saturation, nutrient redistribution, and organic matter–nitrogen dynamics throughout the profile. In contrast, the 50 years stage showed evidence of long-term alteration, with weaker structure–fertility interactions, progressive, base-cation depletion, potassium limitation, and emerging subsoil constraints despite persistently high inherent cation exchange capacity inherited from the smectitic parent material. These results suggest that soil health in smectitic Vertisol is governed not by clay content or exchange capacity alone, but by the maintenance of effective exchange-site occupancy, aggregation, and nutrient cycling throughout the soil profile. Overall, the findings indicate that long-term cultivation reorganizes rather than overrides the inherited sedimentary template, resulting in non-linear and depth-dependent soil quality trajectories. From a management perspective, sustaining these systems requires residue retention, organic inputs, replenishment of base-cations and potassium, controlled traffic on wet clay soils, and regular monitoring of subsoil properties to preserve both surface and subsurface functioning in Sudano-Sahelian agroecosystems.

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1. Introduction

Long-term cultivation is a major driver of soil physicochemical reorganization in semi-arid agroecosystems, where seasonal water limitation, low external nutrient inputs, and continuous crop offtake can progressively alter soil structure, nutrient retention, and biological functioning. In such environments, soil degradation is often diagnosed from surface indicators, although long-term resilience may depend strongly on subsoil processes, including fine-particle redistribution, aggregate reorganization, base-cation dynamics, and organic matter stabilization. This is particularly relevant in deep clay-rich soils, where cultivation-induced changes may propagate vertically and generate soil responses that are not adequately captured by topsoil measurements alone (Tsozué et al., 2020; Peng et al., 2023; Ma et al., 2024; Franzuebbers et al., 2025).

Vertisols represent a distinctive case among semi-arid agricultural soils because their functioning is controlled by the dual role of smectitic clay mineralogy. On the one hand, high clay content and large cation exchange capacity confer substantial nutrient-retention capacity and chemical buffering. On the other hand, shrink-swell behaviour, deep cracking, self-mulching, seasonal swelling, and compaction sensitivity create strong structural constraints under cultivation. Recent studies on Vertisols and other shrink-swell soils have shown that clay mineralogy, wetting-drying cycles, and management history jointly regulate aggregation, hydraulic behaviour, potassium availability, and the persistence of soil organic carbon (Jayaraman et al., 2022; Schweizer et al., 2022; Niaz et al., 2023; Gurav et al., 2024; Barnard et al., 2025; Ponyane et al., 2025; Bhaskar et al., 2026). These characteristics imply that Vertisols may not respond to cultivation through a simple linear degradation pathway, but rather through progressive reorganization of structure-fertility coupling across the soil profile. In this study, soil health is used as the overarching functional concept describing the capacity of soil to sustain biological productivity, nutrient cycling, water regulation, and environmental quality. Soil quality is used in a more operational sense, referring to measurable physical and chemical indicators that diagnose changes in soil functioning. This distinction is essential because soil health cannot be inferred from individual properties alone, but from the extent to which soil structure, organic matter turnover, exchange capacity, nutrient retention, and ionic regulation remain functionally coupled. Recent soil health frameworks emphasize that soil functioning must be interpreted through integrated indicators and process-based relationships rather than through isolated measurements (Lehmann et al., 2020; Rieke et al., 2022; Feeney et al., 2024; Rabot et al., 2024). Accordingly, the present study uses soil quality indicators as diagnostic proxies for assessing depth-dependent soil health trajectories along a cultivation chronosequence.

A growing body of evidence indicates that soil responses to cultivation may involve non-linear or threshold-like transitions, particularly where management effects interact with inherited mineralogical and textural controls. In clay-rich soils, cultivation can initially enhance nutrient redistribution or aggregation under some management contexts, while prolonged use may progressively weaken base saturation, organic matter stabilization, and exchange-site occupancy (Peng et al., 2023; Ma et al., 2024; Mikha et al., 2024; Singh et al., 2025). However, empirical evidence for such trajectories remains limited in semi-arid African agroecosystems, especially for smectitic Vertisols under low-input cultivation. Most available assessments emphasize topsoil fertility or land-use contrasts, whereas depth-explicit chronosequence studies capable of detecting subsoil constraints and whole-profile functional transitions remain scarce.

The Sudano-Sahelian flood-recession systems of southeastern Chad provide a relevant setting for addressing this gap. In these systems, Vertisols developed on fine-grained alluvial parent materials support long-term sorghum cultivation after seasonal flooding. Flood-recession agriculture is a key production system in semi-arid West Africa, where crops are established after water recedes and external inputs are

generally limited (Traore et al., 2020). In southeastern Chad, this agricultural system combines continuous sorghum cultivation, glyphosate-based weed control, no mechanized tillage, and no systematic mineral fertilization or organic amendment (Mouaromba et al., 2025). Such management creates a specific context in which soil trajectories are likely to reflect the balance between inherited Vertisol buffering capacity, shrink-swell pedoturbation, residue-mediated nutrient cycling, and sustained nutrient export through harvest.

The parent-material context is particularly important. Fine-grained alluvial deposition establishes a clay-dominated sedimentary template that can precondition subsequent pedogenesis and cultivation responses. Long-term cultivation does not erase this inheritance, but may rework it through cracking, self-mulching, wetting-drying cycles, aggregate reorganization, and vertical redistribution of fine particles and exchangeable cations. This coupling between sedimentary inheritance and cultivation-induced reorganization is central to understanding why some Vertisol properties may improve at intermediate cultivation stages, while others deteriorate under prolonged use (Niaz et al., 2023; Raymond et al., 2023; Gurav et al., 2024; Ponyane et al., 2025; Bhaskar et al., 2026).

Despite the agronomic importance of these Vertisols, little is known about how their soil quality evolves over several decades of continuous flood-recession sorghum cultivation. In particular, it remains unclear whether cultivation induces gradual degradation, transient functional improvement, or threshold-like shifts in soil health. The role of subsoil processes is also poorly constrained, even though deep structure-fertility coupling may govern the long-term resilience of shrink-swell soils. Addressing this issue requires a depth-resolved approach that integrates soil physical properties, chemical functioning, exchangeable base cations, fertility indices, relative deviation from uncultivated reference conditions, and multivariate analyses. Addressing these issues is essential for understanding how inherited sedimentary characteristics interact with long-term cultivation to shape soil health trajectories in Sudano-Sahelian Vertisols.

This study evaluates depth-dependent soil physicochemical trajectories along a cultivation chronosequence in southeastern Chad, including an uncultivated reference and fields cultivated for approximately 25, 35, and 50 years under continuous flood-recession sorghum production. Specifically, we aimed to: (i) quantify changes in soil physical, chemical and fertility-related properties across soil depth and cultivation duration; (ii) determine whether cultivation induces monotonic degradation or threshold-like soil quality states; (iii) identify the dominant structure-fertility and organic-ionic gradients controlling Vertisol functioning; and (iv) derive management implications for sustaining both topsoil and subsoil health in Sudano-Sahelian agroecosystems. We hypothesize that smectitic Vertisol responses to cultivation are non-linear and depth-dependent, with an intermediate cultivation stage exhibiting enhanced structure-fertility coupling, whereas prolonged cultivation leads to progressive decoupling of physical and biogeochemical soil functions, particularly in deeper horizons.

2. Material and methods

2.1. Study area

The study was conducted in southeastern Chad, between latitudes 10°44'56.9" N and 11°21'34.54" N and longitudes 19°46'59.08" E and 20°14'19.5" E, from November 2022 to December 2023. Three cultivated sites located within the Am-Timan were selected to represent contrasting stages of long-term flood-recession sorghum cultivation: Darasna, in northeast, cultivated for approximately 25 years; Madina, in the southern sector, cultivated for approximately 35 years; and Goz-Mabile, in the western sector, cultivated for approximately 50 years (Figure S1). An uncultivated reference site was established in the Wachoun region, central Chad, under natural vegetation dominated by dense spontaneous

herbaceous cover reaching approximately 2 m in height.

The study area belongs to the Sahelo-Sudanian climatic zone (Aubréville, 1950), characterized by a marked alternation between a short rainy season lasting 3–4 months, with rainfall peaking in August, and a prolonged dry season lasting 5–8 months. Mean annual rainfall is estimated at 938.8 mm (Zagalo et al., 2018), and the P/ETP aridity index ranges from 0.09 to 0.2, indicating an arid to semi-arid conditions highly sensitive to interannual hydroclimatic variability (Olivry, 1996). This strong seasonal contrast is central to the functioning of the studied smectitic Vertisols, because repeated wetting during seasonal flooding and progressive drying during the post-flood recession period promote shrink–swell dynamics, cracking, self-mulching, and vertical redistribution of fine particles and soluble or exchangeable ions. The study sites are positioned across the transition between: Sudanian and Sahelian vegetation zones. The Sudanian zone is characterized by open forests formations dominated by *Combretaceae* and legume species, including *Acacia sieberiana*, *Acacia polyacantha*, *Anogeissus leiocarpus*, *Combretum nigricans*, *Combretum glutinosum*, and *Terminalia* spp. In contrast, the Sahelian zone is dominated by sparse shrublands and wooded savannas, with common species including *Acacia nilotica*, *Balanites aegyptiaca*, *Anogeissus leiocarpus*, *Ziziphus mauritiana*, and *Combretum glutinosum* (Binot, 2010). This vegetation gradient provides the broader ecological context within which natural organic inputs, root activity, and surface residue dynamics may influence soil organic matter turnover and structural development.

The cultivated fields support annual flood-recession sorghum production on smectitic Vertisols developed from fine-grained alluvial parent materials. In this production system, crop establishment follows the recession of seasonal floodwater, and soil functioning is therefore controlled by the interaction between inherited alluvial texture, seasonal hydrological forcing, and long-term low-input management. Across all cultivated sites, glyphosate was applied by smallholder farmers as the principal weed-management input. Herbicide-based weed control was carried out from late September to early October, before transplanting and at the onset of the cropping cycle, while harvesting generally occurred from February to March. The commercial isopropylamine-salt formulation was used at locally prevailing rates of 160 L·ha⁻¹ per application, corresponding to approximately 1.3 kg acid equivalent ha⁻¹ yr⁻¹. No mineral fertiliser, organic amendment, or mechanised tillage was applied, consistent with the low-input character of these systems. Within this management context, glyphosate-based weed control was considered as part of the broader cultivation system rather than as an isolated experimental factor. Its potential effects on soil functioning are likely to be indirect, through changes in weed biomass, residue return, living-root inputs, rhizosphere substrates, and organic matter turnover. In clay-rich Vertisols, glyphosate and its degradation products may also interact with clay minerals and organic matter, potentially influencing residue persistence and microbial exposure. However, glyphosate residues, microbial communities, and enzymatic activities were not directly measured in this study. Consequently, glyphosate management was treated as a contextual feature of the low-input sorghum system, and not as a directly quantified driver of the observed soil health trajectories (Kepler et al., 2020; Brochado et al., 2023; Sibalekile et al., 2025; Köninger et al., 2026).

Soil sampling was conducted using a stratified random design within each experimental plot. At each site, six independent soil profiles were described and sampled at three depths intervals: 0–20, 20–40 and 40–60 cm (Figure S2). This design provided 18 samples per site and a total of 72 samples across the four studied land-use stages. The three cultivated stages corresponded to single contiguous fields of known cultivation history: Darasna for the 25-year stage, Madina for the 35-year stage, and Goz-Mabile for the 50-year stage. Site-level replication within each cultivation stage was therefore provided by the six independent soil profiles sampled within each field, rather than by replicate fields of the same cultivation age.

Because each cultivation duration corresponded to a single field,

cultivation age was necessarily confounded with site. This limitation is inherent to the space-for-time chronosequence approach and was explicitly considered when interpreting the results. Accordingly, the chronosequence was used to represent relative stages of long-term Vertisol cultivation under comparable flood-recession sorghum management, rather than a strictly replicated temporal sequence. The study design therefore provides a depth-explicit framework for assessing how smectitic Vertisols developed on alluvial parent materials reorganize structurally and chemically under prolonged low-input cultivation.

2.2. Soil physicochemical analyses

All laboratory analyses were performed at UMR 242 iEES Paris Centre IRD, Bondy, Île-de-France, France. Bulk density (Bd) was determined using the core cylinder method. Particle-size distribution was assessed on air-dried, disturbed samples by dispersion and sedimentation using the pipette method. Soil dispersion was achieved with 1 M NaOH, and samples were mechanically agitated for 16 h to ensure complete separation of particles. Soil structural stability was quantified through the structural stability index (SI), according to Pieri's formula (Pieri, 1992).

Soil pH was measured in a 1:2.5 soil-to-water suspension with a glass electrode pH meter (Gutián Ojea and Carballas, 1976). Electrical conductivity (EC) was determined in the same 1:2.5 soil-to-water suspension used for pH, using a calibrated conductivity meter, and is reported in dS m⁻¹. Soil organic carbon (SOC) and total nitrogen (TN) were quantified using an elemental CHNS analyzer (Euro EA Elemental Analyzer, USA) coupled with an isotope ratio mass spectrometer (EA-IRMS), following standard protocols for dry combustion analysis.

Available phosphorus (P) was determined using the Bray No. 2 extraction method (Bray and Kurtz, 1945). Exchangeable bases (Ca²⁺, Mg²⁺, K⁺, and Na⁺) were extracted with 1 N ammonium acetate (pH 7) and analyzed by atomic absorption spectrophotometry. Cation exchange capacity (CEC) was measured by the ammonium acetate method at pH 7, followed by displacement with 1 N potassium chloride (KCl) to determine exchangeable sites (Sumner and Miller, 1996).

Relative deviation (Rd, %) of cultivated soils (C_s) compared to control (C_u) soils was calculated using the following expression (Tsozué et al., 2020):

$$R_d(\%) = \frac{C_s - C_u}{C_u} \times 100$$

2.3. Statistical analyses

Normality of the data was assessed using the Shapiro–Wilk test. For variables meeting the assumption of normality, differences among cultivation stages were evaluated using one-way ANOVA, while non-normally distributed variables were analyzed using the Kruskal–Wallis test. Where significant differences were detected, post hoc comparisons (Tukey's HSD test following one-way ANOVA, and Dunn's test with Bonferroni adjustment following the Kruskal–Wallis test) were performed. Relationships among soil properties were examined using Pearson's correlation. All statistical analyses were conducted at a 95% confidence level ($\alpha = 0.05$) using Python (Spyder IDE). The multivariate structure of the soil dataset was examined using two complementary ordination and classification techniques. Principal component analysis (PCA) was applied to the standardized (z-scored) soil variables to identify the dominant gradients of soil functioning, and sampling points were grouped by hierarchical agglomerative clustering (HAC) using Ward's linkage on Euclidean distances to delineate discrete soil-health states. The combined use of PCA and hierarchical clustering enabled the identification of both continuous functional gradients and discrete groupings within the cultivation chronosequence. Both analyses were performed in Python (Spyder IDE).

3. Results and Discussion

Soil physicochemical and fertility-related properties varied significantly with both cultivation duration and soil depth ($p < 0.05$; [Supplementary Material](#)), revealing pronounced vertical and temporal controls on smectitic Vertisols functioning. Rather than following a simple monotonic degradation pathway, soil quality evolved through distinct, threshold-like states governed by interactions among smectitic clay inheritance, shrink–swell dynamics, organic matter turnover, base-cation cycling. These dynamics collectively indicate that Vertisol functioning is governed by non-linear feedbacks between inherited mineralogy and management-driven pedogenic reorganization rather than linear depletion processes. The sections below develop this interpretation along a purposive sequence: from the sedimentary substrate that

conditions all subsequent processes, through depth-resolved physical reorganization and chemical functioning, to fertility dynamics, integrated soil quality trajectories, and, finally, their management implications.

3.1. Textural inheritance and its role as a pedogenic template

Interpreting depth-dependent cultivation responses in these Vertisols requires first establishing the sedimentary template from which all pedogenic reorganization proceeds. Clay content remained high and relatively uniform with depth in all cultivated plots (62–70%) ([Fig. 1a](#)), confirming the dominance of smectitic clays throughout the profile and the persistence of shrink–swell processes at depth. In contrast, the uncultivated control showed significantly lower clay contents (49–54%, p

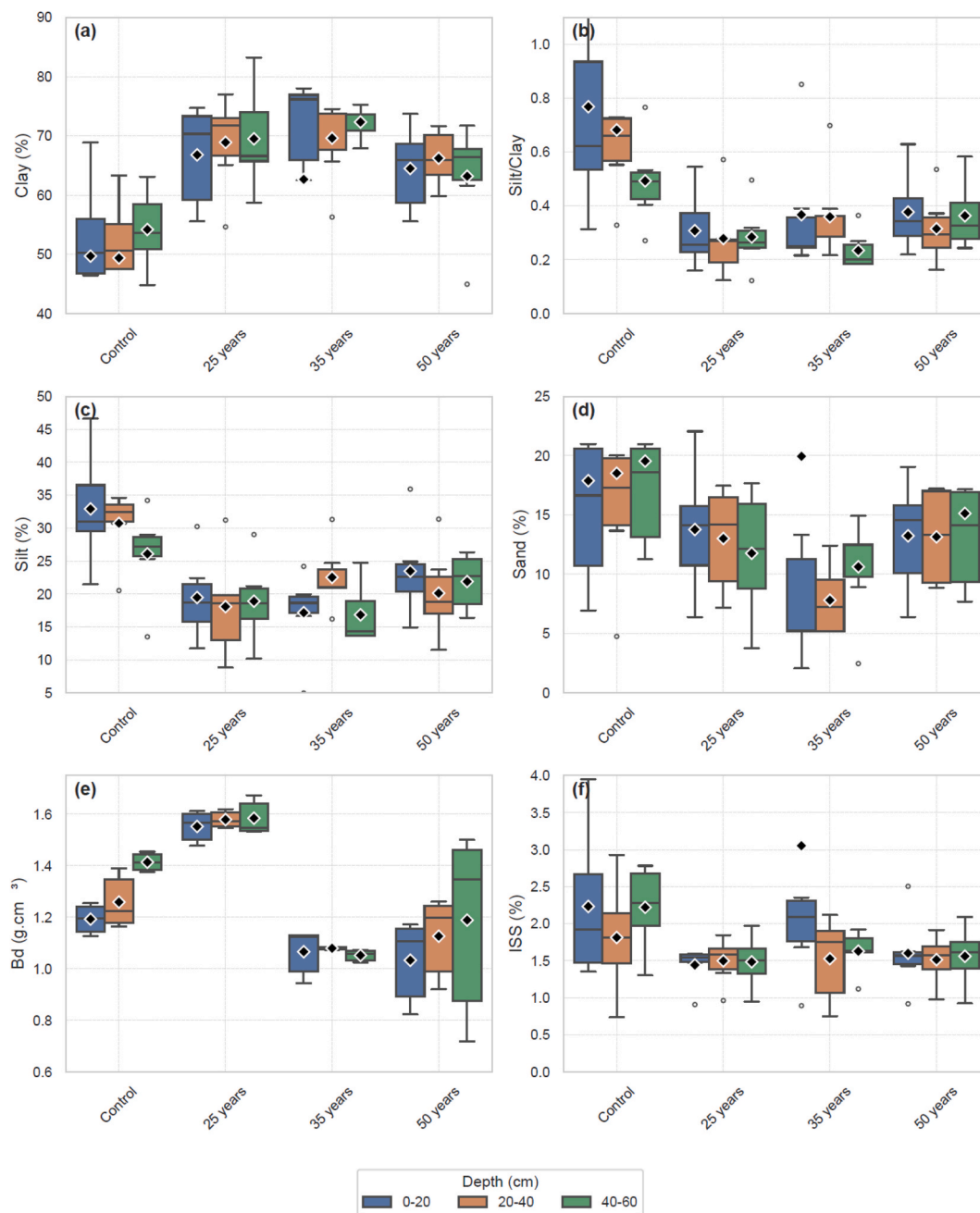


Fig. 1. Depth-specific variation in particle-size distribution (clay, silt, and sand), bulk density and structural stability index (ISS) under contrasting cultivation durations. Boxplots display the 25th–75th percentile range (interquartile range), with the median indicated by a solid line, the mean represented by a diamond symbol, and outliers shown as individual points.

< 0.05) and higher silt proportions (26–33%) (Fig. 1b), yielding elevated silt/clay ratios (0.50–0.77) (Fig. 1c; Table S1). Cultivated plots consistently exhibited low silt/clay ratios (0.23–0.38), particularly in surface horizons, indicating stronger aggregation and reduced textural heterogeneity along the profile (Hamza et al., 2025; Isabokey et al., 2025; Li et al., 2025).

This textural organisation is, in the first instance, inherited from the fine-grained alluvial parent material deposited by repeated flood-recession events, which establishes a smectite-rich, clay-dominated sedimentary template prior to any cultivation (Traore et al., 2020; Sharma et al., 2022; Raymond et al., 2023). Long-term cropping does not erase this sedimentary inheritance but reworks it, redistributing fine particles and reorganising aggregation along the profile (Jayaraman et al., 2022; Schweizer et al., 2022; Niaz et al., 2023; Ponyane et al., 2025). The coupling between this depositional substrate and cultivation-driven reorganisation is therefore central to interpreting the depth-dependent trajectories reported in subsequent sections, particularly in smectite Vertisols, where inheritance-driven homogeneity interacts with vertic mixing to produce apparent pedogenic convergence over time (Bhaskar et al., 2026; Pagouo et al., 2026). Higher silt contents and elevated silt/clay ratios in uncultivated control likely reflect reduced aggregation and pedogenic mixing, leading to greater expression of original textural heterogeneity (Yakubu and Ojanuga, 2013; Onwudike, 2015; Temga et al., 2019).

Particle-size fractions showed the expected internal organization: clay was strongly and negatively correlated ($r = -1.0$; $p = 0.00$) with sand content and the silt/clay ratio (Fig. 1c–d), confirming the dominance of fine fractions in controlling smectitic Vertisol behavior. The uniformity of clay content and colour in these profiles are also consistent to regular profile homogenisation through vertic movements, which promote deep mixing of the soil column and reinforce the clay-dominated template across all depths (Basga et al., 2018; Tamfuh et al., 2011; Bhaskar et al., 2026; Pagouo et al., 2026). This smectitic foundation—setting inherently high cation exchange capacity ($\text{CEC} > 15 \text{ cmol kg}^{-1}$) and strong shrink–swell potential—acts simultaneously as a resilience buffer and a structural constraint (Gurav et al., 2024; Raymond et al., 2023). It enhances nutrient-retention capacity and aggregate reorganisation through wetting–drying cycles, but also conditions the magnitude and reversibility of cultivation-induced changes in soil structure, ionic regulation and fertility functioning (Jayaraman et al., 2022; Schweizer et al., 2022; Niaz et al., 2023; Ponyane et al., 2025).

3.2. Depth-dependent physical reorganisation: compaction, structural loosening, and aggregate dynamics

Against this textural background, cultivation duration induced a clear and non-monotonic reorganization of soil physical properties. Bulk density (Bd) exhibited a strong interaction between cultivation duration and depth (Fig. 1e; Table S2). Recently cultivated plots (25 years) showed consistently elevated Bd values across the entire profile ($1.55\text{--}1.59 \text{ g cm}^{-3}$), indicating a vertically propagated compaction state following land-use conversion. In contrast, the 35-year plots displayed markedly lower Bd values at all depths ($1.05\text{--}1.08 \text{ g cm}^{-3}$), reflecting progressive structural loosening not confined to the surface layer but extending into the subsurface. The 50-year plots showed intermediate Bd values ($1.03\text{--}1.19 \text{ g cm}^{-3}$), suggesting partial structural degradation at depth under prolonged cultivation. The uncultivated control exhibited moderate Bd values ($1.19\text{--}1.41 \text{ g cm}^{-3}$) that increased with depth, consistent with natural subsoil densification in Vertisols (Panagos et al., 2024; Abshiba et al., 2025; Mouaromba et al., 2025). This suggests that cultivated systems may temporarily exceed natural systems in structural efficiency before long-term degradation processes dominate.

The index of structural stability (ISS) exhibited a complementary depth-dependent response (Fig. 1f). Across all treatments, ISS values remained well below the 5% threshold for structural stability (Pieri, 1992), yet relative differences were informative. The highest ISS was

recorded in the surface layer (0–20 cm) of the 35-year plots ($\text{ISS} = 3\%$), suggesting localized improvement driven by biological activity and repeated shrink–swell cycles (Witzgall et al., 2024; Hamza et al., 2025; Su et al., 2025). ISS values generally declined with depth, with the lowest subsoil values observed in the 25- and 50-year plots, reflecting incomplete structural recovery under moderate-term cultivation and structural fatigue under prolonged cultivation, respectively (Martlew et al., 2023; Peng et al., 2023; Rezapour et al., 2024). Interestingly, the uncultivated control exhibited higher subsoil ISS in the subsoil (40–60 cm; $\text{ISS} = 2\%$) than most cultivated plots (Table S2), indicating that long-term cultivation may exacerbate structural degradation at depth even when surface conditions appear adequate (Liebhard et al., 2025; Cui et al., 2026).

Bulk density (Bd) was positively correlated with sand ($r = 0.4$; $p = 0.16$) and negatively correlated with clay content ($r = -0.4$; $p = 0.16$) and ISS ($r = -0.4$; $p = 0.16$) (Fig. S3), indicating that clay-rich conditions favour lower compaction when aggregation processes are sufficiently developed. Mechanistically, this pattern is consistent with the progressive action of smectitic shrink–swell cycling in Vertisols. Repeated wetting during the flood-recession phase and desiccation through the prolonged dry season drive successive volumetric expansion and contraction, generating deep cracking, self-mulching, and the downward translocation of surface material into desiccation cracks (Traore et al., 2020; Niaz et al., 2023; Bhaskar et al., 2026). Over several decades, this pedoturbation can promote profile homogenisation, aggregates reorganisation and partial relaxation post-conversion compaction, allowing structural improvement to extend below the topsoil (>0–20 cm) (Jayaraman et al., 2022; Schweizer et al., 2022; Ponyane et al., 2025). The 35-year stage likely represents the point at which repeated wetting–drying cycles have sufficiently promoted vertic cracking, self-mulching, downward redistribution of surface material, and aggregate reorganization to offset the compaction inherited from earlier cultivation. In this phase, shrink–swell pedoturbation appears to operate in concert with organic matter turnover and $\text{Ca}^{2+}/\text{Mg}^{2+}$ -mediated flocculation, thereby strengthening structure–fertility coupling across the profile. The subsequent weakening observed after 50 years suggests that this regenerative mechanism becomes insufficient when nutrient export, limited organic inputs, K^+ depletion, and base-cation decline progressively reduce the capacity of the soil matrix to sustain aggregation and subsoil fertility. The intermediate (35-year) stage appears to represent the point at which this regenerative process is most effective, as reflected by the lowest Bd, the highest ISS, and the strongest profile-wide coherence of physical properties. Beyond this duration, sustained cultivation limited organic inputs may weaken biological aggregation processes and reduce the capacity of shrink–swell dynamics to offset structural degradation, explaining the partial structural decline observed after 50 years (Du et al., 2024; Nachimuthu et al., 2025; Ponyane et al., 2025). These processes collectively generate a self-organising structural regime in which physical degradation and regeneration co-occur across different depth domains.

3.3. Chemical functioning: pH dynamics, ionic intensity and organic matter turnover

Physical reorganization sets the structural context within which chemical processes unfold. Soil pH varied significantly with both cultivation duration and depth (Fig. 2a; Table S3). The 25-year cultivated plots showed the highest pH values (7.4–7.6) throughout the profile, reflecting a transient alkalisation associated with the release of basic cations during sorghum residue mineralization under no-tillage flood-recession management (Kaduwal et al., 2023; Sadiq et al., 2025). The 35-year plots exhibited the lowest pH (6.2–6.3) at all depths, indicating progressive acidification driven by sustained nutrient export through harvest, depletion of exchangeable bases, and proton generation associated with organic matter mineralisation and nitrogen cycling. The 50-year plots showed intermediate pH values (6.7–6.8), suggesting partial

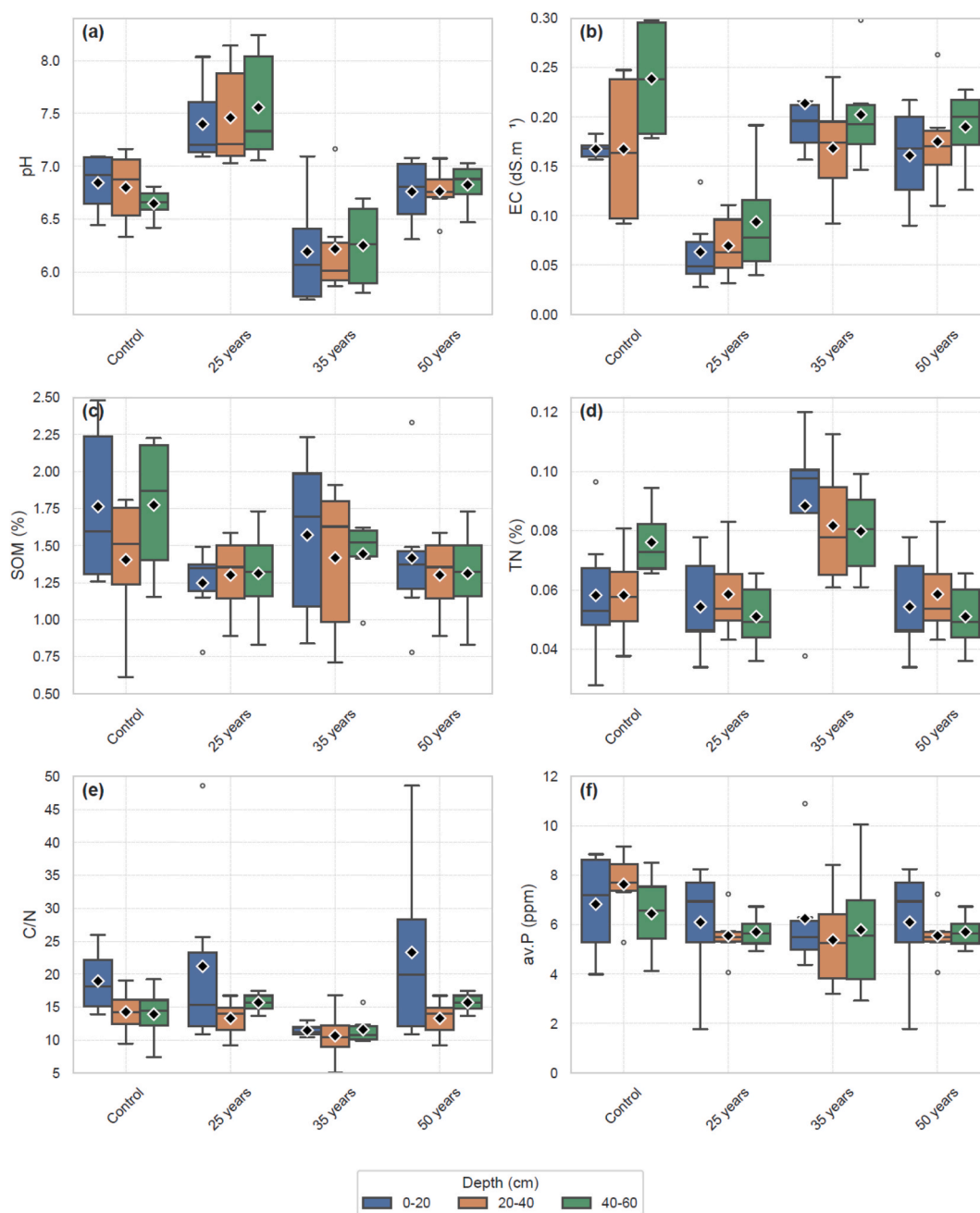


Fig. 2. Depth-related variation in pH, electrical conductivity (EC), soil organic matter (SOM), total nitrogen (TN), C/N ratio, and available phosphorus (av. P) under contrasting cultivation durations. Box plot elements as in Fig. 2.

recovery or stabilisation, likely reflecting the inherent buffering capacity of the smectitic exchange complex and the gradual establishment of a new soil–plant equilibrium. The uncultivated control displayed a slight pH decrease with depth (6.6–6.8), consistent with natural leaching dynamics under limited external inputs (Ma et al., 2024; Chen et al., 2025; Wang et al., 2025).

Soil pH was positively correlated ($r = 0.40$; $p = 0.60$) with exchangeable Ca^{2+} and Mg^{2+} , total exchangeable bases (TEB) and $\text{Ca}^{2+}/\text{Mg}^{2+}$ ratio (Fig. S3), reflecting the buffering role of base saturation in smectitic Vertisols. Negative correlations between pH and SOM ($r = -0.80$; $p = 0.20$), TN ($r = -0.95$; $p = 0.05$), and C/N ($r = -0.80$; $p = 0.20$) indicate that organic matter accumulation and nitrogen enrichment are associated with localized acidification and intensified nutrient cycling, particularly in surface horizons (Mauclet et al., 2023; Suswati, 2023). This interplay base inputs and organic matter turnover shapes soil

chemical health across cultivation stages, with implications for nutrient availability and long-term buffering capacity (Dong et al., 2022; Souza et al., 2023; Mouaromba et al., 2025).

Electrical conductivity (EC) varied significantly ($p < 0.05$) with cultivation duration and depth (Fig. 2b, Table S3), with highest values observed in the subsoil of the control (0.24 dS.m^{-1}) and in the surface layer of the 35-year plots (0.21 dS.m^{-1}). Critically, absolute EC values remained far below the 4 dS.m^{-1} threshold commonly used to define saline soils, indicating that the observed EC variation reflects nutrient-related ionic redistribution rather than incipient salinity. In these clay-rich, shrink–swell Vertisols, EC should therefore be interpreted as an indicator of ionic intensity associated with soluble and exchangeable nutrient pools, rather than as evidence of salinity or sodicity stress (Ismayilov et al., 2021; Basak et al., 2023; Kim and Park, 2024; Rieder et al., 2024). The positive association of EC with exchangeable Ca^{2+} ,

Mg^{2+} , Na^+ and TEB ($r < 0.60$; $p > 0.60$) further supports this interpretation. Conversely, the absence of a positive relationship between EC, Bd ($r = -0.80$; $p = 0.20$) or silt/clay ratio ($r = -0.20$; $p = 0.80$) (Fig. S3) suggests that ionic enrichment occurred without structural dispersion. This is consistent with evidence that clay-rich soils are structurally sensitive to the balance between EC and exchangeable cation composition, with Ca^{2+} - and Mg^{2+} -dominated systems favouring flocculation and structural stability relative to Na-dominated systems (Adeyemo et al., 2022; Zhu et al., 2020; Vieira et al., 2025).

Soil organic matter (SOM) and total nitrogen (TN) exhibited relatively weak responses to cultivation duration in cultivated plots ($p > 0.05$ for differences among 25-, 35-, and 50-year stages; Fig. 2c-d; Table S3) but showed pronounced vertical stratification, () higher values in surface horizons declining with depth (Okolo et al., 2023; Yang et al., 2024; Omwoyo et al., 2025). The uncultivated control retained higher SOM ($\sim 1.77\%$) and TN ($0.06\text{--}0.08\%$) at all depths (Table S3), indicating greater organic matter preservation under natural conditions. These patterns are consistent with the low-input management character of the system: continuous flood-recession sorghum cultivation under glyphosate-based weed control, without mineral fertilisation or tillage, provides little external nutrient replenishment while sustaining continuous crop offtake (Traore et al., 2020; Ludemann et al., 2023; Chiriach et al., 2025). Consequently, bulk organic-matter and nitrogen stocks are buffered against cultivation duration per se but remain strongly structured by depth and by the cultivated-versus-natural land-use contrast (Murindangabo et al., 2023; Okolo et al., 2023).

In contrast to bulk SOM and TN, the C/N ratio showed strong sensitivity to both depth and cultivation duration, with the lowest values consistently observed in the 35-year plots ($10.63 < \text{C/N} < 11.57$) across the profile (Fig. 2e; Table S3), indicating enhanced mineralisation and tighter carbon–nitrogen coupling at the intermediate cultivation stage (Lorenz et al., 2025; Skadell et al., 2025; Song et al., 2025; Xin et al.,

2025). Strong positive correlations between SOM and TN ($r = 0.74$; $p = 0.26$), coupled with their negative relationship with C/N (SOM: $r = -0.80$; $p = 0.20$; TN: $r = -0.95$; $p = 0.05$) (Fig. S3), confirm progressive organic matter mineralisation and nitrogen enrichment with cultivation (Chiriach et al., 2025; Lorenz et al., 2025; Shoumik et al., 2025).

Available phosphorus (P) showed limited sensitivity to cultivation duration but varied with depth, with higher values in the control (6.45–7.64 ppm) (Fig. 2f; Table S3), suggesting that vertical P redistribution is governed more by mineral interactions and biological uptake than by cultivation duration alone in these clay-rich soils (Jian et al., 2022; Gupta et al., 2023; Li et al., 2024; McKenna et al., 2024). Available P was positively correlated with SOM and ISS ($r = 0.95$; $p = 0.05$), TN $r = 0.78$; $p = 0.22$), and cation exchange capacity (CEC) ($r = 0.74$; $p = 0.26$) (Fig. S3), emphasizing the role of organo-mineral interactions and aggregate protection in regulating P availability—a functional link that is strongest at the intermediate cultivation stage and weakens under prolonged management (Li et al., 2020; Tian et al., 2021; Jindo et al., 2023; Zhang et al., 2024; Hamza et al., 2025). This suggests strong geochemical control of P availability in smectitic systems, dominated by sorption and organo-mineral stabilization rather than management intensity.

3.4. Fertility dynamics: vertical distribution of base cations and exchange complex functioning

The functional consequences of the structural and chemical changes described above are most clearly expressed in the behaviour of the exchange complex and its vertical organisation. Exchangeable base cations exhibited strong vertical gradients modulated by cultivation duration. Calcium (Ca^{2+}) and magnesium (Mg^{2+}) dominated the exchange complex and increased with depth in the 25- and 35-year plots (Fig. 3a-b; Table S4), indicating downward translocation and subsoil enrichment

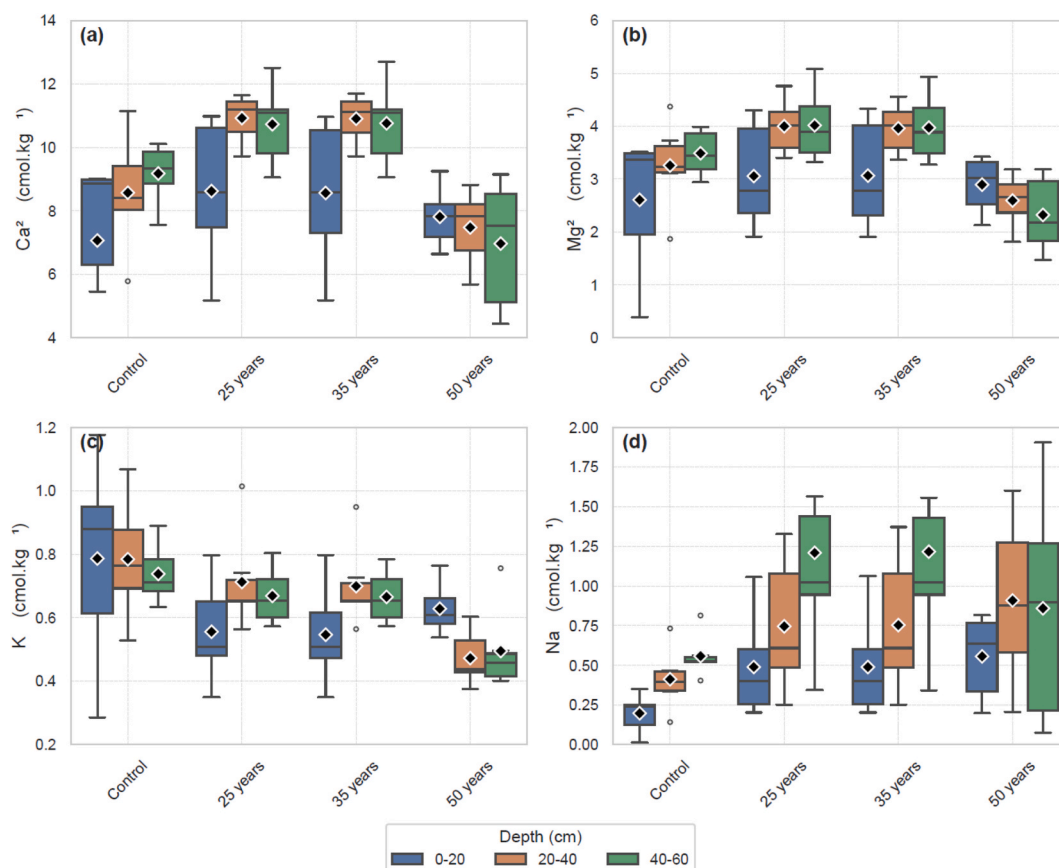


Fig. 3. Depth-dependent variation in exchangeable base cations (Ca^{2+} , Mg^{2+} , K^+ , and Na^+) under contrasting cultivation durations. Box plot elements as in Fig. 2.

over time (Kassie et al., 2025; Lv et al., 2024; Ma et al., 2024). In contrast, significantly lower Ca^{2+} ($6.96 \text{ cmol.kg}^{-1}$) and Mg^{2+} ($2.32 \text{ cmol.kg}^{-1}$) contents in the subsoil of the 50-year plots indicate progressive base depletion or redistribution under long-term cultivation, consistent with sustained crop offtake without replenishment.

Potassium (K^+) was relatively stable in surface horizons but declined significantly with depth in the 50-year plots (from $0.63 \text{ cmol.kg}^{-1}$ to $0.47 \text{ cmol.kg}^{-1}$) (Fig. 3c), reflecting cumulative crop uptake and limited replenishment in deeper layers (Correndo et al., 2021; Artuso et al., 2024; Nath et al., 2025). Sodium (Na^+) showed higher concentrations in the subsoil of the 25-years ($1.21 \text{ cmol.kg}^{-1}$) and 35-years plots ($1.21 \text{ cmol.kg}^{-1}$) (Fig. 3d, Table S4) but remained below sodicity thresholds, indicating base enrichment without structural risk (Andrade Foronda and Colinet, 2023; Ponyane et al., 2025).

Total exchangeable bases (TEB) and base saturation (BS) showed

strong depth-dependent responses to cultivation duration (Fig. 4a-b; Table S4-5). The highest values were consistently observed in the 25- and 35-year plots across all depths, particularly in subsoil layers, indicating efficient vertical retention of bases (Zhang et al., 2023; Ji et al., 2024; Ma et al., 2024). In contrast, significantly lower TEB ($10.62\text{--}11.89 \text{ cmol.kg}^{-1}$) and BS ($63\text{--}70\%$) values in the 50-year plots at depth reflect reduced buffering capacity under prolonged cultivation. CEC remained high ($> 15 \text{ cmol.kg}^{-1}$) across all cultivation duration and depths (Fig. 4c), reflecting the smectitic mineralogy of the Vertisol (Gurav et al., 2024; Barnard et al., 2025; Mouaromba et al., 2025). However, the CEC/clay ratio clearly distinguished cultivated plots from the control ($36\text{--}41\%$) throughout the profile (Fig. 4d; Table S5), with lower values ($24\text{--}27\%$) under cultivation indicating reduced effective charge per unit clay, attributable to aggregation and organo-mineral interactions that restrict exchange-site accessibility (Bi et al., 2023; Zhu and Sun, 2024;

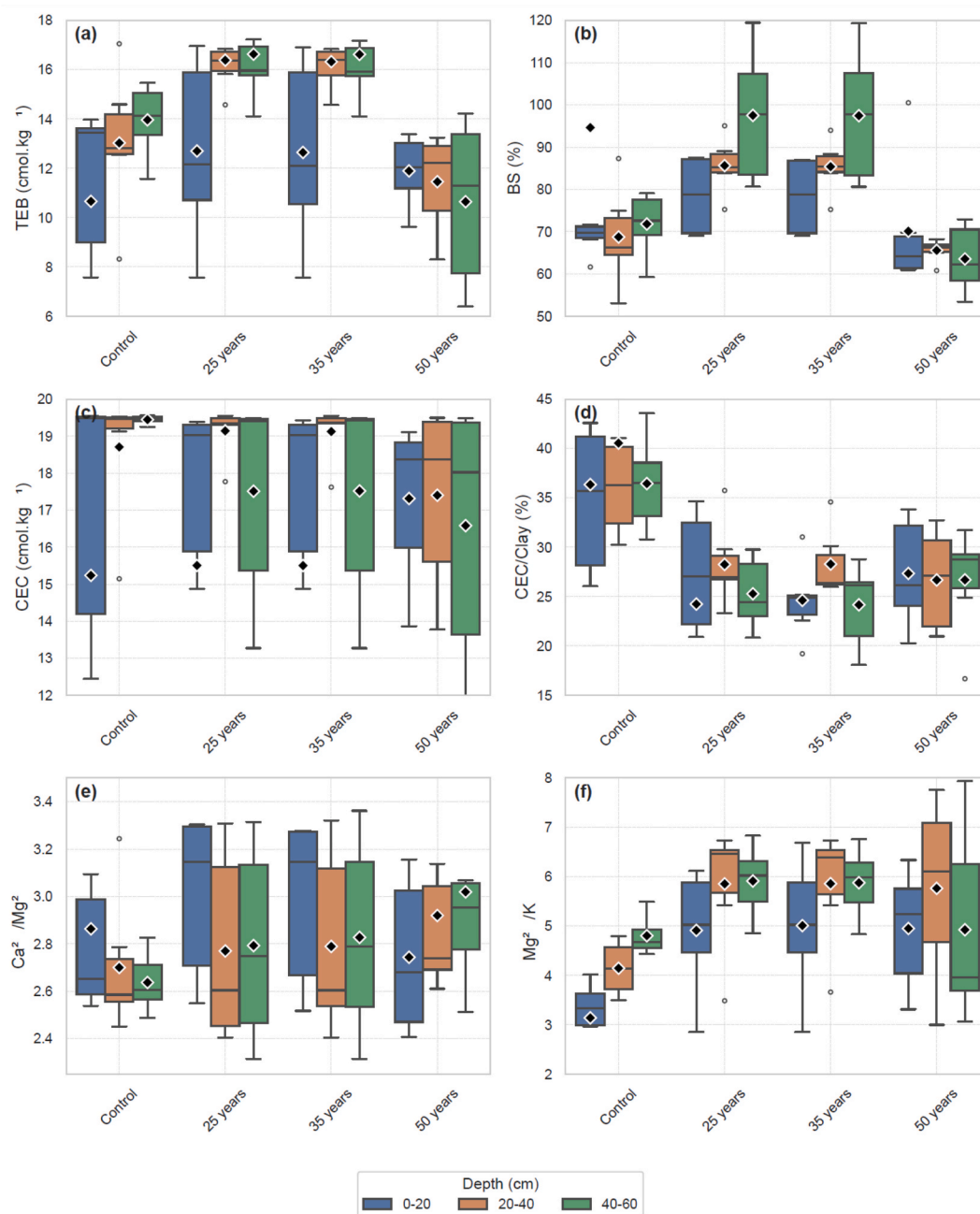


Fig. 4. Variation in total exchangeable bases (TEB), base saturation (BS), cation exchange capacity (CEC), clay-normalized CEC (CEC/clay) and exchangeable cation ratios ($\text{Ca}^{2+}/\text{Mg}^{2+}$ and $\text{Mg}^{2+}/\text{K}^+$) under contrasting cultivation durations. Box plot elements as in Fig. 2.

Abile et al., 2025). The CEC/clay ratio was negatively correlated with clay content ($r = -1.00$; $p = 0.00$) but positively correlated with the silt/clay ratio ($r = 1.00$; $p = 0.00$) (Fig. S3), confirming that structurally stable, clay-dominated systems exhibit lower apparent charge per unit clay due to stronger aggregation—a distinction with important implications for interpreting the relationship between inherent exchange capacity and effective fertility (Jones et al., 2021; Bi et al., 2023; Rabot et al., 2024). However, declining CEC/clay ratios in cultivated systems indicate that effective charge accessibility is reduced by aggregation and organo-mineral complexation, decoupling inherent mineral potential from functional fertility expression.

Cation balance indicators further discriminated soil health states. Balanced $\text{Ca}^{2+}/\text{Mg}^{2+}$ (2.77–4.23) and $\text{Mg}^{2+}/\text{K}^+$ (4.91–5.91) ratios in the 25-year and 35-year plots were strongly associated with high ISS and BS (Fig. S3; Fig. 4e–f; Table S5), underscoring their relevance as depth-integrated indicators of soil health under prolonged cultivation in smectitic Vertisols. In the 50-year plots, the $\text{Ca}^{2+}/\text{Mg}^{2+}$ ratio remained positive (Rd = +5.89%) but K^+ depletion was pronounced (Rd = −30.91%) (Fig. S4; Table S6), indicating a growing cation imbalance that could constrain plant nutrition and further weaken aggregate stability through reduced divalent-cation bridging at exchange sites (Bronick and Lal, 2005; Rengasamy et al., 2022; Pessoa et al., 2024).

3.5. Non-linear stage-dependent deviation patterns

The relative deviation analysis (Rd, %) confirmed that cultivation effects are not expressed as a monotonic degradation trend but as a non-linear sequence of contrasting structural, chemical, and fertility responses (Fig. S4; Table S6). Texture-related indicators displayed some of the largest deviations: clay content increased by +33.86%, +40.63%, and +26.49% after 25, 35, and 50 years of cultivation, respectively, while the silt/clay ratio showed strongly negative deviations (−55.18%, −55.33%, and −45.60%), with the strongest textural contrast at the intermediate stage.

Soil physical indicators showed contrasting responses consistent with the three-phase interpretation developed above. Bulk density increased markedly in the 25-year plots (Rd = +21.96%), reflecting early compaction, but decreased in the 35- and 50-year plots (Rd = −16.76% and −13.42%, respectively), indicating partial structural reorganisation (Mattila and Häkkinen, 2025; Ćopić et al., 2025; Hewelke et al., 2026). ISS remained negative at all cultivation stages (Rd = −29.39%, −21.01%, and −25.37%), demonstrating that the reduction in Bd in older cultivated plots did not correspond to full aggregate stability recovery—a partial decoupling between bulk-density dynamics and aggregate stability that underscores the importance of monitoring both indicators simultaneously.

Chemical properties exhibited stage-specific responses. The most diagnostic pattern is the trajectory of TN: negative deviations in the 25- and 50-year plots (both −14.06%), but a marked positive deviation in the 35-year plots (+29.69%), coupled with a sharp decline in the C/N ratio (Rd = −28.63%) at the same stage. This signals maximum nitrogen enrichment and tightest carbon–nitrogen coupling at the intermediate cultivation duration, consistent with the peak in mineralization activity and biological functioning at 35 years (He et al., 2023; Zou et al., 2024; Lorenz et al., 2025; Wang et al., 2025b). Available P remained consistently depleted across all cultivated plots (Rd = −17.00%, −15.48%, and −17.00%), indicating persistent phosphorus limitation independent of cultivation duration—a constraint attributed to strong mineral sorption in these clay-rich, high-CEC soils (Yang et al., 2024; Singh et al., 2025; Wang et al., 2025).

Exchangeable Ca^{2+} and Mg^{2+} increased in the 25- and 35-year plots (Rd = +22.01% and +23.87% for Ca^{2+} ; +18.38% and +20.17% for Mg^{2+}) but declined in the 50-year plots (Rd = −10.30% for Ca^{2+} ; −16.48% for Mg^{2+}), signalling the onset of base depletion under long-term cultivation (Dong et al., 2022; Lv et al., 2024; Ma et al., 2024). K^+ was depleted at all stages, increasingly so after 50 years (Rd =

−30.91%). Na^+ showed the largest positive deviations among all measured variables (+99–115%), reflecting base enrichment without structural risk at all cultivation durations. Integrated fertility indicators confirmed these patterns: BS decreased from +57.93% at 25 years to +8.90% at 35 years and then to −15.28% at 50 years, indicating that exchange capacity was broadly maintained but effective base occupancy progressively weakened under long-term cultivation (Ma et al., 2024; Kabala et al., 2025). Taken together, these Rd patterns support the interpretation that the 35-year stage represents a transient but functionally coherent condition, whereas both shorter and prolonged cultivation stages are associated with structural incompleteness or emerging subsoil fertility constraints.

3.6. Multivariate soil quality gradients and soil health states

The principal components analysis (PCA) biplot and hierarchical agglomerative clustering (HAC) corroborated and extended the Rd results by revealing the multivariate architecture of smectitic Vertisol soil quality along the cultivation gradient (Fig. 5a–b). The first two principal components explained 81.0% of the total variance (PC1: 53.5%; PC2: 27.5%), indicating that a limited set of coupled processes governs soil functioning across cultivation stages.

PC1 represents a dominant structure–fertility gradient: positive loadings were associated with clay content, ISS, Ca^{2+} , Mg^{2+} , TEB, CEC, BS, and balanced $\text{Ca}^{2+}/\text{Mg}^{2+}$ and $\text{Mg}^{2+}/\text{K}^+$ ratios, while negative loadings were linked to sand, silt, silt/clay ratio, and Bd. This axis captures the central role of clay-controlled aggregation and base saturation in regulating smectitic Vertisol structural stability and nutrients retention. PC2 captures a complementary organic–ionic gradient, dominated by SOM, TN, C/N, available P, EC, and Na^+ , reflecting variability in organic matter turnover, nutrient availability, and ionic intensity. Together, these axes depict soil quality as the outcome of tightly coupled physical, chemical, and biological processes rather than isolated properties (Lal, 2015; FAO/GSP, 2017; Karlen et al., 2019).

The HAC grouped plots according to cultivation duration and overall soil functioning (Fig. 5b). The close clustering of the 25- and 35-year plots indicates progressive improvement in soil quality during the first decades of cultivation, while the separation of the 50-year plot from this cluster reflects divergence toward a distinct soil health state. The uncultivated control formed an independent branch, confirming its contrasting physicochemical organization. This hierarchical structure supports the existence of distinct soil health states along a cultivation gradient (Fig. S5a–b):

- i. an adjustment phase (~25 years) : profile-wide compaction and incomplete structural organization, early base enrichment, elevated pH, but weakened ionic regulation;
- ii. an optimal functioning phase (~35 years): strong structure–fertility–carbon coupling, lowest Bd, highest ISS propagation, balanced cation ratios, high BS and TEB, and elevated ionic intensity without structural penalty;
- iii. a long-term alteration phase (≥ 50 years): progressive structure–fertility decoupling at depth, weakened BS, K^+ depletion, and reduced subsoil buffering capacity despite persistently high CEC.

ISS emerged as a pivotal integrating variable in both the correlation structure and the PCA. Its positive correlations with SOM, TN, Ca^{2+} , Mg^{2+} and available P ($r > 1.00$; $p < 0.26$), and its negative correlations with Bd and the silt/clay ratio ($r = -0.40$; $p = 0.60$), confirm that cultivation duration shapes soil health primarily by reinforcing or weakening the mechanisms that stabilize aggregates through organic binding agents and divalent-cation bridging. Systems where this coupling is strongest—typically at intermediate cultivation stage—exhibit greater resilience to compaction and structural degradation (Rieke et al., 2022; Mikha et al., 2024; Ponyane et al., 2025).

The uncultivated control was distinctly separated from cultivated

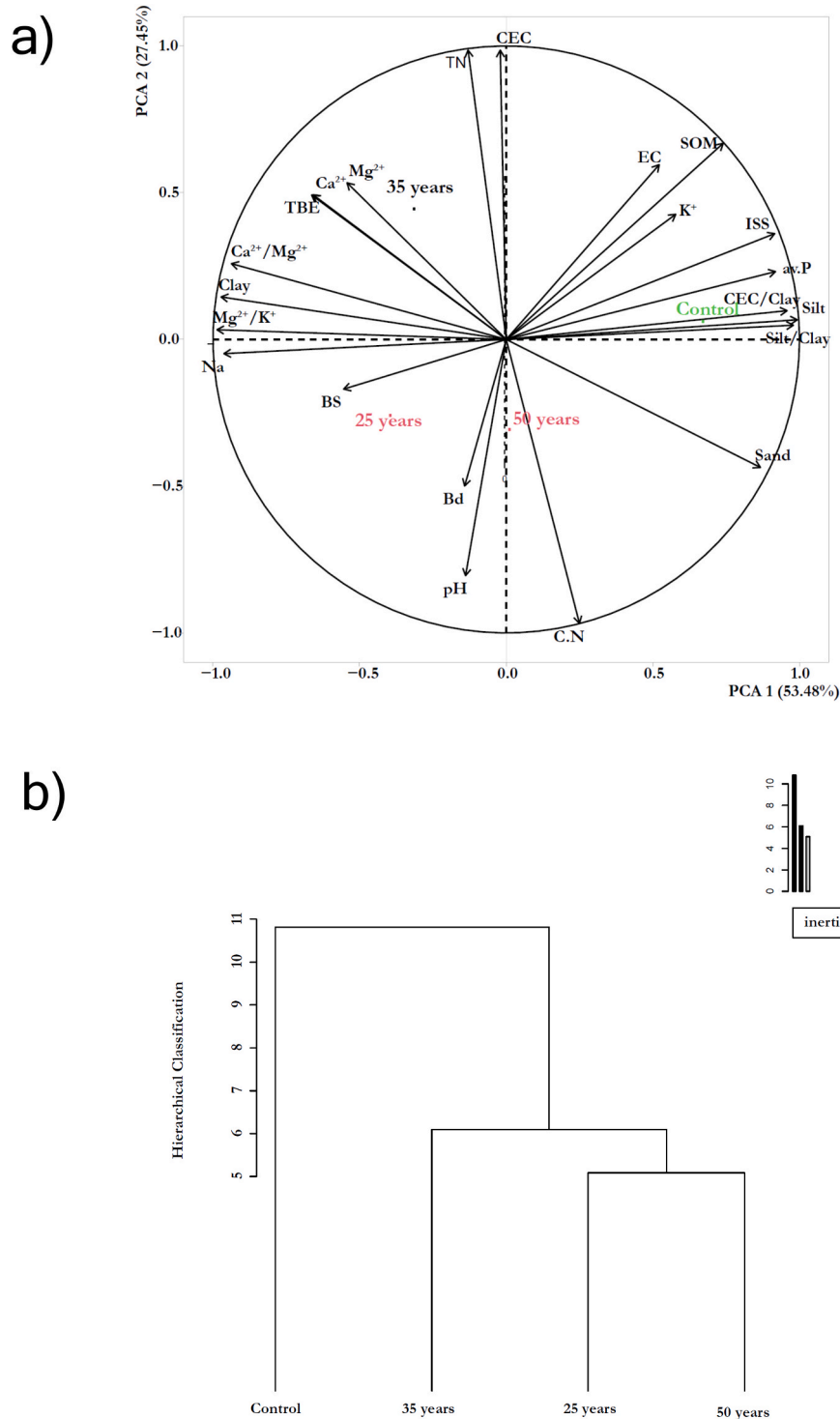


Fig. 5. (a): Principal component analysis (PCA) biplot showing relationships among soil properties and discrimination of cultivation durations along the first two principal components (PC1 and PC2); (b): Hierarchical clustering of cultivation durations based on multivariate soil property patterns, with associated inertia gain.

plots and associated with higher silt content, elevated silt/clay and CEC/clay ratios, and lower structural integration, confirming that natural Vertisol systems maintain a different physicochemical equilibrium—one characterized by high potential exchange capacity but lower effective aggregation and base-driven fertility compared with well-structured cultivated systems (Ponyane et al., 2025). This confirms the interpretation that long-term cultivation, when not exceeding critical thresholds, can develop structural and fertility organization that exceeds the uncultivated reference in functional terms, while also demonstrating the

risk of degradation at extended cultivation durations.

3.7. Alignment with global health frameworks

The non-linear, threshold-like trajectories identified here can be directly interpreted through three internationally recognized soil health frameworks (Fig. 6a). Under the FAO soil health framework (FAO, 2015; FAO/GSP, 2017), soil health soils is defined by the capacity to sustain biological productivity, regulate water and nutrient flows, and

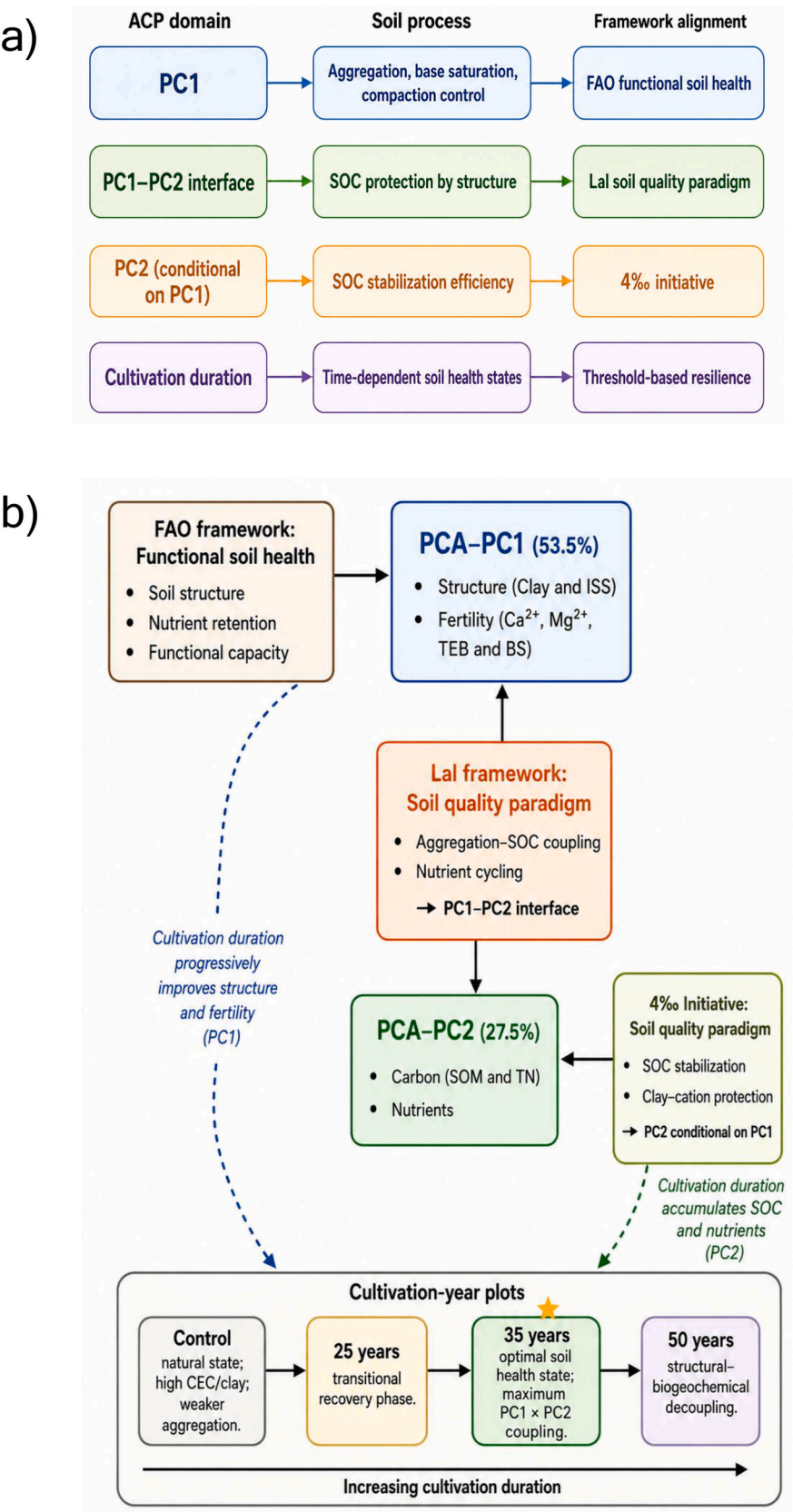


Fig. 6. (a): Conceptual alignment of PCA-derived soil health dimensions with FAO and Lal soil quality frameworks and SOC stabilization paradigms; (b): Conceptual model of soil health trajectories across cultivation durations, illustrating transitions from natural state to structural–biogeochemical decoupling.

maintain environmental quality. PC1 of the PCA—integrating clay content, ISS, base saturation, TEB, and balanced cation ratios—captures this functional capacity (Fig. 9d). The positioning of the 35-year plots along the positive side of PC1 indicates optimal coupling between structure and fertility, corresponding to maximum FAO-defined functional capacity (Fig. 6b; Fig. S5a). Conversely, the displacement of the 50-year plots toward lower BS and weaker ISS reflects a decline in functional efficiency despite high inherent CEC, suggesting reduced soil resilience (Naorem et al., 2023; Ma et al., 2024; Singh et al., 2025). The control plot, while chemically buffered, shows lower structural integration, confirming that natural equilibrium does not necessarily equate to optimal agronomic soil health (Lichtenberg, 2024; Zhu et al., 2024; Ponyane et al., 2025).

Under Lal's soil quality paradigm (Lal, 2015, 2016), ISS emerges as a pivotal integrator: strongly associated with SOM, TN, Ca^{2+} , Mg^{2+} , and available P along PC1 and PC2, it links aggregation, carbon protection, and nutrient-use efficiency in a single functional variable (Fig. 9d). The 35-year plots exemplify Lal's concept of structure–carbon–nutrient coupling, while the 50-year plot illustrates that soil quality degradation is not solely carbon loss but the weakening of the physical–chemical coupling that governs SOC effectiveness—even when total C stocks remain moderate (Kpemoua et al., 2024; Zhang et al., 2024; Li et al., 2025; Cao et al., 2026). From a 4‰ Initiative perspective (Martin et al., 2021; Feeney et al., 2024; Jia et al., 2024; Koutika et al., 2025; Patil et al., 2025), the PCA results show that SOM and TN load primarily on PC2, while their stabilisation potential depends strongly on PC1 variables (ISS, Ca^{2+} , Mg^{2+} , BS) (Fig. 6b).

The 35-year plots represent a system where SOC is not maximized in quantity but is efficiently stabilized through aggregation and cation bridging, aligning with the principle of structural carbon sequestration (Jing et al., 2025; Yadav et al., 2025; Cao et al., 2026; Cheng et al., 2026). By contrast, the control plot, despite higher CEC/clay ratios, exhibits weaker structural integration, implying lower SOC protection efficiency. The 50-year plot suggests that long-term cultivation may compromise SOC stabilization pathways if structural regeneration is not maintained (Hondroudakis et al., 2024; Kpemoua et al., 2024; Zhang et al., 2024). Taken together, this supports a refined 4‰ perspective for Sahelian Vertisols: carbon gains are sustainable only when structural and base-driven stabilization mechanisms are preserved alongside carbon inputs.

3.8. Management implications for Vertisol-based agroecosystems

The identification of threshold-like soil health states along the cultivation gradient has direct implications for the design of sustainable management strategies in Sudano–Sahelian flood-recession systems. Because organic-matter and base-cation stocks—rather than cultivation duration per se—govern the structure–fertility coupling that peaks around 35 years, management priority should be given to sustaining the organic binding agents and divalent-cation supply that stabilise aggregates throughout the profile (Niaz et al., 2023; Du et al., 2024; Ma et al., 2024; Ponyane et al., 2025).

For the smallholder farmers managing these flood-recession Vertisols, this translates into a set of accessible, low-cost practices. Retaining sorghum residues and stubble in the field rather than burning or exporting them sustains the organic inputs and $\text{Ca}^{2+}/\text{Mg}^{2+}$ supply central to aggregate stability; periodic additions of locally available organic amendments (manure, compost, household organic waste) can reinforce subsoil base saturation and buffer the acidification and K^+ depletion that emerge under prolonged cultivation. Limiting soil trafficking on wet clay and timing field operations to the soil moisture state would reduce the profile-wide compaction characteristic of the early adjustment phase (Traore et al., 2020; Jayaraman et al., 2022; Schweizer et al., 2022; Kaduwal et al., 2023; Nath et al., 2025; Sadiq et al., 2025). Where feasible, occasional inclusion of deep-rooted or leguminous species in rotation, and reduced reliance on glyphosate as the sole

weed-management input, would help maintain biological activity and subsoil nutrient replenishment (Meena et al., 2022; Sibalekile et al., 2025).

Crucially, because structural–fertility decoupling in these soils first becomes apparent at depth while surface indicators may remain adequate, soil-health monitoring and extension advice should not be confined to the topsoil. Periodic assessment of subsoil structure (Bd, ISS) and base status (BS, TEB, K^+) at 40–60 cm depth is recommended so that corrective interventions can be implemented before surface indicators decline and before the system crosses the threshold into the long-term alteration phase (Correndo et al., 2021; Rieke et al., 2022; Artuso et al., 2024; Lv et al., 2024). The smectitic Vertisol resilience is substantial but not unlimited: long-term cultivation can progressively weaken subsoil structure–fertility coupling even where inherent exchange capacity remains high, making subsoil monitoring a critical component of sustainable land management in Sudano–Sahelian agroecosystems. Sustainable productivity depends on maintaining the coupling between structure, exchange chemistry, and biological turnover across the full soil profile rather than managing surface properties alone.

4. Conclusion

This study provides a depth-explicit chronosequence assessment of long-term cultivation effects on smectitic Vertisols, developed on fine-grained alluvial parent materials, responses to long-term flood-recession sorghum cultivation under glyphosate management in southeastern Chad. By combining profile-scale sampling (0–60 cm) across an uncultivated reference and three cultivation ages (~25, 35, and 50 years), the results show that smectitic Vertisol soil quality does not follow a simple monotonic degradation pathway. Instead, cultivation induced non-linear, vertically structured trajectories governed by the interaction between sedimentary inheritance, shrink–swell pedoturbation, organic matter turnover, and base-cation regulation. These interacting processes generate emergent soil health states that are only detectable when both temporal and depth dimensions are explicitly considered.

The 25-year stage represented an early adjustment phase characterized by profile-wide compaction, elevated pH, and strong base saturation, but incomplete structural reorganization. The 35-year stage emerged as a transient functioning optimum, with the lowest bulk density, the highest relative structural stability, stronger clay-dominated aggregation, enhanced nitrogen status, and the most coherent coupling between soil structure, base saturation, and nutrient redistribution across the profile. In contrast, the 50-year stage showed evidence of long-term alteration, including weakening base saturation, depletion of Ca^{2+} , Mg^{2+} and K^+ , reduced structure–fertility coupling at depth, and emerging subsoil constraints despite persistently high inherent cation exchange capacity. This trajectory indicates that smectitic Vertisol evolution under cultivation is best conceptualized as a cycle of structural adjustment, functional optimisation, and progressive decoupling rather than linear degradation.

These findings demonstrate that the resilience of cultivated smectitic Vertisols cannot be inferred from clay content or CEC alone. The smectitic clay matrix provides substantial buffering capacity, but this resilience depends on maintaining effective exchange-site occupancy, aggregate stability, organic matter inputs, and balanced cation cycling throughout the soil profile. In particular, the decoupling between inherent mineral fertility (CEC) and effective functional fertility (BS, ISS, and nutrient availability) emerges as a key control on long-term soil performance. The identification of threshold-like soil health states highlights the need to move beyond surface-based fertility assessment and to consider subsoil functioning as a central component of long-term soil sustainability in Sudano–Sahelian flood-recession systems.

Methodologically and conceptually, the main novelty of this study lies in coupling sedimentary inheritance, depth-resolved chronosequence analysis, and multivariate soil quality indicators to identify

threshold-like soil health states in Sudano-Sahelian smectitic Vertisols. This approach demonstrates that the smectitic clay matrix provides substantial buffering capacity, but that inherent clay-related fertility alone is insufficient to maintain soil health when exchange-site occupancy, aggregation, and nutrient cycling become progressively decoupled at depth. By integrating structural, chemical, and functional indicators within a unified depth-resolved framework, this study provides a transferable template for diagnosing non-linear soil system evolution in Vertisol-dominated agroecosystems.

From an agronomic perspective sustaining smectitic Vertisol productivity under continuous sorghum cultivation will require practices that preserve the vertical coupling between structure and fertility. Priority should be given to residue retention, periodic organic amendments, replenishment of base cations and potassium, reduced trafficking on wet clay, and the inclusion of deep-rooted or leguminous species where feasible. Regular monitoring of subsoil bulk density, structural stability, base saturation, and exchangeable K^+ should be integrated into soil-health assessment frameworks, because degradation signals may first emerge at depth while surface indicators remain apparently stable. This underscores the importance of adopting depth-explicit soil monitoring strategies in flood-recession agricultural systems rather than relying solely on topsoil indicators.

Overall, this study shows that smectitic Vertisol resilience is substantial but not unlimited. Long-term cultivation can create a transient phase of enhanced soil functioning, but without nutrient replenishment and profile-scale structural management, this favourable state may shift toward progressive structure–fertility decoupling. These results provide a process-based basis for designing time-aware and depth-aware management strategies for smectitic Vertisol-based agroecosystems in the Sudano-Sahelian zone. More broadly, they highlight that soil sustainability in clay-rich systems is governed by the maintenance of functional coupling among structure, chemistry, and biology rather than the persistence of any single soil property.

CRedit authorship contribution statement

Wavel Mouaromba: . **Abdrmane Abgassi Adoum**: . **Elie Fosso Menkem**: Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Bahouro Arka**: . **Rolf Gael Mabicka Obase**: . **Neil-Yohan Musadji**: . **Simon Djakba Basga**: . **Thomas Z. Lerch**: Supervision, Data curation, Writing – review & editing, Formal analysis. **Gilbert François Ngon Ngon**: .

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.geoderma.2026.118062>.

Data availability

Data will be made available on request.

References

- Abile, H., Fituma, K., Mammo, S., 2025. Impact of land use types on selected soil physicochemical parameters in the case of Liben Jawi district. Ethiopia. Sci. Rep. 15, 27944. <https://doi.org/10.1038/s41598-025-12784-z>.
- Abshiba, K., Sharma, V.K., Kumar, P., Syam, S., Barnwal, P.P., Kumar, S., 2025. A comprehensive review of soil quality indicators under diverse land uses in rainfed areas. Discov. Soil 2, 91. <https://doi.org/10.1007/s44378-025-00109-5>.
- Adeyemo, T., Kramer, I., Levy, G.J., Mau, Y., 2022. Salinity and sodicity can cause hysteresis in soil hydraulic conductivity. Geoderma 413, 115765. <https://doi.org/10.1016/j.geoderma.2022.115765>.
- Andrade Foronda, D., Colinet, G., 2023. Prediction of Soil Salinity/Sodicity and Salt-Affected Soil Classes from Soluble Salt Ions Using Machine Learning Algorithms. Soil Syst. 7, 47. <https://doi.org/10.3390/soilsystems7020047>.
- Artuso, D.R., Moterle, D.F., dos Santos, D.R., Tiecher, T., 2024. Potassium distribution in soil profiles under no-tillage system. Rev Bras Ciênc Solo 48. <https://doi.org/10.36783/18069657rbcs20230125>.
- Aubréville, A., 1950. Flore forestière soudano-guinéenne : AOF. Société d'éditions géographiques, Cameroun, AEF.
- Barnard, M., Dalal, R.C., Weng, Z.H., Schweizer, S.A., Kopittke, P.M., 2025. The influence of fine fraction content on storage and retention of soil organic carbon in Vertisols of subtropical Australia. Geoderma 456, 117269. <https://doi.org/10.1016/j.geoderma.2025.117269>.
- Basak, N., Rai, A.K., Krishnamurthy, S.L., Singh, R.K., Sundha, P., Patel, S., Bedwal, S., Sharma, P.C., 2023. Nutrients availability in salt-affected soils varies with the ionic composition of solid and solution phases of inland and coastal agroecosystems of India. Environ. Earth Sci. 82, 489. <https://doi.org/10.1007/s12665-023-11167-9>.
- Basga, S.D., Temga, J.P., Tsozué, D., Danbé, N., Nguetnkam, J.P., 2018. Morphological, mineralogical and geochemical features of topomorphic vertisols used for sorghum production in North Cameroon. Eurasian J. Soil Sci. 7, 346–354. <https://doi.org/10.18393/ejss.460841>.
- Bhaskar, B.P., Sharma, R.P., Anantwar, S.G., Bobade, S.V., 2026. Evaluation of soil development and weathering intensity of shrink-swell soils within the Painganga valley, Yavatmal district, Maharashtra. India. Discov. Soil 3, 28. <https://doi.org/10.1007/s44378-026-00159-3>.
- Bi, X., Chu, H., Fu, M., Xu, D., Zhao, W., Zhong, Y., Wang, M., Li, K., Zhang, Y., 2023. Distribution characteristics of organic carbon (nitrogen) content, cation exchange capacity, and specific surface area in different soil particle sizes. Sci. Rep. 13, 12242. <https://doi.org/10.1038/s41598-023-38646-0>.
- Binot, A., 2010. La conservation de la nature en Afrique Centrale entre théorie et pratiques. Université Panthéon-Sorbonne, Des espaces protégés à géométrie variable (thesis).
- Bray, R.H., Kurtz, L.T., 1945. Determination of total, organic, and available forms of phosphorus in soils. Soil Sci. 59, 39.
- da Brochado, M.G., S., Silva, L.B.X. da, Lima, A. da C., Guidi, Y.M., Mendes, K.F., 2023. Herbicides versus Nitrogen Cycle: Assessing the Trade-Offs for Soil Integrity and Crop Yield—An In-Depth Systematic Review. Nitrogen 4, 296–310. <https://doi.org/10.3390/nitrogen4030022>.
- Bronick, C.J., Lal, R., 2005. Soil structure and management: a review. Geoderma 124, 3–22. <https://doi.org/10.1016/j.geoderma.2004.03.005>.
- Cao, H., Wang, X., Liu, J., Li, S., Abubakar, S.A., Gao, Y., Ma, S., 2026. Soil organic carbon enhancement via small macroaggregate stabilization under long-term nitrogen and short-term organic amendments. Farming Syst. 4, 100182. <https://doi.org/10.1016/j.farsys.2025.100182>.
- Chen, J., Xie, E., Peng, Y., Yan, G., Jiang, J., Hu, W., Zhao, Y., Saifullah Khan, K., Zhao, Y., 2025. Four-dimensional modelling reveals decline in cropland soil pH during last four decades in China's Mollisols region. Geoderma 453, 117135. <https://doi.org/10.1016/j.geoderma.2024.117135>.
- Cheng, M., Chen, Z., Shi, T., Ma, H., Wen, Y., Li, P., Xu, M., 2026. Soil aggregate carbon stocks and sequestration efficiency under long-term fertilization across China's croplands. Soil Tillage Res. 255, 106828. <https://doi.org/10.1016/j.still.2025.106828>.
- Chiriack, O.P., Pittarello, M., Moretti, B., Zavattaro, L., 2025. Factors influencing nitrogen derived from soil organic matter mineralisation: Results from a long-term experiment. Agric. Ecosyst. Environ. 381, 109444. <https://doi.org/10.1016/j.agee.2024.109444>.
- Correndo, A.A., Rubio, G., García, F.O., Ciampitti, I.A., 2021. Subsoil-potassium depletion accounts for the nutrient budget in high-potassium agricultural soils. Sci. Rep. 11, 11597. <https://doi.org/10.1038/s41598-021-90297-1>.
- Cui, S.-Y., Sun, Z.-X., Duan, S.-Y., Qiu, W.-W., Jiang, Y.-Y., 2026. Cultivation Management Reshapes Soil Profile Configuration and Organic Carbon Sequestration: Evidence from a 45-Year Field Study. Agronomy 16, 110. <https://doi.org/10.3390/agronomy16010110>.
- Dong, Y., Yang, J.-L., Zhao, X.-R., Yang, S.-H., Mulder, J., Dörsch, P., Peng, X.-H., Zhang, G.-L., 2022. Soil acidification and loss of base cations in a subtropical agricultural watershed. Sci. Total Environ. 827, 154338. <https://doi.org/10.1016/j.scitotenv.2022.154338>.
- Du, M., Minasny, B., Rabbi, S.M.F., 2024. Carbon to nitrogen stoichiometry of organic amendments influences the improvement of aggregate stability of a cropping vertisol. Soil Use Manag. 40, 1–8. <https://doi.org/10.1111/sum.13087>.

- FAO, 2015. Status of the World's Soil Resources: Main Report, 1st ed. FAO, Rome, Italy.
- FAO/GSP, 2017. Soil Organic Carbon - the hidden potential. FAO, Rome, Italy.
- Feeeny, C.J., Bentley, L., De Rosa, D., Panagos, P., Emmett, B.A., Thomas, A., Robinson, D.A., 2024. Benchmarking soil organic carbon (SOC) concentration provides more robust soil health assessment than the SOC/clay ratio at European scale. *Sci. Total Environ.* 951, 175642. <https://doi.org/10.1016/j.scitotenv.2024.175642>.
- Franzluebbers, A.J., Farmaha, B.S., Zentella, R., Kafle, A., 2025. Soil-profile fertility is altered by soil texture and land use across physiographic regions in the southeastern United States. *Agron. J.* 117, e70041. <https://doi.org/10.1002/aj2.70041>.
- Guitián Ojea, F., Carballas, T., 1976. Técnicas de análisis de suelos. Pico Sacro.
- Gupta, A.K., Tripathi, L.K., Patra, P.K., 2023. Variation and distribution of phosphorus fractions, their relationship with soil properties in vertisols and aridisols of India. *J. Indian Soc. Soil Sci.* 71, 217–228.
- Gurav, P.P., Ray, S.K., Datta, S.C., Choudhari, P.L., Hartmann, C., 2024. Role of clay cation exchange capacity, location of charge, and clay mineralogy on potassium availability in Indian Vertisols. *Clays Clay Miner.* 72, e3.
- Hamza, A., Karcauskienė, D., Mockevičienė, I., Repšienė, R., Tahir, M.A., Manzoor, M.Z., Kousar, S., Lodhi, S.S., Rasool, N., Ullah, I., 2025. Soil Aggregate Dynamics and Stability: Natural and Anthropogenic Drivers. *Agriculture* 15, 2500. <https://doi.org/10.3390/agriculture15232500>.
- He, C., Chen, Z., Qiu, K.-Y., Chen, J.-S., Bohoussou, Y.N., Dang, Y.P., Zhang, H.-L., 2023. Effects of conservation agriculture on carbon mineralization: A global meta-analysis. *Soil Tillage Res.* 229, 105685. <https://doi.org/10.1016/j.still.2023.105685>.
- Hewelke, E., Weber, J., Mielnik, L., Spaccini, R., Gozdowski, D., Podlasiński, M., Cwiela-Plasecka, I., Jamroz, E., Jerzykiewicz, M., Perzanowska, A., Bogużas, V., Skiniulienė, L., Dębicka, M., 2026. Effect of 55 years of different soil management on soil physical properties and stability of soil organic matter. *Agric. Ecosyst. Environ.* 396, 110005. <https://doi.org/10.1016/j.agee.2025.110005>.
- Hondroudakis, L., Kopittke, P.M., Dalal, R.C., Barnard, M., Weng, Z.H., 2024. The influence of land use and management on the behaviour and persistence of soil organic carbon in a subtropical Ferralsol. *SOIL* 10, 451–465. <https://doi.org/10.5194/soil-10-451-2024>.
- Isaboke, J., Osano, O., Humphrey, O.S., Dowell, S.M., Njoroge, R., Watts, M.J., 2025. Influence of Agricultural Land Use Management on Soil Particle Size Distribution and Nutrient Adsorption in Western Kenya. *Chem. Afr.* 8, 1599–1610. <https://doi.org/10.1007/s42250-025-01202-6>.
- Ismayilov, A.I., Mamedov, A.I., Fujimaki, H., Tsunekawa, A., Levy, G.J., 2021. Soil Salinity Type Effects on the Relationship between the Electrical Conductivity and Salt Content for 1:5 Soil-to-Water Extract. *Sustainability* 13, 3395. <https://doi.org/10.3390/su13063395>.
- Jayaraman, S., Sahu, M., Sinha, N.K., Mohanty, M., Chaudhary, R.S., Yadav, B., Srivastava, L.K., Hati, K.M., Patra, A.K., Dalal, R.C., 2022. Conservation Agricultural Practices Impact on Soil Organic Carbon, Soil Aggregation and Greenhouse Gas Emission in a Vertisol. *Agriculture* 12, 1004. <https://doi.org/10.3390/agriculture12071004>.
- Ji, J., Lü, Z., Liu, S., Hou, H., Liu, Y., Liu, X., Li, X., Lan, X., 2024. Long-Term Application of Chemical Fertilizers Induces Soil Acidification and Soil Exchangeable Base Cation Loss on Paddy in Southern China. *Sci. Agric. Sin.* 57, 2599–2611. <https://doi.org/10.3864/j.issn.0578-1752.2024.13.008>.
- Jia, N., Li, L., Guo, H., Xie, M., 2024. Important role of Fe oxides in global soil carbon stabilization and stocks. *Nat. Commun.* 15, 10318. <https://doi.org/10.1038/s41467-024-54832-8>.
- Jian, Z., Lei, L., Ni, Y., Xu, J., Xiao, W., Zeng, L., 2022. Soil clay is a key factor affecting soil phosphorus availability in the distribution area of Masson pine plantations across subtropical China. *Ecol. Indic.* 144, 109482. <https://doi.org/10.1016/j.ecolind.2022.109482>.
- Jindo, K., Audette, Y., Olivares, F.L., Canellas, L.P., Smith, D.S., Paul Voroney, R., 2023. Biotic and abiotic effects of soil organic matter on the phytoavailable phosphorus in soils: a review. *Chem. Biol. Technol. Agric.* 10, 29. <https://doi.org/10.1186/s40538-023-00401-y>.
- Jing, Z., Zhang, S., Sun, Z., Liu, Z., Liu, S., Ding, X., 2025. Straw Incorporation and Nitrogen Fertilization Enhance Soil Organic Carbon Sequestration by Promoting Aggregate Stability and Iron Oxide Transformation. *Agronomy* 15, 871. <https://doi.org/10.3390/agronomy15040871>.
- Jones, E.J., Filippi, P., Wittig, R., Fajardo, M., Pino, V., McBratney, A.B., 2021. Mapping soil slaking index and assessing the impact of management in a mixed agricultural landscape. *SOIL* 7, 33–46. <https://doi.org/10.5194/soil-7-33-2021>.
- Kabala, C., Mantel, S., Bednik-Dudek, M., Matuszak, M., 2025. Relationships between base saturation, effective base saturation and soil pH as the references for the development and verification of criteria for international soil classification. *Geoderma* 461, 117465. <https://doi.org/10.1016/j.geoderma.2025.117465>.
- Kaduwal, S., Karki, T.B., Neupane, R., Battarai, R.K., Chaulagain, B., Ghimire, P., Gyawali, P., Acharya, R., Paneru, P., Gyawali, C., Das, S.K., 2023. Residue Management and Nutrient Dynamics in Conservation Agriculture: A Review. *Agron. J. Nepal* 7, 139–148. <https://doi.org/10.3126/ajnv7i1.62169>.
- Karlen, D.L., Veum, K.S., Sudduth, K.A., Obrycki, J.F., Nunes, M.R., 2019. Soil health assessment: Past accomplishments, current activities, and future opportunities. *Soil Tillage Res.* 195, 104365. <https://doi.org/10.1016/j.still.2019.104365>.
- Kassie, A.A., Ahmed, A.S., Abdi, A.B., 2025. Variations in Soil Properties Across Land Use Types in the Shemit Watershed. *Northern Ethiopian. Adv. Agric.* 2025, 9313798. <https://doi.org/10.1155/aia/9313798>.
- Kepler, R., M., Schmidt, D., J., E., Yarwood, S., A., Cavigelli, M., A., Reddy, K., N., Duke, S., O., Bradley, C., A., Williams, Jr., M., M., Buyer, J., S., Maul, J., E., 2020. Soil Microbial Communities in Diverse Agroecosystems Exposed to the Herbicide Glyphosate. *Appl. Environ. Microbiol.* 86, 1–16. <https://doi.org/10.1128/AEM.01744-19>.
- Kim, H.N., Park, J.H., 2024. Monitoring of soil EC for the prediction of soil nutrient regime under different soil water and organic matter contents. *Appl. Biol. Chem.* 67, 1. <https://doi.org/10.1186/s13765-023-00849-4>.
- Königer, J., Labouyrie, M., Ballabio, C., Dulya, O., Mikryukov, V., Romero, F., Franco, A., Bahram, M., Panagos, P., Jones, A., Tederloo, L., Orgiazzi, A., Briones, M. J.I., van der Heijden, M.G.A., 2026. Pesticide residues alter taxonomic and functional biodiversity in soils. *Nature* 650, 367–373. <https://doi.org/10.1038/s41586-025-09991-z>.
- Koutika, L.-S., Henry, B., Schepp, C., Olaleye, A., Amiraslani, F., Minasny, B., Ma, Y., Ladha, J., Cardinael, R., Bossio, D., Chenu, C., Espinoza, A.F., Madari, B., Soussana, J.-F., Varela-Ortega, C., Skowronska, M., 2025. Enhancing “4 per 1000” initiative implementation through region-specific agricultural and forestry practices. *Soil Adv.* 4, 100057. <https://doi.org/10.1016/j.soilad.2025.100057>.
- Kpemoua, T.P.I., Barré, P., Houot, S., Baudin, F., Plessis, C., Chenu, C., 2024. What is the stability of additional organic carbon stored thanks to alternative cropping systems and organic waste product application? A multi-method evaluation. *SOIL* 10, 533–549. <https://doi.org/10.5194/soil-10-533-2024>.
- Lal, R., 2016. Soil health and carbon management. *Food Energy Secur.* 5, 212–222. <https://doi.org/10.1002/fes3.96>.
- Lal, R., 2015. Restoring Soil Quality to Mitigate Soil Degradation. *Sustainability* 7, 5875–5895. <https://doi.org/10.3390/su7055875>.
- Lehmann, J., Bossio, D.A., Kögel-Knabner, I., Rillig, M.C., 2020. The concept and future prospects of soil health. *Nat. Rev. Earth Environ.* 1, 544–553. <https://doi.org/10.1038/s43017-020-0080-8>.
- Li, F., Liang, X., Li, H., Jin, Y., Jin, J., He, M., Klumpp, E., Bol, R., 2020. Enhanced soil aggregate stability limits colloidal phosphorus loss potentials in agricultural systems. *Environ. Sci. Eur.* 32, 17. <https://doi.org/10.1186/s12302-020-0299-5>.
- Li, S., Chen, S., Bai, S., Tan, J., Jiang, X., 2024. Intensive agricultural management-induced subsurface accumulation of water-extractable colloidal P in a Vertisol. *SOIL* 10, 49–59. <https://doi.org/10.5194/soil-10-49-2024>.
- Li, Y., Guo, L., Wu, M., Li, C., 2025a. Effects of long-term conservation tillage on soil aggregate carbon fractions and microbial characteristics under rice-oilseed rape rotation systems. *Appl. Soil Ecol.* 206, 105848. <https://doi.org/10.1016/j.apsoil.2024.105848>.
- Li, Y., Xu, Z., Ye, H., Bai, J., Dai, X., Zeng, Y., 2025b. Comparative Analysis of Particle Size Characteristics of Calcareous Soils Under Cultivated and Natural Conditions Based on Fractal Theory. *Agriculture* 15, 1858. <https://doi.org/10.3390/agriculture15171858>.
- Lichtenberg, E., 2024. Thinking about soil health: A conceptual framework. *Soil Secur.* 14, 100130. <https://doi.org/10.1016/j.soisec.2024.100130>.
- Liebhart, G., Toth, M., Stumpp, C., Bodner, G., Klik, A., Zhang, X., Strohmeier, S., Strauss, P., 2025. Developing topsoil structure through conservation management to protect subsoil from compaction. *Soil Tillage Res.* 253, 106669. <https://doi.org/10.1016/j.still.2025.106669>.
- Lorenz, K., Omondi, E., Lal, R., Das, S., Smith, A., 2025. Soil organic carbon and total nitrogen after 34 years under conventional and organic management practices at the Rodale Institute Farming Systems Trial. *Soil Sci. Soc. Am. J.* 89, e14165. <https://doi.org/10.1002/saj2.70000>.
- Ludemann, C.I., Hijbeek, R., van Loon, M.P., Murrell, T.S., Dobermann, A., van Itersum, M.K., 2023. In: Improving cropland N, P and K nutrient budgets through local and global data. *Wageningen University & Research*, pp. 72–73.
- Lv, H., Pang, Z., Chen, F., Ji, H., Wang, W., Zhou, W., Dong, J., Li, J., Liang, B., 2024. Effects of Cultivation Years on the Distribution of Nitrogen and Base Cations in 0–7 m Soil Profiles of Plastic-Greenhouse Pepper. *Agronomy* 14, 1060. <https://doi.org/10.3390/agronomy14051060>.
- Ma, D., He, Z., Zhao, W., Li, R., Sun, W., Wang, W., Lin, P., Wei, L., Ju, W., 2024. Long-term effects of conventional cultivation on soil cation exchange capacity and base saturation in an arid desert region. *Sci. Total Environ.* 949, 175075. <https://doi.org/10.1016/j.scitotenv.2024.175075>.
- Martin, M.P., Dimassi, B., Román Dobarco, M., Guenet, B., Arrouays, D., Angers, D.A., Blache, F., Huard, F., Soussana, J., Pellerin, S., 2021. Feasibility of the 4 per 1000 aspirational target for soil carbon: A case study for France. *Glob. Change Biol.* 27, 2458–2477. <https://doi.org/10.1111/gcb.15547>.
- Martlew, J., Otten, W., Morris, N., De Baets, S., Deeks, L.K., 2023. Long-term impacts of repeated cover cropping and cultivation approaches on subsoil physical properties. *Soil Tillage Res.* 232, 105761. <https://doi.org/10.1016/j.still.2023.105761>.
- Mattila, T.J., Häkkinen, L., 2025. Exploring the effects of soil structure, nutrients, and farm management on crop root biomass and depth distribution. *Field Crops Res.* 327, 109909. <https://doi.org/10.1016/j.fcr.2025.109909>.
- Maulet, E., Villani, M., Monhonval, A., Hirst, C., Schuur, E.A.G., Opfergelt, S., 2023. Quantifying exchangeable base cations in permafrost: a reserve of nutrients about to thaw. *Earth Syst. Sci. Data* 15, 3891–3904. <https://doi.org/10.5194/essd-15-3891-2023>.
- McKenna, B.A., Kopittke, P.M., Bell, M.J., Lombi, E., Klysubun, W., McLaren, T.I., Doolette, C.L., Meyer, G., 2024. Phosphorus availability and speciation in the ferrosphere of three soils over 12 months. *Geoderma* 447, 116913. <https://doi.org/10.1016/j.geoderma.2024.116913>.
- Meena, S.K., Dwivedi, B.S., Meena, M.C., Datta, S.P., Singh, V.K., Mishra, R.P., Chakraborty, D., Dey, A., Meena, V.S., 2022. Impact of Long-Term Nutrient Supply Options on Soil Aggregate Stability after Nineteen Years of Rice–Wheat Cropping System. *Land* 11, 1465. <https://doi.org/10.3390/land11091465>.
- Mikha, M.M., Green, T.R., Untiedt, T.J., Hergert, G.W., 2024. Land management affects soil structural stability: Multi-index principal component analyses of treatment

- interactions. *Soil Tillage Res.* 235, 105890. <https://doi.org/10.1016/j.still.2023.105890>.
- Mouaromba, W., Mabicka Obamel, R.G., Musadji, N.-Y., Adoum, A., Ngon Ngon, G.F., Etame, E., 2025. Effects of cultivation time on soil physical, chemical properties, soil organic carbon, total nitrogen stocks and dioxide carbon emission in Southeast of Chad. *CATENA* 258, 109267. <https://doi.org/10.1016/j.catena.2025.109267>.
- Murindangabo, Y.T., Kopecký, M., Hoang, T.N., Bernas, J., Parajuli, T., Dhakal, S., Konvalina, P., UFITIKIREZI, J. de D.M., Kaneza, G., Khanal, B.R., Dhakal, S.C., Shrestha, A.K., 2023. Comparative analysis of soil organic matter fractions, lability, stability ratios, and carbon management index in various land use types within bharatpur catchment, Chitwan District. Nepal. *Carbon Balance Manag.* 18, 21. <https://doi.org/10.1186/s13021-023-00241-1>.
- Nachimuthu, G., Palmer, B., Jamali, H., Hundt, A., Cunningham, S., Le, D.P., Schwenke, G., 2025. Compaction effects on crop yields in Vertisols: Transient under wet years. *Agrosystems Geosci. Environ.* 8, e70220. <https://doi.org/10.1002/agg2.70220>.
- Naorem, A., Jayaraman, S., Sinha, N.K., Mohanty, M., Chaudhary, R.S., Hati, K.M., Mandal, A., Thakur, J.K., Patra, A.K., Srinivasarao, Ch., Chaudhari, S.K., Dalal, R.C., Lal, R., 2023. Eight-year impacts of conservation agriculture on soil quality, carbon storage, and carbon emission footprint. *Soil Tillage Res.* 232, 105748. <https://doi.org/10.1016/j.still.2023.105748>.
- Nath, C.P., Dutta, A., Hazra, K.K., Kumar, N., Praharaj, C.S., Kumar, M., Hashim, M., Dixit, G.P., 2025. Influence of legume diversification and fertilization on soil potassium pools under distinct cropping system ecologies: insight from 14-years study. *Front. Sustain. Food Syst.* 9. <https://doi.org/10.3389/fsufs.2025.1660079>.
- Niaz, S., Wehr, J.B., Dalal, R.C., Kopittke, P.M., Menzies, N.W., 2023. Wetting and drying cycles, organic amendments, and gypsum play a key role in structure formation and stability of sodic Vertisols. *SOIL* 9, 141–154. <https://doi.org/10.5194/soil-9-141-2023>.
- Okolo, C.C., Gebresamuel, G., Zenebe, A., Haile, M., Orji, J.E., Okebalama, C.B., Eze, C. E., Eze, E., 2023. Soil organic carbon, total nitrogen stocks and CO₂ emissions in top- and subsoils with contrasting management regimes in semi-arid environments. *Sci. Rep.* 13, 1117. <https://doi.org/10.1038/s41598-023-28276-x>.
- Olivry, J.-C., 1996. *Hydrologie du lac Tchad*. Paris Ed. L'ORSTOM Monogr. Hydrol. 266.
- Omwoyo, A.M., Onwonga, R.N., Wasonga, O.V., Kinyanjui, M.J., Chepkemai, J., 2025. Soil organic carbon and total nitrogen stocks as a function of land use and land cover in the drylands of Kibwezi West. *Eastern Kenya. Discov. Soil* 2, 20. <https://doi.org/10.1007/s44378-025-00048-1>.
- 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. *Int. J. Soil Sci.* 177–185. <https://doi.org/10.3923/ijss.2015.177.185>.
- Pagouo, J., Kagonbe, B.P., Yanne, E., Danwe, R., 2026. Mineralogical and Geotechnical Properties of Clayey Vertisols from Northern Cameroon: To Provide a Scientific Basis for Future Stabilization and Engineering Applications. *Int. J. Mater. Sci. Appl.* 15, 62–72. <https://doi.org/10.11648/j.jjmsa.20261502.13>.
- Panagos, P., De Rosa, D., Liakos, L., Labouyrie, M., Borrelli, P., Ballabio, C., 2024. Soil bulk density assessment in Europe. *Agric. Ecosyst. Environ.* 364, 108907. <https://doi.org/10.1016/j.agee.2024.108907>.
- Patil, M., Perumal, C., Choudhari, P., Pasumarthi, R., Sawargaonkar, G., Singh, R., 2025. Differential impacts of regenerative agriculture practices on soil organic carbon: a meta-analysis of studies from India. *Sci. Rep.* 15, 33470. <https://doi.org/10.1038/s41598-025-12149-6>.
- Peng, J., Yang, Q., Zhang, C., Ni, S., Wang, J., Cai, C., 2023. Aggregate pore structure, stability characteristics, and biochemical properties induced by different cultivation durations in the Mollisol region of Northeast China. *Soil Tillage Res.* 233, 105797. <https://doi.org/10.1016/j.still.2023.105797>.
- Pessoa, T.N., Bovi, R.C., Nunes, M.R., Cooper, M., Uteau, D., Peth, S., Libardi, P.L., 2024. Clay mineral composition drives soil structure behavior and the associated physical properties in Brazilian Oxisols. *Geoderma Reg.* 38, e00837. <https://doi.org/10.1016/j.geodrs.2024.e00837>.
- Pieri, C.J.M.G., 1992. *Fertility of Soils: A Future for Farming in the West African Savannah*. Springer Series in Physical Environment. Springer, Berlin, Heidelberg. doi: 10.1007/978-3-642-84320-4.
- Ponyane, P., Dina Ebouel, F.J., Eze, P.N., 2025. Differential impacts of land use regimes on soil aggregate stability and aggregate-associated organic carbon sequestration in semi-arid Vertisols. *Front. Soil Sci.* 5. <https://doi.org/10.3389/fsol.2025.1629431>.
- Rabot, E., Saby, N.P.A., Martin, M.P., Barré, P., Chenu, C., Cousin, I., Arrouays, D., Angers, D., Bispo, A., 2024. Relevance of the organic carbon to clay ratio as a national soil health indicator. *Geoderma* 443, 116829. <https://doi.org/10.1016/j.geoderma.2024.116829>.
- Raymond, N.S., Kopittke, P.M., van der Bom, F.J.T., Barrow, N.J., Bell, M.J., 2023. Short-term phosphorus sorption and desorption in contrasting cropped Vertisols. *Eur. J. Soil Sci.* 74, e13418. <https://doi.org/10.1111/ejss.13418>.
- Rengasamy, P., de Lacerda, C.F., Gheyi, H.R., 2022. Salinity, Sodicity and Alkalinity, in: Oliveira, T.S. de, Bell, R.W. (Eds.), *Subsoil Constraints for Crop Production*. Springer International Publishing, Cham, pp. 83–107. doi: 10.1007/978-3-031-00317-2_4.
- Rezapour, S., Asadzadeh, F., Heidari, M., 2024. Comparative assessment of soil health attributes between topsoil and subsoil influenced by long-term wastewater irrigation. *Agric. Water Manag.* 302, 109012. <https://doi.org/10.1016/j.agwat.2024.109012>.
- Rieder, L., Amann, T., Hartmann, J., 2024. Soil electrical conductivity as a proxy for enhanced weathering in soils. *Front. Clim.* 5. <https://doi.org/10.3389/fclim.2023.1283107>.
- Rieke, E.L., Bagnall, D.K., Morgan, C.L.S., Flynn, K.D., Howe, J.A., Greub, K.L.H., Mac Bean, G., Cappellazzi, S.B., Cope, M., Liptzin, D., Norris, C.E., Tracy, P.W., Aberle, E., Ashworth, A., Bañuelos Tavarez, O., Bary, A.I., Baumhardt, R.L., Borbón Gracia, A., Brainard, D.C., Brennan, J.R., Briones Reyes, D., Bruhjel, D., Carlyle, C.N., Crawford, J.J.W., Creech, C.F., Culman, S.W., Deen, B., Dell, C.J., Derner, J.D., Ducey, T.F., Duiker, S.W., Dyck, M.F., Ellert, B.H., Entz, M.H., Espinosa Solorio, A., Fonte, S.J., Fonteyne, S., Fortuna, A.-M., Foster, J.L., Fultz, L.M., Gamble, A.V., Geddes, C.M., Griffin-LaHue, D., Grove, J.H., Hamilton, S.K., Hao, X., Hayden, Z.D., Honsdorf, N., Ippolito, J.A., Johnson, G.A., Kautz, M.A., Kitchen, N.R., Kumar, S., Kurtz, K.S.M., Larney, F.J., Lewis, K.L., Liebman, M., Lopez Ramirez, A., Machado, S., Maharjan, B., Martinez Gamiño, M.A., May, W.E., McClaran, M.P., McDaniel, M.D., Millar, N., Mitchell, J.P., Moore, A.D., Moore, P.A., Mora Gutiérrez, M., Nelson, K.A., Omondi, E.C., Osborne, S.L., Osorio Alcalá, L., Owens, P., Pena-Yewtukhiw, E.M., Poffenbarger, H.J., Ponce Lira, B., Reeve, J.R., Reinbott, T.M., Reiter, M.S., Ritchey, E.L., Roozeboom, K.L., Rui, Y., Sadeghpour, A., Sainju, U.M., Sanford, G.R., Schillinger, W.F., Schindelbeck, R.R., Schipanski, M.E., Schlegel, A.J., Scow, K.M., Sherrod, L.A., Shober, A.L., Sidhu, S.S., Solís Moya, E., St. Luce, M., Strock, J.S., Suyker, A.E., Sykes, V.R., Tao, H., Trujillo Campos, A., Van Eerd, L.L., van Es, H.M., Verhulst, N., Vyn, T.J., Wang, Y., Watts, D.B., Wright, D.L., Zhang, T., Honeycutt, C.W., 2022. Evaluation of aggregate stability methods for soil health. *Geoderma* 428, 116156. <https://doi.org/10.1016/j.geoderma.2022.116156>.
- Sadiq, F.K., Anyebe, O., Tanko, F., Abdulkadir, A., Manono, B.O., Matsika, T.A., Abubakar, F., Bello, S.K., 2025. Conservation Agriculture for Sustainable Soil Health Management: A Review of Impacts, Benefits and Future Directions. *Soil Syst.* 9, 103. <https://doi.org/10.3390/soilsystems9030103>.
- Schweizer, S.A., Graf-Rosenfellner, M., Bhat, N., Kayse, G., Sisodia, B., Kirchhof, G., Zikeli, S., Cadisch, G., Bhullar, G.S., 2022. Responses of soil organic carbon, aggregate diameters, and hydraulic properties to long-term organic and conventional farming on a Vertisol in India. *Land Degrad. Dev.* 33, 785–797. <https://doi.org/10.1002/ldr.4216>.
- Sharma, R.P., Bhaskar, B.P., Naitam, R.K., Dash, B., Tiwari, G., Jangir, A., 2022. *Mineralogy of Alluvial Soils Developed in Narmada River Basin in West Coast of Gujarat*. *J. Indian Soc. Soil Sci.* 70, 394–406.
- Shoumik, B.A.A., Khan, M.Z., Błońska, E., Lasota, J., 2025. Dynamics of soil organic carbon and total nitrogen in particulate and mineral-associated organic matter fractions under different continuous land use patterns across Europe. *Agric. Ecosyst. Environ.* 381, 109411. <https://doi.org/10.1016/j.agee.2024.109411>.
- Sibalekile, A., Araya, T., Castillo Hernandez, J., Kotzé, E., 2025. Glyphosate-microbial interactions: metagenomic insights and future directions. *Front. Microbiol.* 16. <https://doi.org/10.3389/fmicb.2025.1570235>.
- Singh, A., Kiboi, M., Bhullar, G.S., Sisodia, B.S., Bautze, D., Patidar, I., Konde, N., Ledroit, C., Riari, A., 2025a. Long-term impacts of farming systems and preceding crops on soil organic carbon and physiochemical properties in Vertisols of subtropical India. *Soil Adv.* 4, 100083. <https://doi.org/10.1016/j.soilad.2025.100083>.
- Singh, P., Dheri, G.S., Nazir, G., Singh, S., 2025b. Impact of long-term use of fertilizers on soil phosphorus fractions and its uptake. *Geoderma Reg.* 43, e01021. <https://doi.org/10.1016/j.geodrs.2025.e01021>.
- Skadell, L.E., Schneider, F., Bauke, S.L., Amelung, W., Don, A., 2025. Long-term management effects on depth gradients of 13C, 15N and C/N ratio in agricultural soils. *Geoderma* 458, 117341. <https://doi.org/10.1016/j.geoderma.2025.117341>.
- Song, X., Yang, L., Nong, H., Lyu, S., Wang, J., 2025. Depth-Dependent Impacts of Long-Term Vegetation Restoration on Soil Carbon Stability and C/N Stoichiometry in Subtropical Plantations. *Forests* 16, 108. <https://doi.org/10.3390/f16010108>.
- Souza, J.L.B., Antonangelo, J.A., Zhang, H., Reed, V., Finch, B., Arnall, B., 2023. Impact of long-term fertilization in no-till on the stratification of soil acidity and related parameters. *Soil Tillage Res.* 228, 105624. <https://doi.org/10.1016/j.still.2022.105624>.
- Su, Z., Zhu, S., Wei, Z., He, Y., Su, B., Zhang, K., Ma, X., Shangguan, Z., 2025. Vegetation restoration change the soil aggregate stability and aggregate carbon stabilization pathway according to δ13C signatures. *Agric. Ecosyst. Environ.* 378, 109317. <https://doi.org/10.1016/j.agee.2024.109317>.
- Sumner, M.E., Miller, W.P., 1996. Cation Exchange Capacity and Exchange Coefficients, in: *Methods of Soil Analysis*. John Wiley & Sons, Ltd, pp. 1201–1229. doi: 10.2136/sssabooker5.3.c40.
- Suswati, D., 2023. The role of red mud and cow manure for sustainable post-gold mining land rehabilitation. *SAINS TANAH - J. Soil Sci. Agroclimatol.* 20, 240–249. <https://doi.org/10.20961/stjsa.v20i2.75543>.
- Tamfuh, P., A., Woumfo, E., D., Bitom, D., Njopwouo, D., 2011. Petrological, Physico-Chemical and Mechanical Characterization of the Topomorphic Vertisols from the Sudano-Sahelian Region of North Cameroon. *Open Geol. J.* 7, 1. <https://doi.org/10.2174/1874262901105010033>.
- Tenga, J.P., Primus, A.T., Simon, B.D., Philemon, Z.Z., Hamadjida, G., Monique, A., Jean Pierre, N., Dieudonné Lucien, B., 2019. Characteristics, classification and genesis of vertisols under seasonally contrasted climate in the Lake Chad Basin. *Central Africa. J. Afr. Earth Sci.* 150, 176–193. <https://doi.org/10.1016/j.jafrearsci.2018.11.003>.
- Tian, H., Qiao, J., Zhu, Y., Jia, X., Shao, M., 2021. Vertical distribution of soil available phosphorus and soil available potassium in the critical zone on the Loess Plateau. *China. Sci. Rep.* 11, 3159. <https://doi.org/10.1038/s41598-021-82677-4>.
- Țopa, D.-C., Căpșună, S., Calistru, A.-E., Ailincăi, C., 2025. Sustainable Practices for Enhancing Soil Health and Crop Quality in Modern Agriculture: A Review. *Agriculture* 15, 998. <https://doi.org/10.3390/agriculture15090998>.
- Traore, K., Traore, B., Synnevåg, G., Aune, J.B., 2020. Intensification of Sorghum Production in Flood Recession Agriculture in Yelimane. *Western Mali. Agronomy* 10, 726. <https://doi.org/10.3390/agronomy10050726>.
- Tsozé, D., Nafissa, B., Basga, S.D., Balna, J., 2020. Soil change in Arenosols under long term cultivation in the sudano-sahelian zone of Cameroon. *Geoderma Reg.* 23, e00338. <https://doi.org/10.1016/j.geodrs.2020.e00338>.

- Vieira, C.B., Silva, G.H.M.C., de Almeida, B.G., Pessoa, L.G.M., Freire, F.J., de Souza Junior, V.S., de Melo, H.F., de Lima, L.G.G., Paiva, R.F., do N., Ferreira, J.F. da S., Freire, M.B.G. dos S., 2025. Saturated Hydraulic Conductivity of Nine Soils According to Water Quality, Soil Texture, and Clay Mineralogy. *Agronomy* 15, 864. <https://doi.org/10.3390/agronomy15040864>.
- Wang, D., Liu, B., Li, F., Wang, Z., Hou, J., Cao, R., Zheng, Y., Yang, W., 2025a. Status and influential factors of soil nutrients and acidification in Chinese tea plantations: a meta-analysis. *SOIL* 11, 175–191. <https://doi.org/10.5194/soil-11-175-2025>.
- Wang, G., Zhu, Z., Cao, J., Zhu, T., Zhou, J., Müller, C., Li, J., Freese, D., Le Roux, X., 2025b. Agricultural cultivation duration affects soil inorganic N turnover and supply capacity: Evidence in subtropical karst regions. *Agric. Ecosyst. Environ.* 381, 109462. <https://doi.org/10.1016/j.agee.2024.109462>.
- Wang, Y., Zhao, Z., Wang, J., Jiang, S., Ma, X., Gao, L., Liu, H., 2025c. Study on the dynamics of phosphorus adsorption and the risk of release in black soils by conservation tillage. *Sci. Rep.* 15, 18417. <https://doi.org/10.1038/s41598-025-02522-w>.
- Witzgall, K., Steiner, F.A., Hesse, B.D., Riveras-Muñoz, N., Rodríguez, V., Teixeira, P.P.C., Li, M., Osés, R., Seguel, O., Seitz, S., Wagner, D., Scholten, T., Buegger, F., Angst, G., Mueller, C.W., 2024. Living and decaying roots as regulators of soil aggregation and organic matter formation—from the rhizosphere to the detritusphere. *Soil Biol. Biochem.* 197, 109503. <https://doi.org/10.1016/j.soilbio.2024.109503>.
- Xin, H., Lv, C., Li, N., Peng, L., Chang, M., Li, Y., Geng, Q., Chen, S., Lai, N., 2025. Analysis of Soil Nutrient Content and Carbon Pool Dynamics Under Different Cropping Systems. *Sustainability* 17, 3881. <https://doi.org/10.3390/su17093881>.
- Yadav, M., Mittal, R., Kumari, A., Bhatia, A., Khatri, A., Bhateria, R., 2025. Soil carbon fractions and their role in climate-resilient agriculture: A review. *Sustain. Chem. Clim. Action* 7, 100127. <https://doi.org/10.1016/j.scca.2025.100127>.
- Yakubu, M., Ojanuga, A.G., 2013. Pedogenesis, weathering status and mineralogy of the soils on ironstone plateaus (laterites), Sokoto Nigeria. *Bayero J. Pure Appl. Sci.* 6, 93–100. <https://doi.org/10.4314/bajopas.v6i2.19>.
- Yang, S., White, B., Regan, F., Kent, N., Hall, R.L., Daly, K., 2024a. Integrating soil phosphorus sorption capacity with agronomic indices to improve sustainable P use in agriculture. *J. Soils Sediments* 24, 3396–3406. <https://doi.org/10.1007/s11368-024-03900-z>.
- Yang, X., Xu, J., Wang, H., Quan, H., Yu, H., Luan, J., Wang, D., Li, Y., Lv, D., 2024b. Vertical distribution characteristics of soil organic carbon and vegetation types under different elevation gradients in Cangshan. Dali. *PeerJ* 12, e16686. <https://doi.org/10.7717/peerj.16686>.
- Zagalo, A.H., Ngapgue, F., Kwekam, M., Tchere, I.G., 2018. Caractérisation physique des sols de la ville d'Amtiman (Tchad) comme assises de fondation. *Sci. Appliquées Ing.* 2, 54–58.
- Zhang, J., Qu, X., Song, X., Xiao, Y., Wang, A., Li, D., 2023. Spatial Variation in Soil Base Saturation and Exchangeable Cations in Tropical and Subtropical China. *Agronomy* 13, 781. <https://doi.org/10.3390/agronomy13030781>.
- Zhang, N., Wang, Q., Chen, Y., Zhang, S., Zhang, X., Feng, G., Gao, H., Peng, C., Zhu, P., 2024a. Phosphorus Distribution within Aggregates in Long-Term Fertilized Black Soil: Regulatory Mechanisms of Soil Organic Matter and pH as Key Impact Factors. *Agronomy* 14, 936. <https://doi.org/10.3390/agronomy14050936>.
- Zhang, S., Hu, W., Zhang, J., Yu, G., Liu, Y., Kong, Z., Wu, L., 2024b. Long-term cultivation reduces soil carbon storage by altering microbial network complexity and metabolism activity in macroaggregates. *Sci. Total Environ.* 930, 172788. <https://doi.org/10.1016/j.scitotenv.2024.172788>.
- Zhu, J., Sun, Z.-X., 2024. Estimation of Cation Exchange Capacity for Low-Activity Clay Soil Fractions Using Experimental Data from South China. *Agronomy* 14, 2671. <https://doi.org/10.3390/agronomy14112671>.
- Zhu, Y., Marchuk, A., Bennett, J.M., 2020. Ionicity of Clay–Cation Bonds in Relation to Dispersive Behavior of Mg and K Soil Clays as Influenced by pH. *Clays Clay Miner.* 68, 588–600. <https://doi.org/10.1007/s42860-020-00100-x>.
- Zhu, Y., Zhang, M., Han, X., Lu, X., Chen, X., Feng, H., Wu, Z., Liu, C., Yan, J., Zou, W., 2024. Evaluation of the soil aggregate stability under long term manure and chemical fertilizer applications: Insights from organic carbon and humic acid structure in aggregates. *Agric. Ecosyst. Environ.* 376, 109217. <https://doi.org/10.1016/j.agee.2024.109217>.
- Zou, H., Xu, M., Ren, K., Li, D., Zhang, W., Lu, C., Duan, Y., 2024. Discrepant long-term nitrogen mineralization in soil at early and later period after fertilization. *EGU sphere* 1–22. <https://doi.org/10.5194/egusphere-2024-330>.