https://doi.org/10.17221/648/2024-PSE

Long-term effects of sugarcane monoculture on soil pedomorphology and physicochemical properties in tropical agroecosystems

Anna Kusumawati[1]*, *Amir Noviyanto*[2]

[1]*Department of Plantation Management, Polytechnic of Lembaga Pendidikan Perkebunan, Yogyakarta, Indonesia*

[2]*Department of Agrotechnology, Faculty of Agriculture, Stiper Agricultural University, Yogyakarta, Indonesia*

**Corresponding author: kusumawatianna@gmail.com*

Citation: Kusumawati A., Noviyanto A. (2025): Long-term effects of sugarcane monoculture on soil pedomorphology and physicochemical properties in tropical agroecosystems. Plant Soil Environ., 71: 213–231.

Abstract: This study investigates the impact of prolonged sugarcane cultivation on the pedo-morphological characteristics and physicochemical properties of three soil types: Entisols, Inceptisols, and Vertisols, as a basis for determining the improvement step ensuring the sustainability of sugarcane production in Indonesia. Soil samples were collected from fields of sugarcane cultivated for 10, 20, and 30 years to analyse pedo-morphological and physicochemical properties. The results indicate that while Entisols and Inceptisols exhibited significant changes in soil properties with increasing cultivation duration, the pedo-morphology of Vertisols remained relatively stable. All soil types developed Ap horizons due to sugarcane cultivation, with anthropogenic practices leading to more dynamic changes in surface horizons. Extended cultivation reduced soil organic matter, N-total, and available nitrogen, while phosphorus and exchangeable cation availability were influenced by mineral composition. Notably, cation exchange capacity (CEC) decreased in Entisols and Inceptisols but increased in Vertisols. For productivity, Vertisols demonstrated the most stable and highest sugarcane productivity with long-term monoculture cultivation. There is a need for tailored sustainable soil management across different soil types and practices to mitigate soil degradation and maintain nutrient availability to ensure the sustainability of sugarcane production in Indonesia.

Keywords: *Saccharum officinarum* L.; sugarcane sustainable

Sugarcane (*Saccharum officinarum* L.) is a crucial crop in tropical and subtropical regions, cultivated primarily for sugar production and bioenergy generation. By 2017, it was grown in over 100 countries, with Brazil and India leading global production. Indonesia ranks 11th, producing approximately 27.26 million tonnes annually, with most plantations concentrated in Java and Sumatra. Despite its historical peak in the 1930s and subsequent decline (Putra et al. 2020), sugarcane remains an important agricultural commodity. However, intensive monoculture cultivation raises long-term sustainability concerns, particularly in regions where soil properties significantly influence productivity (Sulaiman et al. 2019).

Java contributes about 63% of Indonesia's white sugar output, which is central to national production (Solomon et al. 2016). However, continuous monoculture farming has led to soil degradation, including nutrient depletion, organic matter loss, and structural changes. Combined with intensive mechanisation, prolonged mineral fertiliser and pesticide use can cause soil compaction, reduced water infiltration, and altered microbial activity (Bigott et al. 2019). These pedo-morphological changes threaten soil productivity and sustainability, requiring a better understanding of their impact across different soil types to develop effective land management strategies.

https://doi.org/10.17221/648/2024-PSE

Long-term monoculture can alter soil structure, porosity, and stability, leading to increased compaction, erosion susceptibility, and reduced biodiversity. In tropical agricultural systems, these issues impair nutrient cycling and organic carbon decomposition, negatively affecting productivity (Jean Pierre et al. 2019). While such effects are well-documented in cereal and legume monocultures, research on their impact on sugarcane farming remains limited, especially concerning varying soil types. Java's sugarcane plantations are primarily found on Entisols, Inceptisols, and Vertisols, each responding differently to long-term cultivation. Entisols degrade quickly due to low organic carbon and poor water retention, Inceptisols face nutrient depletion and compaction risks and Vertisols suffer from aeration issues and waterlogging under intensive tillage (Wang et al. 2021).

This study aims to evaluate the long-term effects of sugarcane monoculture on soil pedo-morphological characteristics in Java, specifically across Entisols, Inceptisols, and Vertisols over periods of 10, 20, and 30 years. By analysing soil structure, compaction, organic carbon content, and nutrient availability, this research seeks to inform sustainable land management strategies. Understanding these impacts is crucial for policymakers and farmers to mitigate soil degradation and ensure the long-term viability of sugarcane production in Indonesia (Pang et al. 2021) including in China. The response of soil bacteria, fungal, and arbuscular mycorrhizae (AM).

MATERIAL AND METHODS

Description of the study areas and land management practices. This study was conducted on nine smallholder sugarcane plantations partnered with Madukismo Sugar Factory, selected based on land use duration (10, 20, and 30 years) and soil type Entisols (L1–L3), Inceptisols (L4–L6), and Vertisols (L7–L9). All study sites are located in a tropical climate (Am) according to the Köppen-Geiger classification, with annual rainfall ranging from 1 500 to 3 000 mm, temperatures between 24–30 °C, and humidity levels of 70–88%. The Madukismo Sugar Factory has consistently applied land management practices for decades, including standardised fertilisation, pest control, and leaf removal. Fertilisation was conducted twice, at 1–2 weeks and 6–8 weeks after planting, using 500 kg/ha ammonium sulfate (N 20.8%, S 23.8%) and 400 kg/ha Phonska (N 15%, P 15%, K 15%). Organic fertilisers were not applied. Pest control was performed using mechanical, biological, and chemical methods depending on the type and severity of pest infestations. Dried sugarcane leaves were manually removed to improve crop quality.

Soil sampling and laboratory measurement. Soil pedo-morphological characteristics were observed in each soil profile following USDA guidelines (Field Book for Describing and Sampling Soils by U.S. Department of Agriculture National Resources Conservation Service), including assessments of horizon depth, boundaries, structure, consistency, and colour. Soil samples were collected from each horizon (when the plant was 2 months old), with disturbed samples stored in labelled plastic bags and undisturbed samples extracted using 5 × 5 cm rings. Laboratory analyses were conducted to evaluate the soil's physical and chemical properties. Physical parameters included aggregate stability (De-Boodt), bulk density (ring method), porosity, and particle size distribution (pipette method). Chemical properties measured were organic carbon (Walkley and Black), total nitrogen (Kjeldahl), available nitrogen (Cottenie), available phosphorus (Bray I/Olsen), exchangeable bases (NH_4Cl extract), available boron (Azomethine-H), available zinc (DTPA extraction), and cation exchange capacity (NH_4OAc, pH 7). Soil mineralogy was analysed using X-ray diffraction. Soil physicochemical properties were statistically analysed for correlations using Minitab 16 software (Pennsylvania, USA). At the same time, sugarcane productivity was assessed at each site and analysed using ANOVA at a 5% significance level, followed by Duncan's multiple range test (DMRT) for mean comparisons. Creating correlation heatmap images using the phyton programme (USA).

RESULTS

Pedo-morphology characteristics. Despite its subjectivity, pedo-morphological observation is crucial for assessing soil conditions, as land use and management influence soil colour, structure, and root distribution, impacting root growth, soil erodibility, water flow, and nutrient cycling (Vasu et al. 2021). Consistent land management over time leads to gradual changes in soil pedo-morphology and physicochemical properties (Melo et al. 2017). Table 1 presents the pedo-morphological characteristics of Entisols, Inceptisols, and Vertisols over 10, 20, and 30 years of sugarcane cultivation.

https://doi.org/10.17221/648/2024-PSE

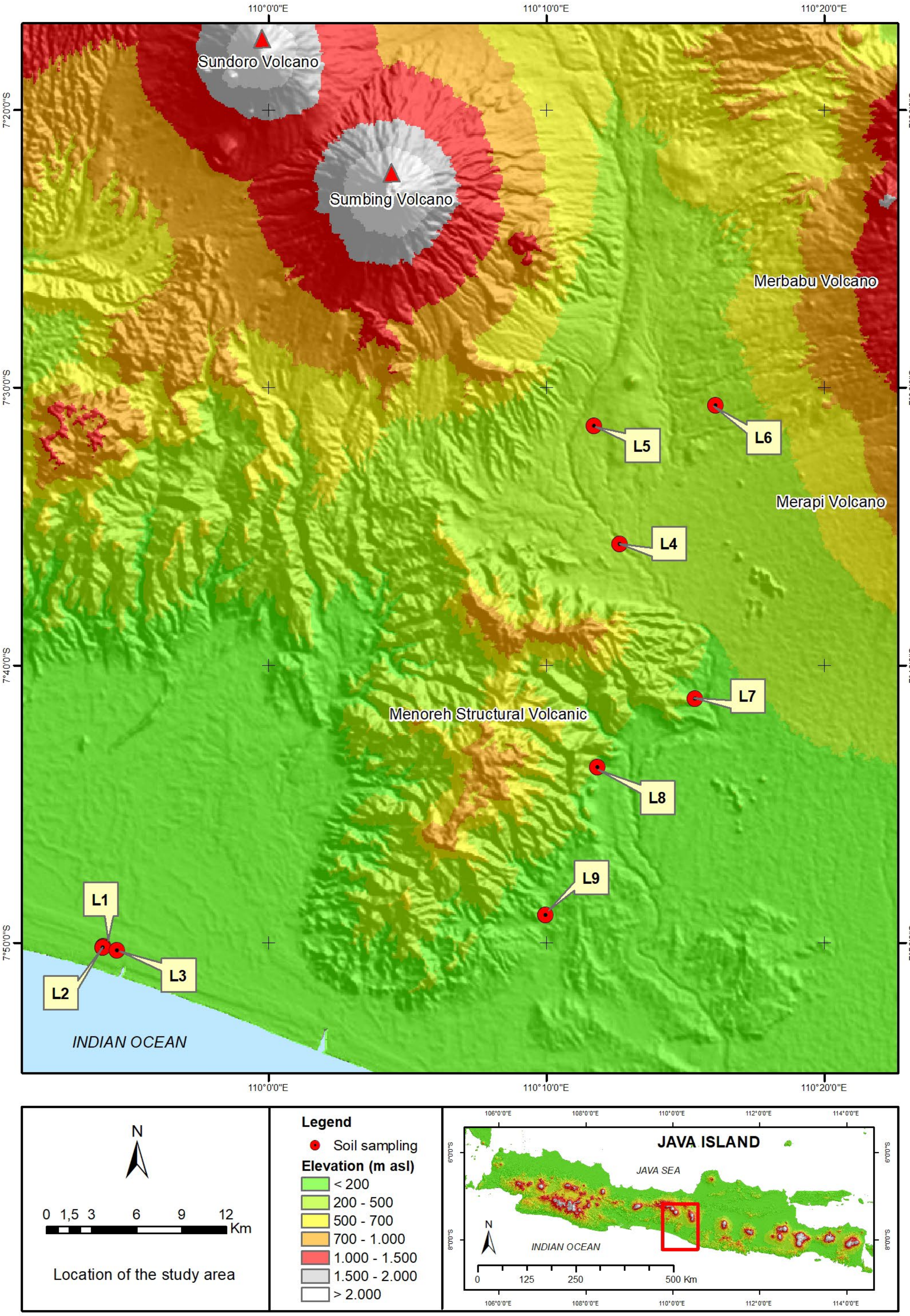

Figure 1. Location of the study area

https://doi.org/10.17221/648/2024-PSE

Table 1. Pedo-morphology characteristics of Entisols, Inceptisols, and Vertisols

Code	Soil horizon	Depth (cm)	Horizon boundary	Colour (moist)	Texture	Structure types	Consistency	Root
L1	Ap	0–25	C, S	10 YR 3/2	LS	GR	SO-PO	F, 2
	A1	25–41	G, S	7.5 YR 2.5/2	SL	GR	SS-PO	F, 1
	A2	41–80	D, S	7.5 YR 2.5/2	SL	GR	SO-PO	F, 1
	A3	80–120	D, S	7.5 YR 2.5/2	SL	GR	SO-PO	F, 1
	A4	> 120	–	7.5 YR 2.5/2	LS	GR	SO-PO	–
L2	Ap	0–28	C, S	10 YR 3/1	LS	GR	SO-PO	F, 2
	A1	28–85	D, S	7.5 YR 3/2	LS	GR	SO-PO	F, 1
	A2	85–110	D, S	7.5 YR 2.5/2	LS	GR	SO-PO	M, 1
	A3	> 110	–	10 YR 2/2	LS	GR	SO-PO	C, 1
L3	Ap1	0–16	C, S	10 YR 3/1	LS	GR	SO-PO	F, 1
	Ap2	16–39	G, S	10 YR 3/2	LS	GR	SO-PO	F, 1
	A1	39–75	D, S	10 YR 2/1	LS	GR	SO-PO	F, 1
	A2	75–99	D, S	10 YR 2/1	LS	GR	SO-PO	F, 1
	A3	99–137	D, S	10 YR 3/1	LS	GR	SO-PO	F, 1
	A4	> 137	–	10 YR 3/2	LS	GR	SO-PO	F, 1
L4	Ap	0–30	C, S	10 YR 4/6	SL	SBK	MS-MP	F, 1
	A	30–61	C, S	10 YR 4/6	CL	SBK	SS-PO	–
	Bw1	61–73	C, S	10 YR 4/3	SL	SBK	SS-PO	–
	Bw2	73–100	D, S	10 YR 4/4	SL	SBK	SS-PO	–
	Bw3	100–117	D, S	7.5 YR 4/3	L	SBK	SS-PO	–
	Bw4	117–158	C, S	7.5 YR 4/3	L	SBK	SS-PO	C, 1
	Bw5/C	> 158	–	5 YR 4/4	SL	SBK	MS-MP	–
L5	Ap1	0–10	G, S	10 YR 3/1	SCL	SBK	FR	F, 2
	Ap2	10–52	G, W	10 YR 2/2	SL	SBK	FR	M, 2
	Bw1	52–75	D, S	10 YR 3/2	SCL	SBK	FR	M, 1
	Bw2	75–116	D, S	10 YR 3/3	CL	SBK	FI	M, 3
	Bw3	116–150	D, S	10 YR 3/3	C	SBK	FI	C, 1
	Bw4/C	> 150	–	10 YR 3/4	C	SBK	FI	–
L6	Ap	0–20	G, S	10 YR 3/2	SL	GR	SO-PO	F, 3
	B1	20–40	G, S	10 YR 3/2	SL	GR	FR	F, 1
	B2	40–58	G, S	10 YR 3/3	SL	GR	FR	F, 1
	B3	58–95	D, S	10 YR 3/2	SCL	SBK	FR	M, 1
	B4	95–140	D, S	7.5 YR 3/4	SCL	SBK	FR	F, 1
	B5/C	> 140	–	7.5 YR 3/2	SCL	SBK	FR	F, 1
L7	Ap1	0–15	C, S	10 YR 4/6	CL	SBK	MS-MP	F, 2
	Ap2	15–40	D, S	10 YR 4/3	C	ABK	MS-MP	F, 1
	A1	40–80	D, S	10 YR 4/2	SC	ABK	VS-VP	F, 1
	A2	> 80	–	10 YR 7/1	C	ABK	VS-VP	F, 1
L8	Ap1	0–10	C, S	10 YR 4/2	C	SBK	MS-MP	C, 3
	Ap2	10–35	D, S	10 YR 4/3	C	SBK	MS-MP	C, 2
	A1	35–62	D, S	10 YR 6/2	C	ABK	VS-VP	M, 2
	A2	62–120	D, S	10 YR 7/2	SiC	ABK	VS-VP	F, 2
	A3	> 120	–	10 YR 7/2	C	ABK	VS-VP	F, 1
L9	Ap1	0–20	C, S	10 YR 4/1	C	SBK	VS-VP	M, 2
	Ap2	20–60	D, S	10 YR 4/6	C	SBK	VS-VP	F, 2
	A1	60–95	D, S	10 YR 4/3	C	ABK	VS-VP	F, 1
	A2	95–134	D, S	5 YR 4/2	CL	ABK	MS-MP	F, 1
	A3	> 134	–	7.5 YR 5/4	SL	ABK	VS-VP	F, 1

Horizon distinctness – clear (C); gradual (G); diffuse (D); horizon topography – smooth (S); wavy (W); soil colour – 10 YR 7/2 (light gray); 10 YR 7/1 (light gray); 10 YR 6/2 (light brownish gray); 10 YR 4/6 (dark yellowish brown); 10 YR 4/4 (dark yellowish brown) 10 YR 4/3 (brown); 10 YR 4/2 (dark greyish brown); 10 YR 4/1 (dark gray); 10 YR 3/4 (dark yellowish brown); 10 YR 3/3 (dark brown); 10 YR 3/2 (very dark greyish brown); 10 YR 3/1 (very dark gray); 10 YR 2/2 (very dark brown); 10 YR 2/1 (black); 7.5 YR 5/4 (brown); 7.5 YR 4/3 (brown); 7.5 YR 3/4 (dark brown); 7.5 YR 3/2 (dark brown); 7.5 YR 2.5/2 (very dark brown); 5 YR 4/4 (reddish brown); 5 YR 4/2 (dark reddish gray). Texture – loamy sand (LS); sandy loam (SL); loam (L); sandy clay loam (SCL); clay loam (CL); sandy clay (SC); silty clay (SiC); clay (C); structure type – granular (GR); angular blocky (ABK); sub angular blocky (SBK); consistence – friable (FR); firm (FI); nonsticky (SO); slightly sticky (SS); moderately sticky (MS); very sticky (VS); nonplastic (PO); moderately plastic (MP); very plastic (VP); root quantity – few (1); common (2); many (3); root size – fine (F); medium (M); coarse (C)

https://doi.org/10.17221/648/2024-PSE

Entisols exhibit a simpler horizon sequence in 10-year (L1) and 20-year (L2) plots compared to the 30-year plot (L3) (Figure 2A). The Ap horizon, formed due to continuous ploughing, becomes thicker and more structured over time. Loamy sand to sandy loam textures dominate, contributing to good water infiltration in L1, while root abundance decreases with prolonged cultivation. Inceptisols, being more developed, display a cambic endopedon (Bw) and a fuller horizon sequence (Figure 2B). The Ap horizon remains prominent across all cultivation periods, with greater thickness at 10 and 20 years. The presence of an A horizon beneath the Ap in the 10-year plot (L4) suggests minimal anthropogenic disturbance. Similar to Entisols, endoaquic conditions in L4 indicate efficient water infiltration.

The parent material remains visible between the Bw and C horizons, likely derived from Mt. Merbabu and Mt. Merapi, consisting of volcanic ash and sediment deposits. These materials weather easily, forming

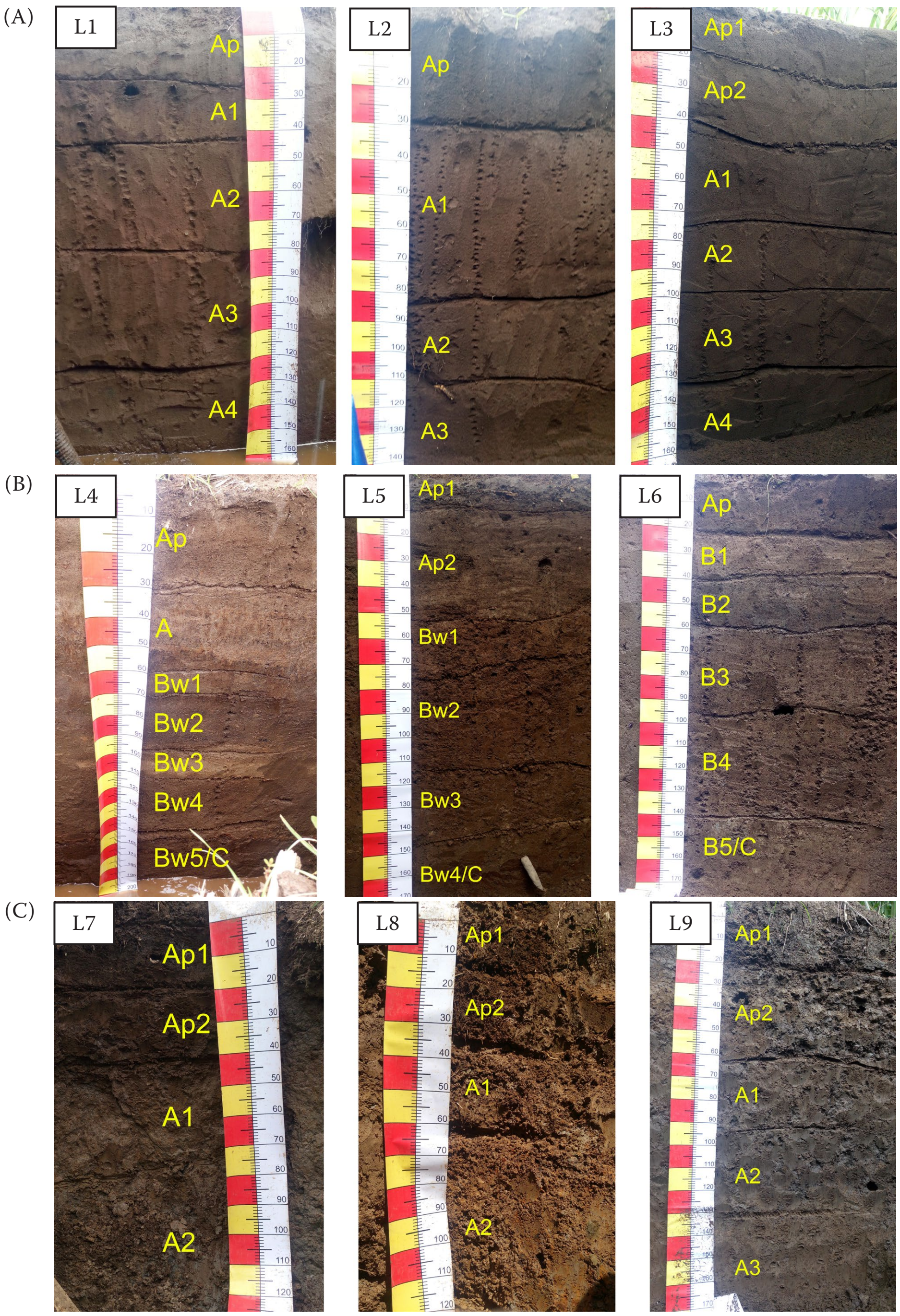

Figure 2. Pedo-morphology characteristics of (A) Entisols; (B) Inceptisols and (C) Vertisols

https://doi.org/10.17221/648/2024-PSE

minimal clay layers (Table 1). Inceptisol textures range from sandy loam to sandy clay loam across all cultivation periods. L4 and L5 exhibit rounded clod structures, while L6's surface horizon is more granular due to unweathered volcanic ash deposits. Soil consistency and root quantity vary, as shown in Figure 2B.

Vertisols, formed from base cation dissolution and fine particle deposition, predominantly exhibit clay textures (Table 1). Their development is influenced by limestone from the Sentolo formation. Across all cultivation periods, they feature only Ap and A horizons, with no B horizon due to shrink-swell behaviour, which forms slickensides at depths > 80 cm (Figure 2C). This process creates angular clods in subsurface horizons, while surface clumps may result from human or plant activity. Unlike Entisols and Inceptisols, no water emerges in L7 due to the dense structure.

Vertisols remain sticky to very sticky, making ploughing labour-intensive. Cultivation duration has minimal impact on their pedo-morphology, as pedoturbation limits further soil development. Surface cracking can hinder root growth, though favourable chemical properties support plant productivity. Figure 2C illustrates Vertisol pedo-morphology over 10-, 20-, and 30-year sugarcane periods.

Particle size distribution. The particle size distributions of Entisols, Inceptisols, and Vertisols vary significantly. Figure 3 illustrates these variations across soil types and cultivation periods. Entisols remain sand-dominant (60–80%) with < 20% silt and clay across all cultivation periods. Inceptisols exhibit a broader range, with sand at 20–80%, silt at 15–40%, and clay at 10–50%, while Vertisols contain the highest clay content (40–70%), with sand and silt each below 40% clay content in Inceptisols generally increases with depth, whereas Vertisols show fluctuations due to pedoturbation. Cultivation duration has minimal impact on particle size distribution, which is primarily influenced by parent material, pedogenic weathering, volcanic ash deposition, erosion, and human activity.

Soil physical properties. Sugarcane cultivation over 10–30 years affects soil structure, particularly in surface horizons. While aggregate stability in the surface layer (< 30 cm) remains largely unchanged due to continuous land management, it increases in subsurface layers (> 60 cm) over time, influenced by clay translocation. However, stability across all soil types remains within the low to medium range (40–100) (Figure 4).

Bulk density. Bulk density, a sensitive indicator of soil disturbance, generally increases with depth. In the surface horizon (< 30 cm), it remains stable regardless of cultivation duration, while in the subsurface, it increases over time in Entisols and Inceptisols. Across all periods, bulk density stays within the medium range (1–1.5 g/cm^3) (Figure 4).

Porosity. Porosity, which influences air circulation, water infiltration, and root growth, varies among soil types. It declines over time in Entisols, increases in Inceptisols, and remains stable in Vertisols. Entisols maintain higher porosity (50–60%) with their coarser texture, while finer-textured Vertisols exhibit lower porosity (30–40%). Despite these differences, porosity remains above 30%, supporting sugarcane growth. Figure 4 summarises the soil's physical properties across cultivation periods.

Soil chemical properties. Soil organic carbon is essential for improving soil structure, water retention, microbial activity, carbon storage, and nutrient cycling. In Entisols, organic carbon decreases with prolonged sugarcane cultivation across all horizons, while Inceptisols show a decline only at depths > 100 cm, with an increase at 0–100 cm during cultivation. Similarly, Vertisols exhibit increased organic carbon at depths > 40 cm (Figure 5). The average organic carbon content across research sites ranges from 1 to 2.5 mg/100 g, classified as low to medium. Although sugarcane monoculture does not add organic carbon, sugarcane residue after harvest enhances soil organic carbon levels compared to burning residues.

All soil types' total nitrogen (N) is very low, ranging from 0.05 to 0.2 mg/100 g, with optimal levels found at 0–60 cm depth. Extended cultivation reduces N-total in Entisols and Inceptisols at depths > 80 cm. Phosphorus (P) availability varies, peaking in Vertisols at 30 mg/kg, while Entisols show an increase over time, and Inceptisols and Vertisols experience declines. Cation exchange capacity (CEC) is affected by organic matter and particle size distribution. CEC decreases in Entisols and Inceptisols with longer cultivation periods but increases in Vertisols, reaching 40 $cmol_+$/kg (high category) after > 20 years of cultivation. CEC values for Entisols and Inceptisols range from 10 to 20 $cmol_+$/kg (low to medium), with Inceptisols showing higher values than Entisols (Figure 5). Figure 5 illustrates the soil chemical properties (organic carbon, N-total, available P, CEC) across all sugarcane cultivation periods in Entisols, Inceptisols, and Vertisols.

The average exchangeable sodium (Na) content is highest in Entisols. After 10 years of sugarcane

https://doi.org/10.17221/648/2024-PSE

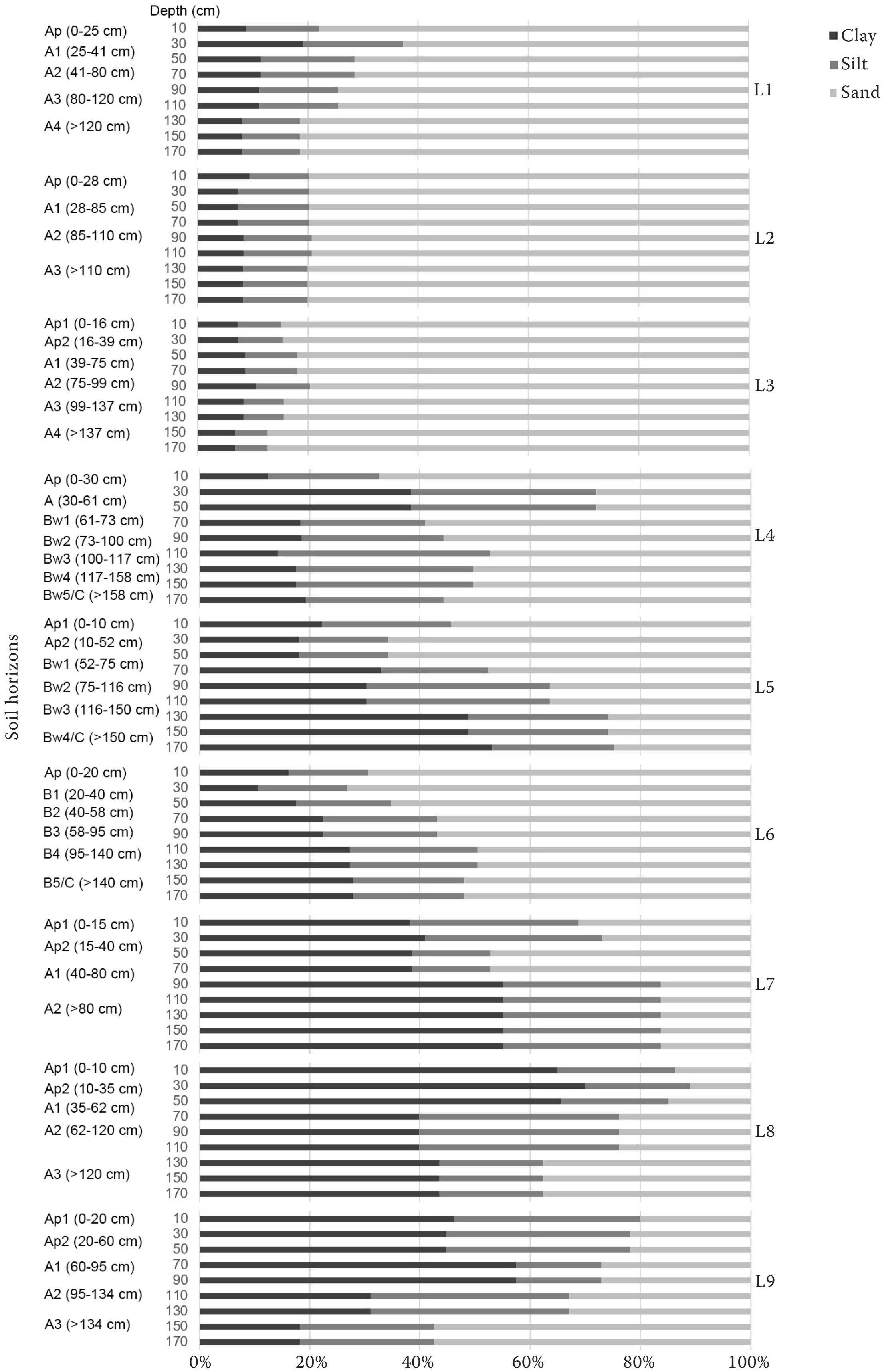

Figure 3. Particle size distribution of soils

https://doi.org/10.17221/648/2024-PSE

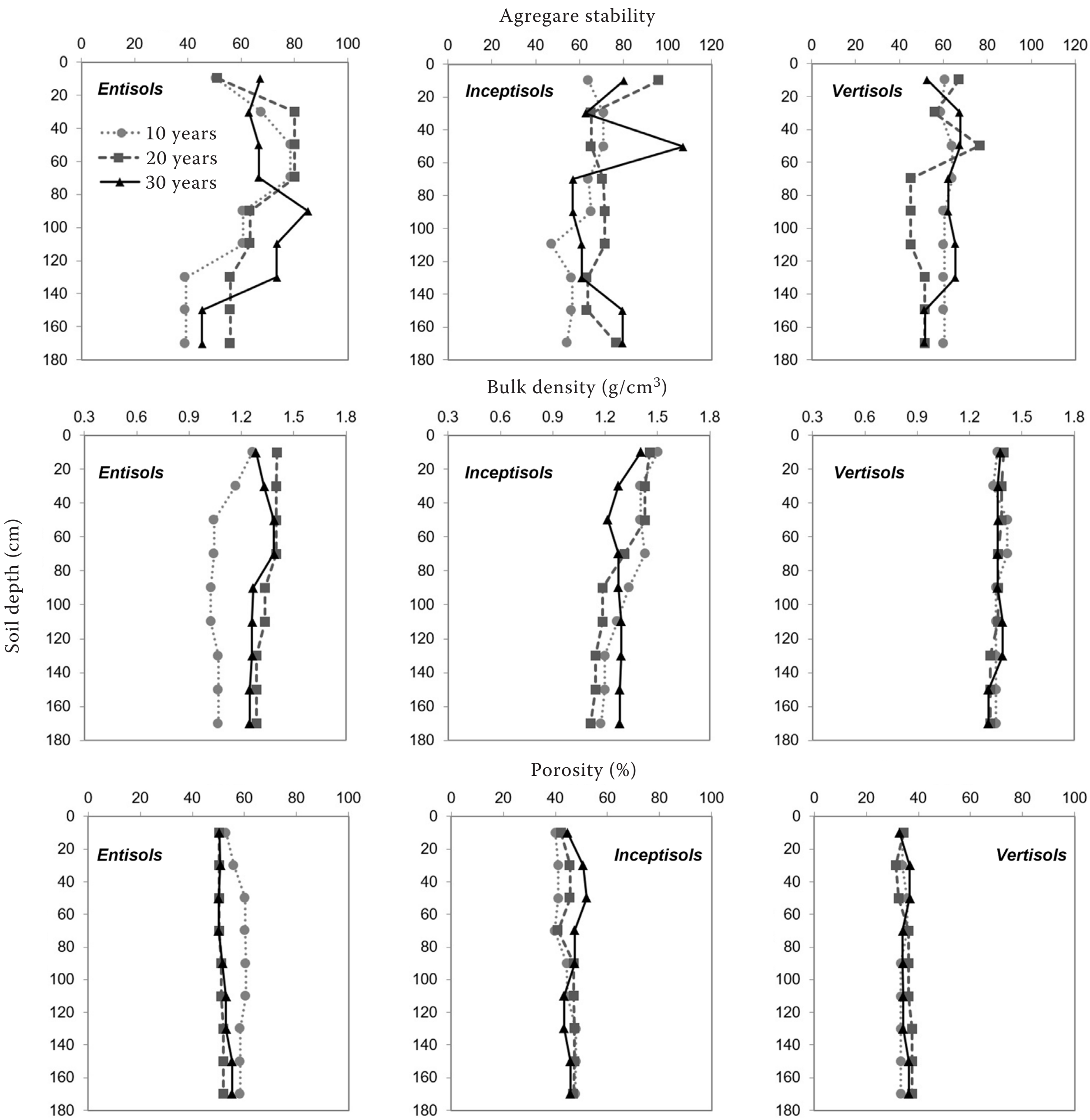

Figure 4. Soil physical properties

cultivation, the Na content in Entisols (0.8 $cmol_+$/kg) is comparable to that in Inceptisols and Vertisols (Figure 6). This content increases to 1.6 $cmol_+$/kg during the 20- to 30-year period, with levels > 0.8 $cmol_+$/kg classified as high. However, the duration of cultivation does not significantly affect Na content in Inceptisols and Vertisols.

In Entisols and Inceptisols, exchangeable potassium (K) is lower during the 10- and 30-year periods compared to the 20 years (Figure 6). In Vertisols, K levels decline with longer cultivation periods. Soil depth has a more significant impact on reducing exchangeable K than on other base cations (Na, Ca, Mg), with surface horizon K content classified as high (> 0.6 $cmol_+$/kg) and decreasing to medium (0.4–0.6 $cmol_+$/kg) (Figure 6).

The duration of sugarcane cultivation influences exchangeable calcium (Ca) content across all soil types, increasing in Entisols while decreasing in Inceptisols and Vertisols (Figure 6). Although there are variations in Ca content, these are not significant among cultivation periods. The exchangeable Ca in

https://doi.org/10.17221/648/2024-PSE

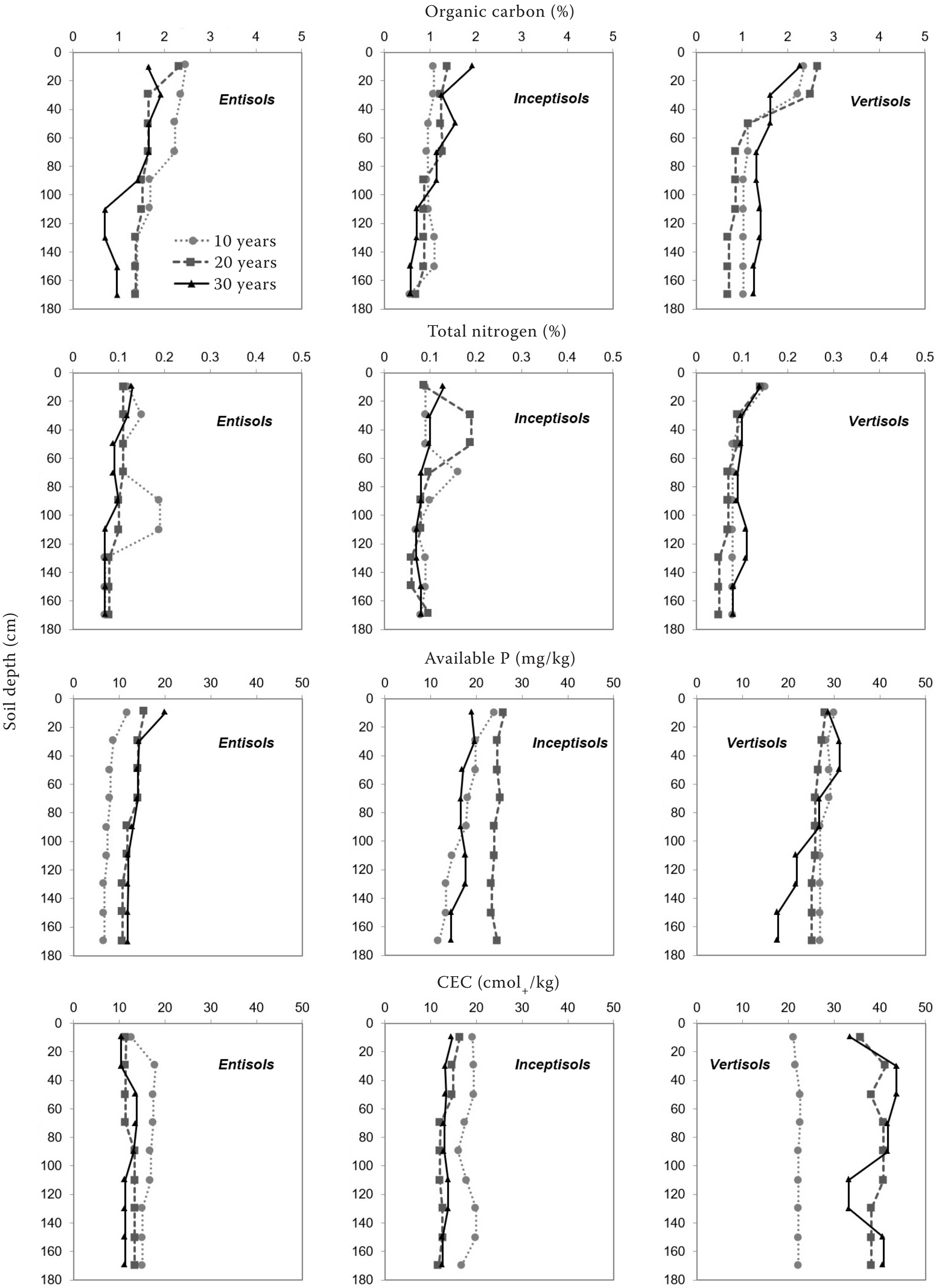

Figure 5. Soil chemical properties, organic carbon, total nitrogen (N), available phosphorus (P), and cation exchange capacity (CEC)

https://doi.org/10.17221/648/2024-PSE

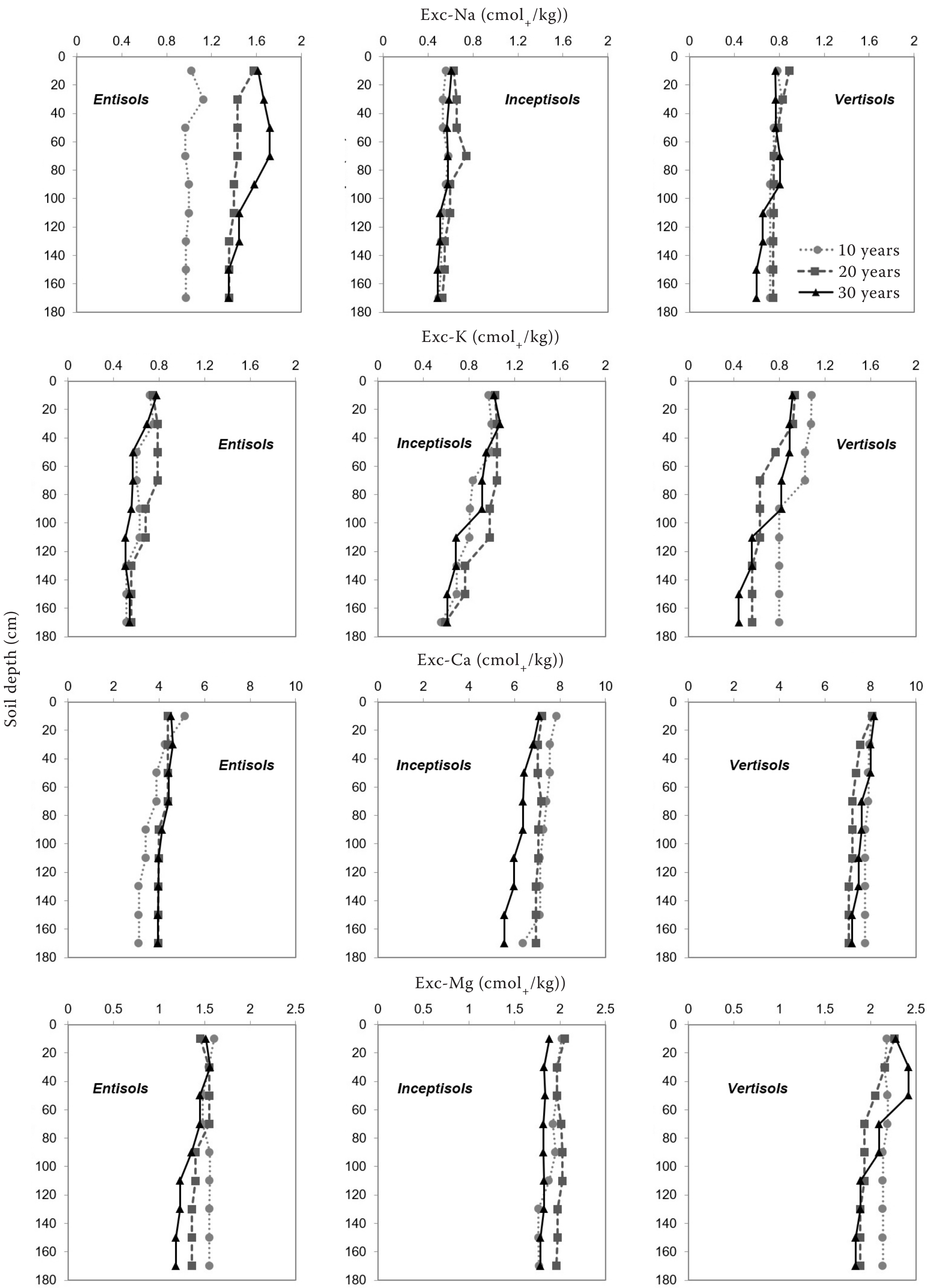

Figure 6. Exchangeable base cation in the soils (Na, K, Ca, Mg)

https://doi.org/10.17221/648/2024-PSE

the surface horizon of Entisols is lower (< 5 $cmol_+$/kg), while in Inceptisols and Vertisols, it ranges from 7 to 8 $cmol_+$/kg (Figure 6). Increased soil depth affects Ca reduction but is insignificant compared to the surface horizon.

In Entisols, exchangeable magnesium (Mg) content shows no significant differences at depths < 100 cm during the cultivation periods, but it declines gradually at depths > 100 cm (Figure 6). In Inceptisols, Mg remains relatively constant from the surface to subsurface horizons, while Vertisols display an unclear pattern below 100 cm but show significant declines at greater depths (Figure 6).

Exchangeable bases (Na, K, Ca, Mg) are crucial for plant growth, with their sources varying by location and influenced by the sugarcane cultivation environment. In Entisols, proximity to the sea increases Na levels, while Inceptisols, derived from weathered volcanic material, likely contain more Ca and Mg. Vertisols, formed from limestone dissolution, may have higher base content compared to Entisols and Inceptisols. Figure 6 illustrates the exchangeable base content across different soil types and sugarcane cultivation periods.

Plants absorb nitrogen (N) from the soil as ammonium (NH_4^+-N) and nitrate (NO_3^--N). NH_4^+-N content in Entisols and Vertisols ranges from 40 to 80 mg/kg, while Inceptisols exceed 80 mg/kg at depths of 60 to 120 cm (Figure 7). In the surface horizon (depth < 30 cm), the highest NH_4^+-N levels are found in Vertisols after 10 years of sugarcane cultivation. NH_4^+-N content generally decreases with soil depth but remains around 40 to 60 mg/kg, except in Entisols after 20 years and Vertisols after 10 years (Figure 9). The differences in cultivation periods show no clear pattern in surface horizons, though the lowest ammonium content occurs at 30 years in the subsurface horizon.

In the surface horizon, the highest NO_3^--N content (80–100 mg/kg) is found in Vertisols after 20 years of sugarcane cultivation, while the lowest NO_3^--N level (20 mg/kg) is also in Vertisols at depths of 60 to 120 cm. Overall, NO_3^--N content in the three soil types does not demonstrate a clear correlation with sugarcane cultivation duration or increasing soil depth. Figure 7 illustrates the available nitrogen content as NH_4^+-N and NO_3^--N across all research sites.

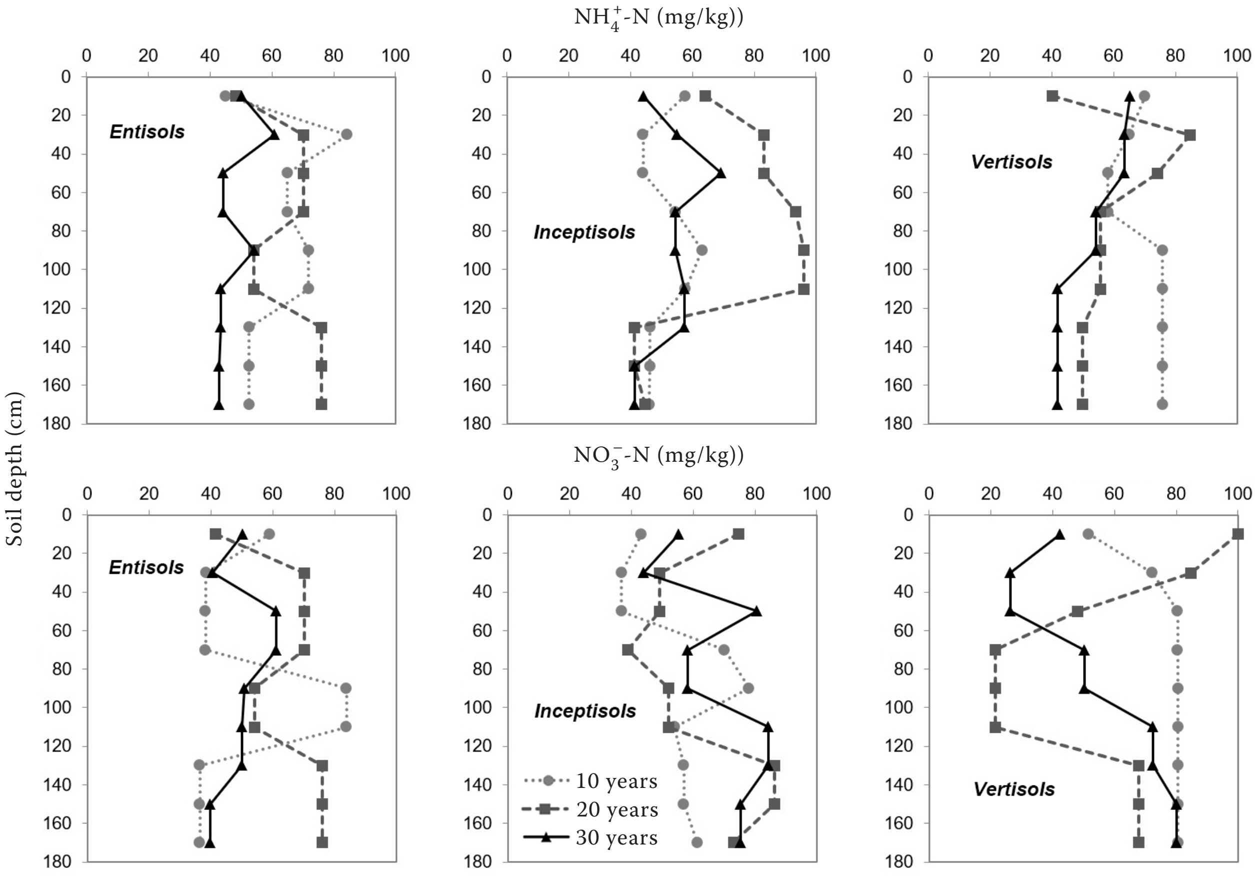

Figure 7. Available nitrogen (N) in the soils, NH_4^+-N and NO_3^--N

https://doi.org/10.17221/648/2024-PSE

The availability of micronutrients boron (B) and zinc (Zn) is essential in sugarcane cultivation to enhance sugar content. In Entisols, the available B content remains stable over time and does not vary significantly with soil depth. Inceptisols, available B decreases from 0.6 mg/kg at 10 years to 0.2 mg/kg at 30 years, while in Vertisols, it increases to 0.4 mg/kg with longer cultivation periods. The available Zn content in both Entisols and Vertisols averages around 0.4 mg/kg, with no significant changes over time, although the 30-year period tends to show lower values. Inceptisols, available Zn increases, peaking at 0.8–1.6 mg/kg after 20 years, likely due to leaching processes. Figure 8 illustrates the availability of micronutrients B and Zn across all research sites.

Soil mineralogy. Mineral types can reveal soil parent material origins and pedological processes, both key in influencing soil physicochemical properties. In Entisols, the minerals present vary across cultivation periods: plagioclase and antigorite are found in the 10- and 30-year periods, while plagioclase and kaolinite appear in the 20 years. Plagioclase, a consistent component in Entisols, includes anorthite (100% Ca) and albite (100% Na) members. Its presence likely impacts exchangeable base content, especially for Ca and Na. Antigorite and kaolinite, 1:1 (Si) silicate minerals, have minimal charge and limited effect on soil chemistry. Figure 9 illustrates mineral types in Entisols across different cultivation periods.

Inceptisols exhibit a diverse range of soil minerals. In Inceptisols under a 10-year sugarcane cultivation period, minerals include pyrophyllite, antigorite, dickite, and paragonite. After 20 years, minerals shift to vivianite, gibbsite, kaolinite, and hematite, while after 30 years, they include lapygorskite, halloysite, antigorite, and paragonite. Pyrophyllite, a 2:1 mineral with a simple composition, lacks isomorphic substitution. Gibbsite is commonly found in tropical soils, and hematite originates from volcanic rock parent materials. Like kaolinite but with two water molecules in the interlayer space, Halloysite also forms through volcanic ash weathering. Despite the mineral variety, many minerals in Inceptisols signify volcanic material weathering processes. Figure 10 illustrates these mineral types across different Inceptisol cultivation periods.

Vertisols, typically rich in 2:1 type minerals, exhibit varying mineral compositions across sugarcane

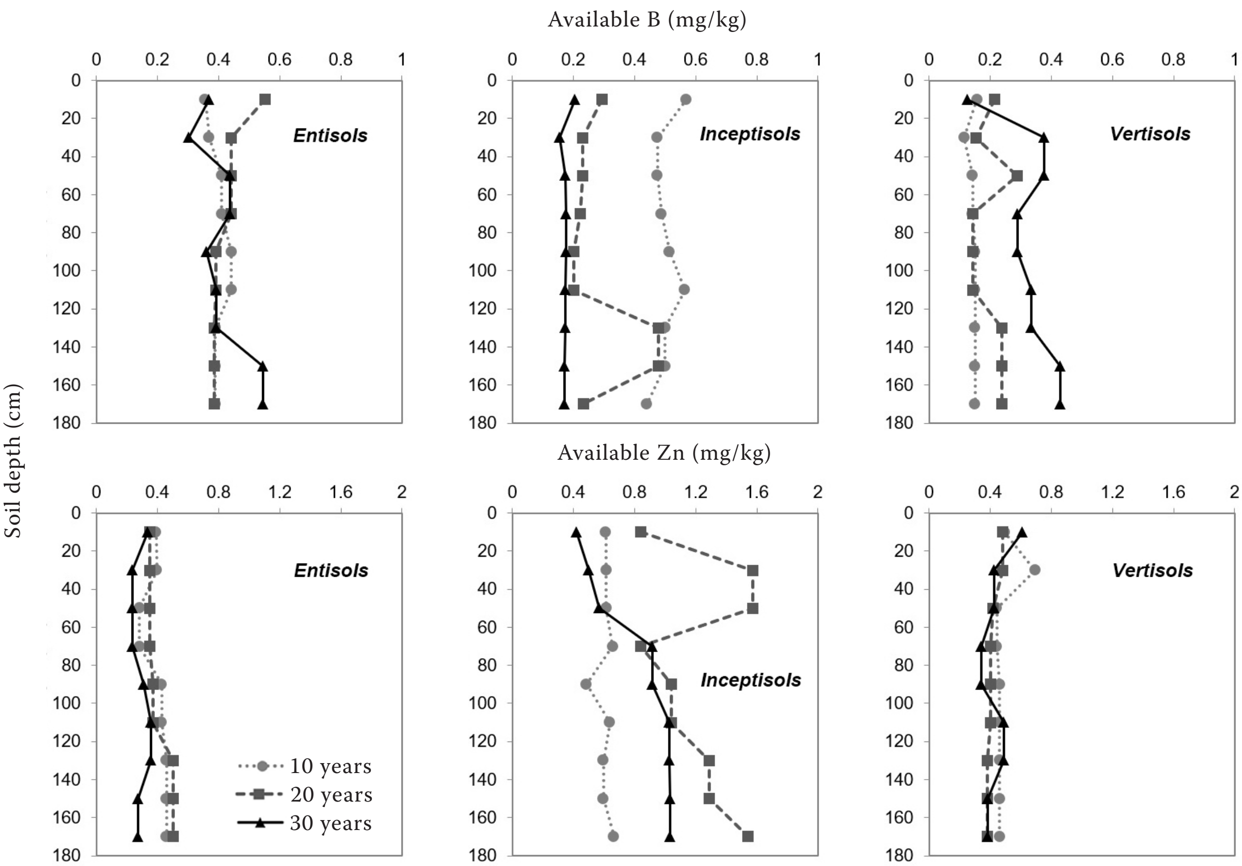

Figure 8. Available micronutrients in the soils (B and Zn)

https://doi.org/10.17221/648/2024-PSE

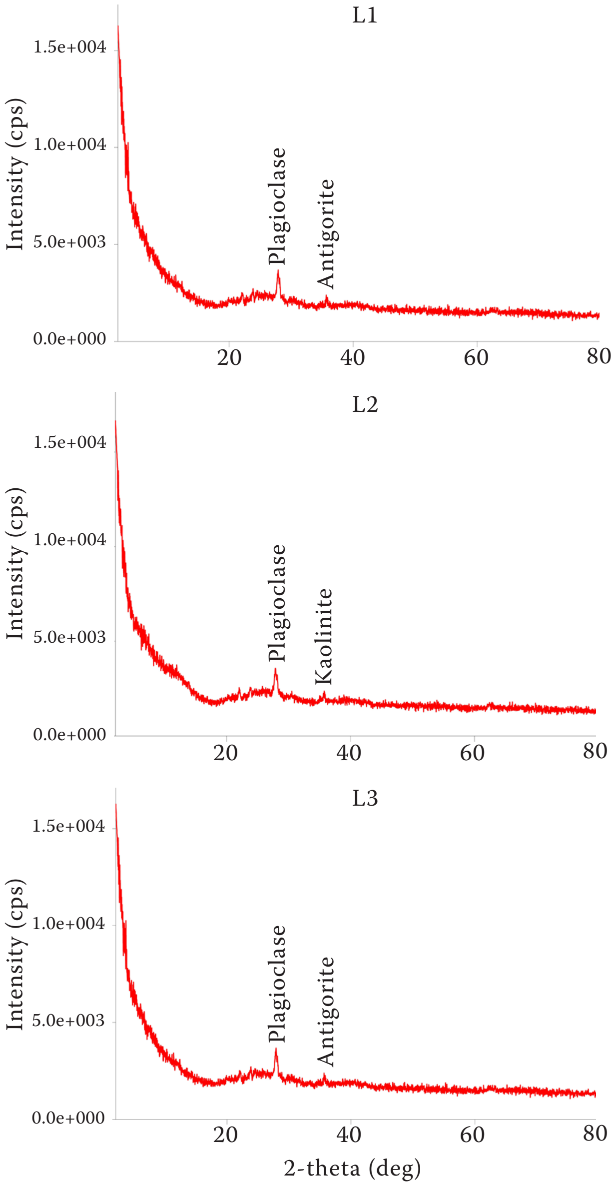

Figure 9. Mineralogy types in Entisols

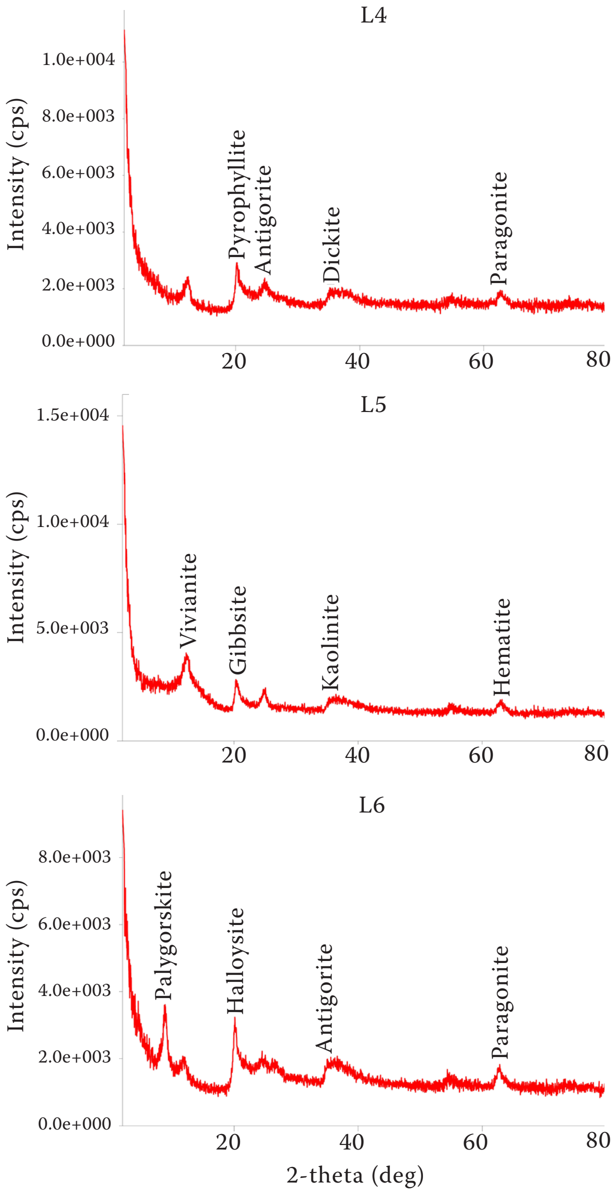

Figure 10. Mineralogy types in Inceptisols

cultivation periods. After 10 years of cultivation, Vertisols contain fibroferrite, natrolite, vermiculite, and chamosite. In the 20 years, minerals include vivianite, paragonite, kaolinite, and periclase, while the 30-year period shows paragonite, stevensite, and kaolin. Vermiculite, a 2:1 layer structure mineral, features Mg^{2+} in its interlayer, whereas natrolite, part of the zeolite group, has high Na^{+} content. Vivianite, an iron phosphate mineral, is stable in sediment-rich environments. Paragonite is a mica with Na^{+} dominating the interlayer. Periclase is a magnesium (MgO) mineral commonly found in limestone or dolomite, while stevensite, a member of the montmorillonite group, imparts expansion and contraction properties to the soil. Figure 11 illustrates the mineral types in Vertisols across different cultivation periods.

DISCUSSION

Long-term monoculture sugarcane cultivation significantly impacts soil pedo-morphological characteristics and physicochemical properties, affecting both surface and subsurface horizons. Increasing cultivation duration contributes to forming Ap horizons, which land management practices influence. Although the thickness of the Ap horizon varies

https://doi.org/10.17221/648/2024-PSE

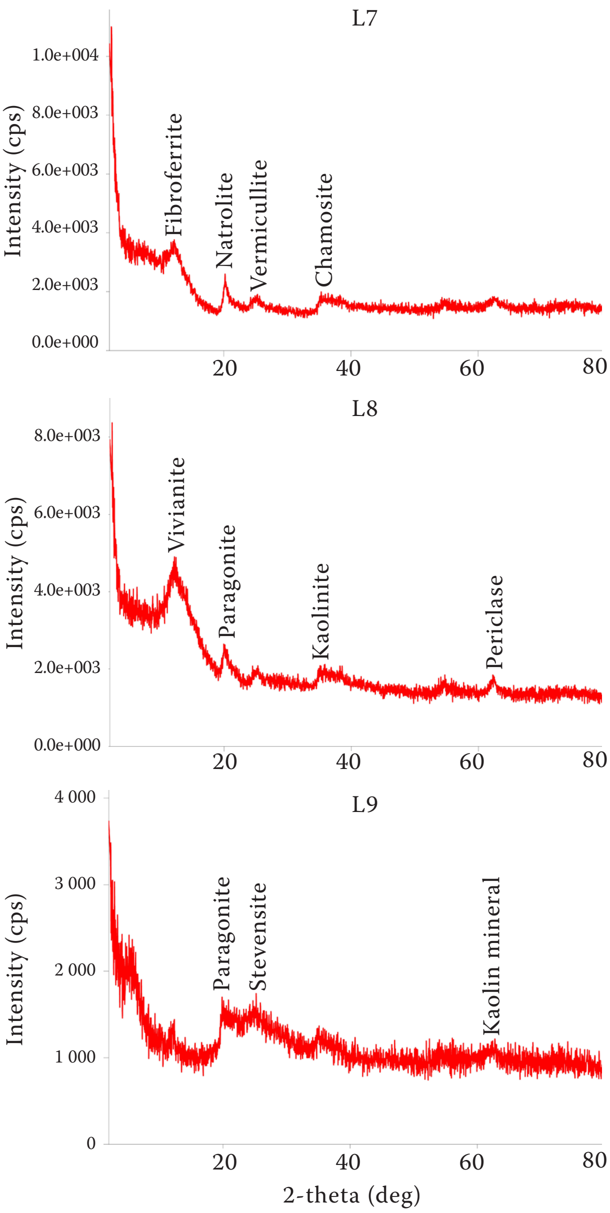

Figure 11. Mineralogy types in Vertisols

among soil types, it generally increases with extended sugarcane cultivation. However, the Ap horizon may be shallower in longer cultivation periods due to disturbances like erosion, which reduces surface soil material. Additionally, the formation of the Ap horizon can be hindered by the accumulation of volcanic ash or sedimentation (Schoonover and Crim 2015). Across all soil types, Ap horizons tend to be darker, with chroma values less than 2 and higher organic matter content compared to underlying horizons. Other pedogenic horizons, such as the Bw horizon in Inceptisols, show minimal influence from sugarcane cultivation duration.

Changes in soil physical properties are more pronounced in the Ap horizon and tend to decrease in deeper horizons. Seasonal management practices – such as tillage, planting, fertilisation, and harvesting – are crucial in affecting bulk density and porosity. Initial tillage can lower bulk density, but subsequent soil reconsolidation often restores it (Reichert et al. 2017). Bulk density is generally higher in surface horizons than subsurface ones, likely due to soil compaction (De Lima et al. 2017). Bulk density and porosity variations across different soil types and monoculture durations stem from contrasting clay content (Sekucia et al. 2020). Entisols exhibit greater variability in bulk density and porosity due to their lower clay content (< 20%), whereas Vertisols, with higher clay content (> 40%), show consistent bulk density and porosity across cultivation periods. Higher clay content enhances the soil's ability to retain physical properties against anthropogenic disturbances (Tolimir et al. 2020).

High clay content also aids in maintaining organic carbon stability. Organic matter is vital for long-term sugarcane cultivation, supporting soil fertility and enhancing yield (Chi et al. 2017). In Entisols, organic carbon tends to decrease in subsurface horizons, unlike in Inceptisols and Vertisols, where higher clay content slows organic carbon decomposition, leading to organic carbon accumulation. Clay particles help stabilise soil aggregates, improving soil structure (Qi et al. 2022). Due to lower clay content, tillage in Entisols is typically lighter than in Inceptisols and Vertisols. This may increase aggregate damage and facilitate oxygen flow into the soil, stimulating microbial activity and producing organic carbon loss as carbon dioxide emissions. The low surface area of kaolinitic minerals in Entisols can also limit the soil's carbon retention capacity (Georgiou et al. 2022) but the amount and global capacity for storage in this form remain unquantified. Here, we produce spatially-resolved global estimates of mineral-associated organic carbon stocks and carbon-storage capacity by analyzing 1 144 globally-distributed soil profiles. We show that current stocks total 899 Pg C to a depth of 1 m in non-permafrost mineral soils. Although this constitutes 66% and 70% of soil carbon in surface and deeper layers, respectively, it is only 42% and 21% of the mineralogical capacity. Regions under agricultural management and deeper soil layers show the largest undersaturation of mineral-associated carbon. Critically, the degree of undersaturation indicates sequestration efficiency over years to decades. We show that, across 103 carbon-accrual measurements

https://doi.org/10.17221/648/2024-PSE

spanning management interventions globally, soils furthest from their mineralogical capacity are more effective at accruing carbon; sequestration rates average 3-times higher in soils at one tenth of their capacity compared to soils at one half of their capacity. Our findings provide insights into the world's soils, their capacity to store carbon, and priority regions and actions for soil carbon management.","container-title":"Nature Communications".

Organic carbon positively correlates with total nitrogen (Figure 12). The absence of organic fertiliser in sugarcane fields results in low total nitrogen across all study sites despite nitrogen's essential role in plant growth and yield. Lal (2014) emphasised the need to maintain carbon and nitrogen levels to prevent soil degradation, supporting sustainable agricultural productivity. Currently, sugarcane cultivation relies primarily on sugarcane residue for organic matter at harvest. Residue can increase organic carbon levels by 5 g/kg after eight years (Galdos et al. 2009) and 9.2 g/kg after 55 years (Canellas et al. 2010) either with or without burning crop residues when harvesting. Continuous incorporation of sugar cane residues increased carbon. While sugarcane residue contributes to organic matter and total nitrogen levels, the intensity and quality of organic matter need to be considered to sustain soil health (Purwanto and Alam 2020). Adding organic matter can enhance nitrogen mineralisation, promoting the availability of ammonium and nitrate for plant uptake.

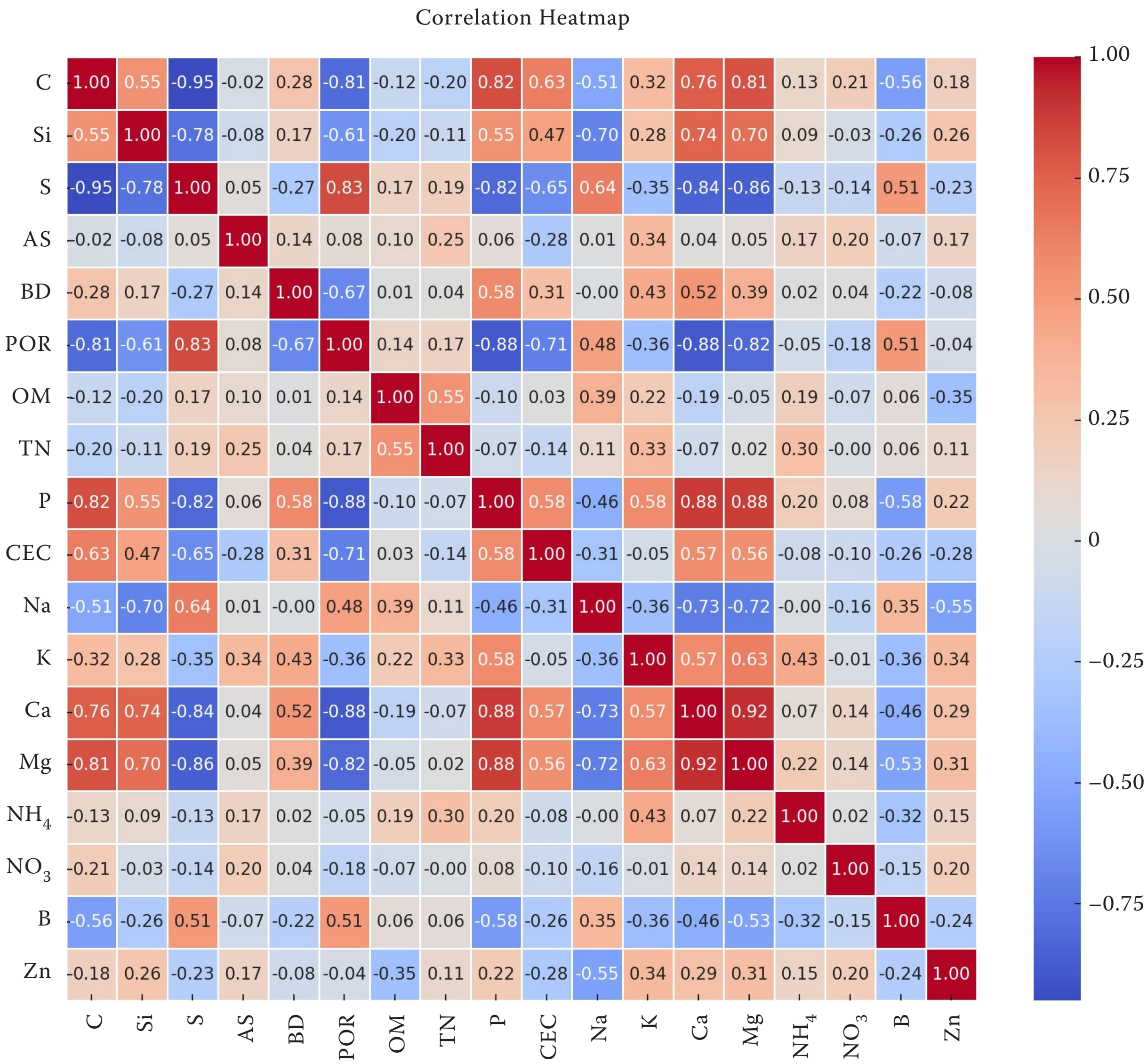

Figure 12. Correlation between variables. AS – aggregate stability; BD – bulk density; POR – soil porosity; OM – organic matter; TN – total nitrogen; CEC – cation exchange capacity

https://doi.org/10.17221/648/2024-PSE

Prolonged sugarcane cultivation decreases ammonium levels in the soil, particularly in Entisols. The high porosity in Entisols may result in greater ammonium loss compared to Inceptisols and Vertisols. However, clay mineral type also influences ammonium fixation, preventing its leaching by water. Clay minerals possess negative charges, which balance with cations in the soil. Cations similar to ammonium, such as potassium, share comparable ionic radii and low hydration energy (Zhang et al. 2021). A positive correlation between ammonium and potassium levels (Figure 12) suggests that ammonium fixation capacity may also depend on potassium saturation. Kaolinite in Entisols does not effectively fix ammonium due to limited interlayer expansion (Gurav et al. 2024) charge density, as well as the location of charge in smectitic soil clay minerals and their relationship with potassium. Nitrate availability varies across study locations and does not correlate with other variables (Figure 12).

The mineralogical composition of the soil is crucial in determining its chemical properties, including nutrient availability, cation exchange capacity, and soil pH. Primary minerals, such as plagioclase and pyroxenes, gradually weather into secondary minerals like kaolinite, smectite, and gibbsite, influencing soil fertility by releasing essential cations (Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}) into the soil solution. For example, Entisols with abundant plagioclase tend to have higher exchangeable Ca and Na, while Vertisols, rich in 2:1 clay minerals like smectite and vermiculite, exhibit higher CEC due to their greater surface charge and interlayer cation retention. In contrast, highly weathered minerals such as kaolinite and gibbsite, dominant in tropical soils like Inceptisols, contribute to lower CEC but improved structural stability (Noviyanto et al. 2020) occurring mostly in volcanic area with thick and clay rich soils. Examining the changes of land surface and soil morphology brought about by a particular landslide is usually the first step required for vegetative rehabilitation. Most examinations to date, however, have been based on general characters rather than on soil morphology, including physical and chemical characteristics of the soil, which are usually locally specific. This study investigates the morphological characteristics of soil in a landslide-prone slope region of Sumbing Volcano, in Central Java Province of Indonesia. The field investigations are conducted at three landslides sites. It starts with interpreting small format areal-photographs which have been geo-corrected, followed by the delineation of landslide zones (i.e. crowns, main scarps, heads, bodies and toes. Furthermore, iron oxide minerals (e.g., hematite and goethite) influence soil pH by acting as pH buffers, while zeolite minerals like natrolite enhance sodium retention (Zhuang et al. 2022). The transformation of primary to secondary minerals through pedogenic processes thus directly affects soil nutrient dynamics, buffering capacity, and overall fertility, shaping the soil's ability to support plant growth.

Available phosphorus and CEC are governed by inherent soil properties such as mineral type and particle size. Phosphorus adsorption by clay minerals is crucial for its availability in the soil (Amadou et al. 2022). Phosphorus deficiency is critical, as it limits plant growth, making phosphorus fertilisation a necessary measure to enhance soil availability. Lu and Tian (2017) noted that phosphorus fertiliser use in Asia is increasing, particularly in sugarcane cultivation across study locations. Available phosphorus levels are highest in Inceptisols and Vertisols, likely due to finer particle size and greater surface area. Finer soil particles increase surface area, thus enhancing CEC (Bi et al. 2023) (as demonstrated in Vertisols with higher CEC than Entisols and Inceptisols. CEC results from negative charges in clay minerals or organic matter, allowing for the retention of positively charged ions like Na, K, Ca, Mg, Zn, Cu, B, and Fe.

Base cations and micronutrients are crucial for sustainable sugarcane cultivation. Agricultural productivity can decline due to deficiencies in base cations and micronutrients (Denton-Thompson and Sayer 2022). The availability of base cations and micronutrients is influenced by various soil properties, including organic matter content, cation exchange capacity, soil texture, and mineral type. Notable base cation availability among the three soil types includes exchangeable sodium in Entisols and exchangeable K, Ca, and Mg in Vertisols. The presence of plagioclase minerals in Entisols may drive higher exchangeable sodium levels and proximity to the sea, allowing for seawater intrusion. Organic matter correlates positively with sodium and potassium availability in the soil (Figure 12). Vertisols, formed from limestone dissolution, enrich soil potassium, calcium, and magnesium, although organic matter does not correlate with calcium and magnesium levels (Figure 12).

Micronutrients like boron and zinc play vital roles in sugar production. Micronutrient deficiencies (B and Zn) are significant global limiting factors for sugarcane yields. Boron functions in sugar transport and

https://doi.org/10.17221/648/2024-PSE

carbohydrate translocation within sugarcane. High potassium and calcium levels can exacerbate boron deficiency, consistent with the observed negative correlation between boron and potassium/calcium levels in soil (Figure 12). The highest boron levels were found in Entisols across all sugarcane cultivation periods, while zinc levels peaked in Inceptisols, exhibiting variable patterns. Zinc positively influences sugarcane by regulating carbohydrate metabolism and enhancing sucrose content in stems. Zinc availability negatively correlates with organic matter levels (Figure 12). Zinc can be fixed on organic matter surfaces through electrostatic bonding, and its availability in sugarcane cultivation can improve sugar quality (Marangoni et al. 2019). Figure 12 presents the correlation results among variables.

The impact of extended sugarcane cultivation periods on productivity varies across different soil types. In Entisols, sugarcane productivity decreases, while in Inceptisols and Vertisols, productivity increases. In Entisols, productivity declines by approximately 20 t/ha in the 20 years and by 15 t/ha in the 30 years, with no significant difference between the two periods. The productivity increase in Inceptisols over 20 years is similar to that in Vertisols over 10 years. Inceptisols, productivity rises by about 8 t/ha from 10 to 20 years and by 10 t/ha from 20 to 30 years. In Vertisols, productivity increases by about 5 t/ha from 10 to 20 years and by 8 t/ha from 20 to 30 years. Figure 13 presents the correlation between the extended periods of sugarcane cultivation and its productivity.

Vertisols show the most favourable response to long-term monoculture sugarcane productivity among the three soil types, followed by Inceptisols. The physicochemical properties of Vertisols and Inceptisols play a key role in supporting root growth and development, which is crucial for the sustainability of sugarcane cultivation. The dominant clay particle size in Vertisols enhances CEC and stabilises organic C content. However, Vertisols' cracking and shrink-swell behaviour can sometimes damage sugarcane roots, potentially disrupting growth and lowering productivity. Consequently, Inceptisols exhibit the highest productivity increase per decade. The physical properties of Inceptisols, which provide pore space for root development and volcanic ash that slowly releases nutrients, significantly contribute to sugarcane productivity gains (Fiantis et al. 2019) tons of volcanic ash materials are ejected to the atmosphere and deposited on land. The hazard posed by volcanic ash is not limited to the area in proximity to the volcano, but can also affect a vast area. Ashes ejected from volcano's affect people's daily life and disrupts agricultural activities and damages crops. However, the positive outcome of this natural event is that it secures fertile soil for the future. This paper examines volcanic ash (tephra).

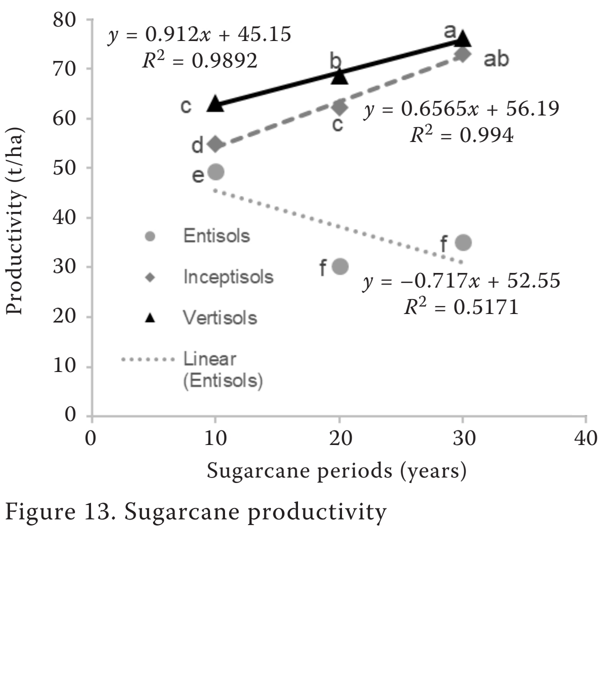

Figure 13. Sugarcane productivity

In conclusion, long-term monoculture sugarcane cultivation affects productivity and soil properties differently across soil types in Indonesia. In Entisols, productivity declines by 20 t/ha over 20 years, while in Inceptisols and Vertisols, it increases by 8 t/ha and 5 t/ha, respectively, between 10 and 20 years. Cultivation duration influences pedo-morphological characteristics, notably the formation and thickening of Ap horizons, which generally darken due to higher organic matter content. However, deeper horizons, such as the Bw in Inceptisols, show minimal changes. Soil degradation indicators vary among soil types. In Entisols, organic matter declines from 1.5% to 0.8%, bulk density increases, reducing porosity and water retention by 15%, and CEC drops from 8 $cmol_+$/kg to 5 $cmol_+$/kg. Inceptisols, organic carbon decreases from 2.2% to 1.0%, available phosphorus drops by 45%, and CEC declines from 12 $cmol_+$/kg to 8 $cmol_+$/kg. Vertisols show minor changes, with organic carbon slightly decreasing (2.8% to 2.5%), exchangeable potassium reducing by 30%, and a slight increase in CEC. These findings highlight the need for soil-specific management strategies to mitigate degradation and maintain nutrient availability. Sustainable practices, including soil conditioners, are essential to preserve soil quality and ensure long-term sugarcane productivity.

https://doi.org/10.17221/648/2024-PSE

Acknowledgement. We would like to extend our heartfelt gratitude to the Politeknik Perkebunan (LPP) Yogyakarta for their exceptional support in this research. We deeply appreciate the financial assistance provided for publication funding.

REFERENCES

Amadou I., Faucon M.-P., Houben D. (2022): Role of soil minerals on organic phosphorus availability and phosphorus uptake by plants. Geoderma, 428: 116125.

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. Scientific Reports, 13: 12242.

Bigott A.F., Hoy J.W., Fultz L.M. (2019): Soil properties, microbial communities, and sugarcane yield in paired fields with short- or long-term sugarcane cultivation histories. Applied Soil Ecology, 142: 166–176.

Canellas L.P., Busato J.G., Dobbss L.B., Baldotto M.A., Rumjanek V.M., Olivares F.L. (2010): Soil organic matter and nutrient pools under long-term non-burning management of sugar cane. European Journal of Soil Science, 61: 375–383.

Chi L., Mendoza-Vega J., Huerta E., Álvarez-Solís J.D. (2017): Effect of long-term sugarcane (*Saccharum* spp.) cultivation on chemical and physical properties of soils in Belize. Communications in Soil Science and Plant Analysis, 00103624.2016.1254794.

De Lima R.P., Da Silva A.P., Giarola N.F.B., Da Silva A.R., Rolim M.M. (2017): Changes in soil compaction indicators in response to agricultural field traffic. Biosystems Engineering, 162: 1–10.

Denton-Thompson S.M., Sayer E.J. (2022): Micronutrients in food production: what can we learn from natural ecosystems? Soil Systems, 6: 8.

Fiantis D., Ginting F., Gusnidar, Nelson M., Minasny B. (2019): Volcanic ash, insecurity for the people but securing fertile soil for the future. Sustainability, 11: 3072.

Galdos M.V., Cerri C.C., Cerri C.E.P. (2009): Soil carbon stocks under burned and unburned sugarcane in Brazil. Geoderma, 153: 347–352.

Georgiou K., Jackson R.B., Vindušková O., Abramoff R.Z., Ahlström A., Feng W., Harden J.W., Pellegrini A.F.A., Polley H.W., Soong J.L., Riley W.J., Torn M.S. (2022): Global stocks and capacity of mineral-associated soil organic carbon. Nature Communications, 13: 3797.

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 and Clay Minerals, 72: e3.

Jean Pierre T., 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. Journal of African Earth Sciences, 150: 176–193.

Lal R. (2014): Soil carbon management and climate change. In: Hartemink A.E., McSweeney K. (eds.): Soil Carbon. Dordrecht, Springer International Publishing, 339–361.

Lu C., Tian H. (2017): Global nitrogen and phosphorus fertilizer use for agriculture production in the past half-century: shifted hot spots and nutrient imbalance. Earth System Science Data, 9: 181–192.

Marangoni F.F., Otto R., De Almeida R.F., Casarin V., Vitti G.C., Tiritan C.S. (2019): Soluble sources of zinc and boron on sugarcane yield in Southeast Brazil. Sugar Tech, 21: 917–924.

Melo V.F., Orrutéa A.G., Motta A.C.V., Testoni S.A. (2017): Land use and changes in soil morphology and physical-chemical properties in Southern Amazon. Revista Brasileira de Ciência Do Solo, 41: e0170034.

Noviyanto A., Sartohadi J., Purwanto B.H. (2020): The distribution of soil morphological characteristics for landslide-impacted Sumbing Volcano, Central Java – Indonesia. Geoenvironmental Disasters, 7: 25.

Pang Z., Tayyab M., Kong C., Liu Q., Liu Y., Hu C., Huang J., Weng P., Islam W., Lin W., Yuan Z. (2021): Continuous sugarcane planting negatively impacts soil microbial community structure, soil fertility, and sugarcane agronomic parameters. Microorganisms, 9: 2008.

Purwanto B.H., Alam S. (2020): Impact of intensive agricultural management on carbon and nitrogen dynamics in the humid tropics. Soil Science and Plant Nutrition, 66: 50–59.

Putra R.P., Muhammad R.R.R., Muhammad S.R., Rahmad S., Vita A.K.D. (2020): Short communication: investigating environmental impacts of long-term monoculture of sugarcane farming in Indonesia through DPSIR framework. Biodiversitas Journal of Biological Diversity, 21: 211061.

Qi J.Y., Han S.W., Lin B.J., Xiao X.P., Jensen J.L., Munkholm L.J., Zhang H.L. (2022): Improved soil structural stability under no-tillage is related to increased soil carbon in rice paddies: evidence from literature review and field experiment. Environmental Technology and Innovation, 26: 102248.

Reichert J.M., Brandt A.A., Rodrigues M.F., Da Veiga M., Reinert D.J. (2017): Is chiseling or inverting tillage required to improve mechanical and hydraulic properties of sandy clay loam soil under long-term no-tillage? Geoderma, 301: 72–79.

Schoonover J.E., Crim J.F. (2015): An introduction to soil concepts and the role of soils in watershed management. Journal of Contemporary Water Research and Education, 154: 21–47.

Sekucia F., Dlapa P., Kollár J., Cerdá A., Hrabovský A., Svobodová L. (2020): Land-use impact on porosity and water retention of soils rich in rock fragments. Catena, 195: 104807.

Solomon S., Swapna M., Xuan V.T., Mon Y.Y. (2016): Development of sugar industry in ASEAN countries. Sugar Tech, 18: 559–575.

https://doi.org/10.17221/648/2024-PSE

Sulaiman A.A., Sulaeman Y., Mustikasari N., Nursyamsi D., Syakir A.M. (2019): Increasing sugar production in Indonesia through land suitability analysis and sugar mill restructuring. Land, 8: 61.

Tolimir M., Kresović B., Životić L., Dragović S., Dragović R., Sredojević Z., Gajić B. (2020): The conversion of forestland into agricultural land without appropriate measures to conserve SOM leads to the degradation of physical and rheological soil properties. Scientific Reports, 10: 13668.

Vasu D., Tiwari G., Sahoo S., Dash B., Jangir A., Sharma R.P., Naitam R., Tiwary P., Karthikeyan K., Chandran P. (2021): A minimum data set of soil morphological properties for quantifying soil quality in coastal agroecosystems. Catena, 198: 105042.

Wang Y.K., Zhang Z.B., Jiang F.H., Guo Z.C., Peng X.H. (2021): Evaluating soil physical quality indicators of a Vertisol as affected by different tillage practices under wheat-maize system in the North China Plain. Soil and Tillage Research, 209: 104970.

Zhang W., Wang Z., Liu Y., Feng J., Han J., Yan W. (2021): Effective removal of ammonium nitrogen using titanate adsorbent: capacity evaluation focusing on cation exchange. Science of The Total Environment, 771: 144800.

Zhuang Y., Zhu J., Shi L., Fu Q., Hu H., Huang Q. (2022): Influence mechanisms of iron, aluminum and manganese oxides on the mineralization of organic matter in paddy soil. Journal of Environmental Management, 301: 113916.

Received: December 11, 2024
Accepted: March 12, 2025
Published online: March 26, 2025