

Soil morphological characteristics and profile variability across sugarcane landscapes

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ABSTRACT

This research aimed to characterise soil morphological features and assess profile variability across sugarcane-dominated landscapes. This research will significantly advance our understanding of soil morphology in sugarcane-dominated volcanic ash soils. The research was conducted in Central Lampung, and topographic maps at a scale of 1:5,000 were used to describe the survey area. Approximately fifty-eight soil samples with twelve profile descriptions were collected from soil pits at three soil catenas (two under sugarcane and one under forest), and completely analyzed in the laboratory. The research found that relationships between soil morphology and soil characters exist due to intensive leaching and erosion. All profiles were increasingly leached from the hilltop to the lower slopes. The lowest boundaries of the leaching process are impermeable hard iron layers between the tertiary and quaternary sediments (krokos layers) found in the BC or B₃ horizons (depths of 70-120 cm). This phenomenon tends to form the open system in the sugarcane landscape; however, the forest system was closed. All soil characteristics are presented as depth functions to facilitate analysis. Fertilisation and dolomite application on the sugarcane soils increased only pH, P content, base saturation, and exchangeable bases, while decreasing exchangeable Al and Al saturation in topsoils; these characteristics were relatively constant across all subsoils. Other soil properties were relatively constant. Soil compaction due to mechanisation was a serious problem of soil degradation and fertility reduction, and became more serious due to decreasing infiltration rates from hilltop to lower slopes.

Keywords: characters, soil morphology, soil profiles, soil variability, sugarcane landscape

INTRODUCTION

Soil morphological characteristics observed within soil profiles provide fundamental insights into soil genesis, hydrological behaviour, and functional capacity for agricultural production (Negassa et al., 2019). Features such as horizon differentiation, colour, structure, texture, consistence, and redoximorphic traits reflect the combined influences of parent material, climate, topography, biotic activity, and land use history (Armanto & Wildayana, 2023). In agricultural landscapes, soil morphology also serves as a sensitive indicator of management-induced changes that may affect long-term soil quality and sustainability (Beccarelli & Foggia, 2022).

Sugarcane (*Saccharum officinarum* L.) is a major plantation crop in tropical and subtropical regions and plays a critical role in food, energy, and bioindustry systems (Suyana et al., 2024). The crop requires deep, well-drained soils with favourable physical conditions to support extensive root development and high biomass yields. However, sugarcane cultivation is often associated with intensive land preparation, repeated harvesting cycles, residue management, and heavy machinery, all of which can alter soil structural integrity, compaction status, and horizon expression. These practices, when interacting with natural soil-forming processes, contribute to pronounced soil profile variability within sugarcane landscapes (Basuki & Sari, 2024).

Landscape position is a key driver of soil variability, influencing water movement, erosion-deposition processes, and material redistribution along topographic gradients. Consequently, soils along a sugarcane landscape may differ markedly in horizon thickness, colour patterns, texture, drainage conditions, and the occurrence of redox features (He et al., 2023). Examining soil profiles across landscape positions provides a systematic framework for understanding soil-landscape relationships and identifying zones with distinct morphological and functional characteristics (Armanto et al., 2022).

Publications on soil morphology and sugarcane characteristics in the landscape are limited, particularly for Lampung volcanic ash soils (Safitri et al., 2024). A review on the relationship of soil morphology with cane growth is also not available (Lima et al., 2022). Most studies on volcanic ash soils and their morphological characteristics are limited, and the toposequence approach is also limited (Kusumawati & Noviyanto, 2025).

The Lampung plain, dominated by Ultisols (Udults, US Soil Taxonomy), is an important base of sugarcane production. Ultisols are often called 'the marginal or sub-optimal soils' and are very precious national land resources. Most parts of the landscape are leached and endangered by water erosion. Water erosion and leaching are the main soil degradation processes in the area, especially occurring in sloping landscapes (Wildayana & Armanto, 2018a; 2018b).

They reduce soil productivity, where intensive rains detach soil aggregates and heavy runoff leads to erosion forms from sheet via rill to severe gully erosion. During erosion, aggregated particles break up into smaller pieces, or primary particles. Smaller and lighter soil particles are more easily moved by erosion, leaving the coarser particles behind (Zhang et al., 2023; Zhang, 2023).

Erosion classifies soil particles according to size and weight. Skeletal components increase in association with high erosion intensity and remain on the eroded site (Silva et al., 2024; Varone et al., 2021). Nutrients are vulnerable to selective desorption and adsorption between the separated particles and water as they travel downstream. Therefore, the selective removal of

soil nutrients with runoff sediments is a well-known process (Moraes et al., 2021). The research of this study was to characterize soil morphological features and assess profile variability across a sugarcane-dominated landscape. Specifically, the objectives are to describe soil horizon morphology across different landscape positions, evaluate spatial variability in key morphological attributes within and between profiles, and interpret the influence of landscape processes and management practices on soil profile development. The results are expected to enhance understanding of soil heterogeneity in sugarcane systems and provide a scientific basis for site-specific soil management and sustainable sugarcane production.

MATERIALS AND METHODS

The Research Area

The research location is situated 90 kilometers north of Teluk Betung, Indonesia, Central Lampung. The region was located between latitudes 4°35'-4°50' South and longitudes 105°-105°30' East. The research site was located between five and thirty-five meters above sea level. The term "Sungai" refers to the numerous little rivers found in the fields. The slopes were partially flattened due to soil denudation and erosion. The area had an average value of about 8% and a slope of about 3–25% (Figure 1 & Figure 2).

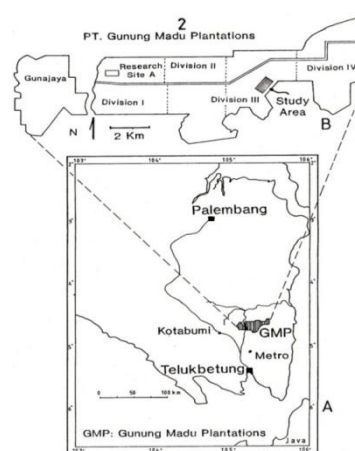


Figure 1. The research location

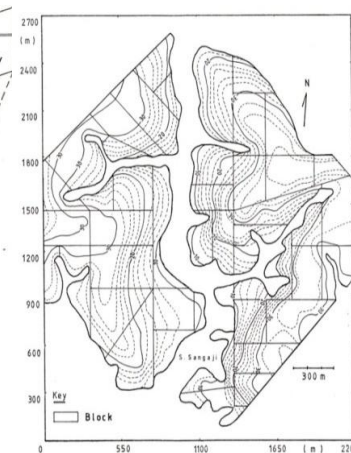


Figure 2. The research area topographical map

With a total size of 20,000 ha (about 4,000 ha each division), the area was split up into five

divisions. For nearly 50 years, the area had been grown in sugarcane monoculture. After eight to nine months, the sugarcane was taken from its cuttings and grows again into a ratoon. This system rotates for four cycles, or around four years. The achieves a high productivity level even on adverse soils because of rigorous management, which includes a high P-fertilization level (100 kg TSP/ha per a year) and scientific production control.

Scheme for Soil Sampling

Soil pits and borings were used to carry out the soil sampling plan; Figure 3 showed the intensity of soil sampling. The survey type was highly detailed, and the maps that were utilized had scales of 1:5,000. Pits, borings, and landscapes were typically described in the field and soil profile guidelines. The borders of soil variability are marked on the maps using Landsat photos. Ultisols were the most common soil type. A 1:100,000-scale geological map showed that the chosen research parent materials were volcanic tuff rocks. Soil pits and borings were used to record and sample soil intensities at two stages: overall and catena.



Figure 3. Whole sampling locations

The geomorphology of the region was considered when conducting the overall survey. 1,765 soil samples were collected at depths of 0-20 cm, 20-35 cm, 35-60 cm, 60-90 cm, and 90-120 cm using an auger bore. Soil sampling was limited to 20–40 meters from the highways due to the dense sugarcane canopy and challenges with the technical field survey. We collected 58 soil samples from three catenas with 12 profile

descriptions (two beneath the sugarcane and one under the forest).

The soil sampling scheme in this research was designed to represent both overall soil conditions and variations related to topography. Overall soil sampling was conducted at an intensity of approximately one boring per hectare, resulting in 353 soil borings and 1,765 soil samples collected for laboratory analysis. In addition, catena-based sampling was carried out to capture soil variability along landscape gradients. Each catena consisted of three to five soil profiles, for a total of 12 profiles and 58 soil samples. Each soil profile comprised five to six samples taken from different depths, allowing for a detailed assessment of vertical soil property variations. The combination of extensive overall sampling and targeted catena-based profiling ensured adequate representation of both spatial and vertical soil variability in the research area.

Descriptions of soil fields

Soil descriptions were completed for 12 profiles in the catenas and 353 profiles in an extended survey region throughout the fieldwork. For all intensities, the field descriptions of pits, borings, and landscapes were often separated into two categories:

- 1) General field descriptions and soil profile convention requirements (vegetation, land use, climate, elevation, relief shape, conventional profile, and descriptions). Lastly, pictures of the landscapes and pits were taken (Ahmad & Wilkins, 2025).
- 2) Particular explanations (designation of horizon depths, soil colours, mottles, concretion depths, bulk density, gravel content, texture, and roots).
- 3) Using remote sensing image interpretations, the classification of soils was tested on each individual soil description that matched the analytical data and relief form.

Capital letters that denoted master horizons and lower-case letters that qualified as suffixes to the master horizons were used to identify the principal horizons. Transitional horizons were written in a combination of capital letters. The Munsell Soil Colour Charts provided standard colour notations (Hue, Value, and Chroma) for describing the colours and mottles (abundance

and size of mottles) of the damp soil. The augering profile was observed in the fields to establish the depth. The amount of roots was computed in dm². Following the completion of the dideskripsi ground profile, composite soil samples were collected and examined in a lab (Braun & Clarke, 2025).

RESULTS

Vegetation and Landuses

The native vegetation of the Lampung plain is a primary tropical forest, which was used through shifting cultivations for the first time around 100 years ago. The primary forest was removed by burning. Then, it was planted with upland rice (*Oryza sativa* L.) or cassava (*Manihot utilisima* L.).

The shrubs are characterised by dense undergrowth or interference by alang-alang. It was difficult to separate residual native rubber, alang-alang, and shrubs within a complex type of secondary forest. Trees of seru (*Schima wallichii* Korth), cente (*Porosema caporcors* J.), bungur (*Lagerstroemia spaciara* P.), simpur (*Dillonia exelen* D.), leban (*Vitex pubescent* V.), and rengas (*Gluta rengas*) make up the majority of the vegetation. Rumpit merdeka (*Eupatorium javanicum*), saliar (*Lantana camara*), merawan (*Ropea mengerawan* M.), belangiran (*Shorea belangiran*), sungkai (*Peromena causcent*), and mahang (*Macaranga thypoleuca*) were among the plants under growth.

A monoculture of sugarcane had been grown for more 50 years. After eight to nine months, the sugarcane was taken from its cuttings and grew again into a ratoon. This system rotates for four cycles, or around four years. The area achieves a high output level even on adverse soils because of rigorous management, which includes scientific production control and a high P-fertilisation level (100 kg TSP/ha per year). Erosion threatens certain areas of the leached Ultisols.

Geo-and Pedogenesis

The underlying parent material of soils was known as tertiary deposits (1.5 Mill years ago), called the first sediment. They consist of tuffaceous sandstone, conglomerate, and volcanic

breccias originating in the volcanoes of the Bukit Barisan complex. They are massive and weakly structured. In the early Pleistocene (0.16 Mill years ago), the landscapes rose out of the sea, and the rivers cut down the area.

The top layer seems to be influenced by volcanic glass, hypersthene, and augite. These relatively young sediments were characterized by at least one of the following diagnostics: (1) a blocky structure and well-developed clay skins, (2) the ratio of silt to clay was more than 0.15, and (3) there were more than 3 % weatherable minerals.

The differences between the first and second sediments are characterised by differences in the degree of hydration and of iron oxides, which were influenced by drainage conditions and the degree of weathering. These iron oxides were mixed with quartzite gravel/sand to form hard iron nodules. These nodules, mainly gravel-sized, were commonly found in the transition horizons (BC or B₃) to the first sediment, especially in areas above impermeable first sediments. They were called "Krokos" by Indonesian scientists. The krokos forms irregular nodules with diameters of 0.5 to 3.0 cm with low content of organic matter. The formation of krokos was irreversible. Active plinthite formations, the first stage of krokos formation, are associated with a relatively young landscape overlying an old one. If the plinthite was very hard and not easily crushed by fingers, it was named krokos. Humid and warm climates accelerate soil formation, leaching of bases, decomposition of organic matter, and erosion processes. Therefore, the soils are classified as very acidic soils. They contain low levels of nutrients, organic matter, and mineral reserves.

The soil-forming processes in the Lampung plain are characterised by weak podzolisation with argillic B horizons (Bt). The soils are highly leached, clayey, and mostly classified as Udufts. Aquults are found in level areas with high groundwater levels and are subject to flooding in the wet season. If Bt-horizons are too weak, the soils were classified as Dystropepts.

Dystropepts are especially found in undulating relief. The soils have weak to moderate cambic B-horizons and a deep and sandy loam texture. In the low-lying areas, the soils are poorly drained.

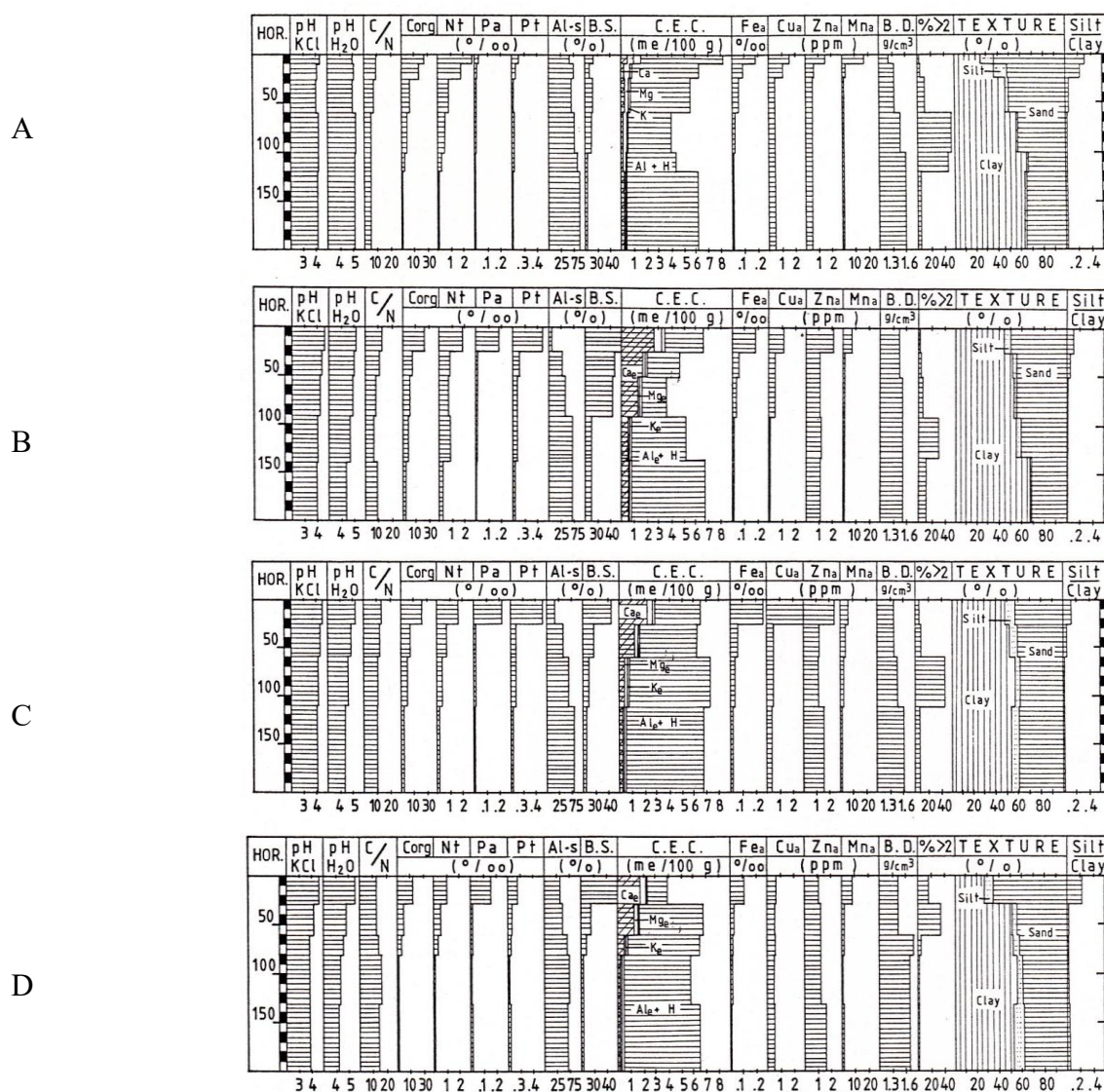
The poorly drained soils, combined with gley phenomena and argillic horizons, form Aquults. Gley phenomena in the depression and lower slopes are affected by groundwater to form Tropaquepts. The soils were categorized as typic and oxic Dystropepts in higher to middle slope situations, typic and plinthic Tropaquepts in lower slope positions, and plinthic and typic Kanhapludults on hilltops.

The soils were intensively surveyed and classified into 6 great groups: Tropaquents, Tropaquepts, Dystropepts, Tropaquults, Plinthudults, and Tropudults. They are classified into 9 soil Subgroups, namely Typic Tropaquents

(0.8 %), Typic Tropaquepts (4.1%), Oxic Dystropepts (3.3%), Typic Tropaquults (1%), Umbric Tropaquults (0.5%), Plinthudults (1.5%), Dystropeptic Tropudults (4.9%), Orthoxic Tropudults (70.7%) and Plinthic Tropudults (13.2%).

Soil Physical Characters

Soil variability of physical in the profile is also presented in forms of depth functions (Figure 4, Table 1–4). With helping Figure 4 and Table 2-5, it could be illustrated and compared physical characters relating to topographic positions in the landscape.



A (Forest soils); B (Hilltop position); C (Middle slope position); D (Foot slope position)

Figure 4. Depth function of soil characteristics

Table 1. Description of profile G3.1, secondary forests

Horizon	Profile Descriptions
Ah1 (0–10 cm)	10YR2.5/2, sandy clay loam, strongly humose, fresh, very strong rooting, very slightly stony, crumbs, pH 5.26, BD 1.2
Ah2 (10–25 cm)	10YR3.5/3, sandy clay, humose, fresh, very strong rooting, very slightly stony, subpolyhedral, pH 4.15, BD 1.3
E (25–60 cm)	10YR5.5/6, sandy clay, slightly humose, fresh, strong rooting, slightly stony, subpolyhedral, pH 4.03, BD 1.3
Bc (60–100 cm)	10YR6.5/5, common medium sized krokos (**): 10R4/6, clayey, very slightly humose, fresh, weak rooting, very stony, subpolyhedral, pH 4.21, BD 1.4
BC1 */ (100–130 cm)	10YR6/8, many medium sized krokos: 10R4/6, clayey, very slightly humose, fresh, weak rooting, very stony, subpolyhedral, pH 4.22, BD 1.6
C2 */ (130–230 cm)	10YR4.5/6, common medium sized krokos: 10R3/3, clayey, very slightly humose, moist, very weak rooting, very stony, subpolyhedral, pH 4.16, BD 1.6
Slope : 2–4%, Hilltop, 33 m above sea level (asl), Soil Subgroup : Plinthic Kanhapludult (Kp), Groundwater: > 230 cm	
Note: */ C designates material (of old B-horizons) which was strongly weathered in earlier cycles, BD: Soil bulk density in kg/l, **/ Krokos was local name for iron-concretions BD: Soil bulk density in kg/l	

Table 2. Description of profile G2.1, block 62/17

Horizon	Profile Descriptions
Ap (0–25 cm)	10YR3/2, common small mottles: 10YR5/6, sandy clay loam, humose, fresh, strong rooting, slightly stony, crumbs, pH 5.70, BD 1.4
EB (25–50 cm)	10YR5.5/6, common medium sized mottles: 10YR5/6, sandy clay, slightly humose, fresh, moderate rooting, stony, subpolyhedral, pH 4.40, BD 1.5
Bc (50–90 cm)	7.5YR5.5/8, common small krokos: 2.5YR5/8, sandy clay, slightly humose, fresh, weak rooting, very stony, subpolyhedral, pH 4.29, BD 1.5
BC1 */ (90–140 cm)	10YR6.5/6, common medium sized krokos: 2.5YR4/8, clayey, slightly humose, fresh, weak rooting, very stony, subpolyhedral, pH 4.13, BD 1.6
C2 */ (140–170 cm)	10YR7/6, common medium sized krokos: 10R4/6, clayey, very slightly humose, moist, very stony, pH 4.09, BD 1.6
Slope: 2–5%, Hilltop, 34 m a.s.l. Soil Subgroup: Plinthic Kanhapludult (Kp), Groundwater: > 170 cm	
Note: */ C designates material (of old B-horizons) which was strongly weathered in earlier cycles, BD: Soil bulk density in kg/l	

Table 3. Description of profile G2.2, block 61/17

Horizon	Profile Descriptions
Ap (0–25 cm)	10YR3.5/2, many medium-sized mottles: 10YR5/6, sandy clay, strongly humose, fresh, very strong rooting, slightly stony, crumbs, pH 4.59, BD 1.4
EB (25–60 cm)	10YR5/6, few medium-sized mottles: 7.5YR5/8, clayey, slightly humose, fresh, moderate rooting, slightly stony, subpolyhedral, pH 4.22, BD 1.4
BcC1 */ (60–110 cm)	7.5YR5/6, many medium-sized krokos: 10R3.5/6, clayey, slightly humose, fresh, weak rooting, very stony, subpolyhedral, pH 4.03, BD 1.5
C2 */ (110–160 cm)	10YR7/3, common medium-sized krokos: 10R4/6, clayey, very slightly humose, fresh, weak rooting, very stony, subpolyhedral, pH 4.05, BD 1.6
Slope: 8–10%, Middle slope, 26 m a.s.l., Soil Subgroup: Plinthic Kanhapludult (Kp), Groundwater: 150 cm	
Note: */ C designates material (of old B-horizons) which was strongly weathered in earlier cycles, BD: Soil bulk density in kg/l	

Table 4. Description of profile G2.4, block 61/17

Horizon	Profile Descriptions
Ap (0–28 cm)	10YR3/3, many medium-sized mottles: 7.5YR5.5/6, sandy clay loam, humose, moist, strong rooting, stony, crumbs, pH 5.85, BD 1.4
BGo (28–60 cm)	7.5YR5.5/6, many medium-sized mottles: 2.5YR4/6, sandy clay, slightly humose, moist, weak rooting, stony, subpolyhedral, pH 4.06, BD 1.5
Bg (60–80 cm)	10YR7.5/8, many medium-sized mottles: 2.5YR4/8, clayey, very slightly humose, moist, very weak rooting, slightly stony, subpolyhedral, pH 3.88, BD 1.6
BgC1 */ (80–130 cm)	10YR7/2, many medium-sized mottles: 2.5YR5/8, clayey, very slightly humose, moist, slightly stony, subpolyhedral, pH 3.85, BD 1.7
BgC2 */ (130–160 cm)	10YR7/2, many medium-sized mottles: 10R4/6, clayey, very slightly humose, wet, slightly stony, subpolyhedral, pH 3.84, BD 1.6
Slope: 2–3%, Depression, 10 m a.s.l., Soil Subgroup: Plinthic Tropaquepts (Tp), Groundwater: 110 cm	
Note: */ C designates material (of old B-horizons) which was strongly weathered in earlier cycles, BD: Soil bulk density in kg/l	

Table 5. Infiltration rate and its evaluation

Positions in the Catena	Average Infiltration Rate after 120 minutes (cm/hour)	Evaluation (FAO, 2006)
Hilltops	3.85	High
Upper slopes	2.71	Medium
Middle slopes	1.62	Medium
Lower slopes	0.53	Low
Depression	0.44	Low

Soil Colors

Topsoils have hues between 5 and 10 YR, chromas between 2 and 6, and Munsell values between 3 and 6. Hues of 5YR–7.5YR, Munsell values of 5–6, and chromas of 6–8 are characteristics of subsoils. No reports of Oxisols' typical red hues (Hue < 5YR) were found in the region. Since organic matter is strongly mineralized, coluvia at subsoil depths were difficult to differentiate from non-colluviated material by Munsell values.

Bulk Density

A bulk density range of 0.70–1.20 g cm⁻³ was generally regarded as normal for soils developed from tuffaceous sediments. Values greater than 1.20 g cm⁻³ may indicate soil compaction, reduced organic matter content, and/or the presence of older, more intensely weathered horizons. Compared to the forest soils, the Bulk Density for all sugarcane soils, especially at lower elevations show significant compaction. The highest increase in the sugarcane soils takes place at a depth of 40–45 cm in the hilltop and at a depth of 60–90 cm in the lower slope. The gleying horizons have high bulk density, especially in the middle slopes to the lower slope. With increasing mechanization of sugarcane production, compaction may become a very severe matter of soil degradation and fertility reduction.

Particle Size-Distributions

Around 40–70% clay and 2–10% silt make up the particle-size distribution of soils. The clay content increases by more than 10% with soil depth and meets the criteria for classification as an argillic diagnostic horizon. The catena exhibits a systematic change in soil texture, with soils becoming sandier towards the lower slope and clayey on hilltops. The skeleton fractions of forest soils were lowest in surface soils and highest between 60 and 120 cm below the

surface. Maximum concentrations of krosos concretions were also present in these layers. Skeletal fractions may be a significant factor in the current erosion indices in sugarcane soils. It appears that the finer fractions flow into the rivers while the coarser fractions remain in the lower slope. Clay migration beneath the forest was extremely high (around 40%) based on variations in clay concentration between A- and B-horizons. In sugarcane soils, clay migration reaches the maximum value in the upper slopes and decreases continuously with decreasing elevation. Clay also shows indices of erosion in the catena. In the lower horizons, particle size distributions were similar in all profiles, both under the forest and the sugarcanes.

Indices to Soil Weathering and Development

The silt-to-clay ratio indicated weathering and soil development. This was predicated on the idea that a soil's silt content decreases with increasing weathering. The soils were categorized as heavily weathered if the silt clay ratio was less than 0.15, and as (relatively) youthful if the ratio is greater than 0.15. With the exception of the topsoils, all of the chosen profiles were categorized as extensively worn. Only the Ah-horizon had a high silt-clay ratio (0.33), indicating that the forest profile was likewise heavily worn.

Infiltration Rates

Because rain usually does not last longer than 120 minutes, measurements were taken for this duration only. According to Figure 5 and Table 5, the infiltration rate still decreases even after 120 minutes of infiltration on hilltops and upper slopes, while equilibrium was reached at the middle slopes. On the lower slope and depression, the rate stays stable after 60 minutes, but on a much lower level than the upper slopes. The infiltration could be rated from high to low following the slope and the scheme of ASTM

International, (2025). Thus, the heavy rains infiltrate and percolate more easily at upper slope positions, causing high interflow rates, especially at the middle slopes (as was observed at the time of fieldwork). At lower slopes, runoff will exceed infiltration, which was hampered by excess water and limited soil permeability.

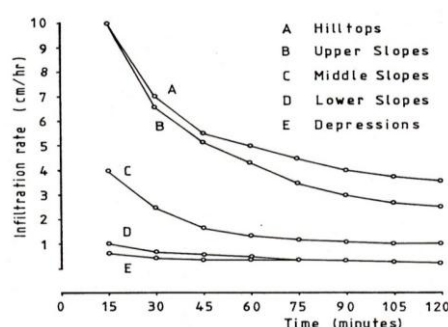


Figure 5. Infiltration rates versus time of the research soils

Soil Chemical Characters

Soil variability of chemical characters in the profile was presented as depth functions (Figure 4). Figure 4 illustrates and compares chemical characters across topographic positions in the landscape.

Soil Reaction, Al-and Base Saturation

Both the pH-KCl levels and their range are extremely low. Throughout the profiles, there were very minor variations in pH levels. Small increases were provided from upper to lower horizons beneath the forest, with the exception of the Oh/Ah (recycled bases). Fertilisation and liming of the sugarcane soils have affected a gentle increase in pH in Ap compared with B-horizons, but the difference was only about 0.5. The effect of fertilizing and liming was demonstrated even more clearly by the saturation of bases, which, contrary to depth functions of saturated Al (Al saturation). No major differences in Al saturation between top- and sub-horizons exist under the forest, but diminishing ones exist under the sugarcane.

Total N and Organic C

With the exception of the upper two layers, the forest soils typically have low levels of organic C and total N. Total C and total N under the sugarcane exhibit a fast decline with depth and mild downslopes, reaching their greatest levels in hilltop to intermediate slope places. It

must be taken into account that the contents of total C and N will not have reached a climax stage because of the short time since farming started (40 years) and an increasing ploughing depth. However, both fractions are crucial for soil fertility, particularly when taking into account the topsoils' ion exchange complexes, structure, and erodibility.

Total and Available P

Total and available P are highly correlated in both the forest and the sugarcane topsoils in the form of depth functions. The pH-KCl values were very low across the observed range, and a significant association was found between pH-KCl and both total P and available P. Except for the forest soils, available P was about 40-50% of total P. All soils, especially those of the sugarcane soils, show a well-expressed depth function decreasing sharply with depth. No increase in the Ap (or M) horizons following the slope could be recorded. Instead, the values of both fractions tend to be lower at the lower slope profiles.

Cation Exchange Capacity (CEC), Absorbed Acid and Bases

The CEC depth function of the soils had a complex pattern influenced by the overlay of two primary elements, i.e., increased CEC was caused by increasing clay content (with depth). A significant number of pH-variable charges were induced by acidification and the creation of Al/Fe complexes. All soils, however, have a very low CEC. As a result, the soils must be categorised as having a "kandic horizon," or low-activity clay. The CEC does not appear to be significantly affected by organic materials. Although the total number of exchangeable bases normally decreases with depth, they were typically much higher under sugarcane than under the forest because of the extensive fertilisation. It was possible to classify the overall amount of bases and the CA:Mg:K ratio as enough for high-yielding sugarcane production.

Trace Elements (Mn, Zn, Cu, and Fe)

Only in the uppermost topsoils are there remarkable contents of all micronutrients, while in the subsoils, very limited amounts are left.

Ploughing to about 20 cm has thinned the sugarcane topsoil, but this was counterbalanced by micronutrient fertilisation. At the lower slopes, low values of micronutrients—due to high removal by sugarcane and/or outwashing—may have caused a relative deficiency.

DISCUSSION

Landuses and Landscape

After 3 to 10 years of shifting cultivation, soils lost productivity due to degradation, such as soil erosion and nutrient leaching (Martini et al., 2021). Abandoned due to productivity loss, the soils became infested with alang-alang (*Imperata cylindrica* L.). Its rooting system is resistant to burning. After that, the soils were often planted with rubber (*Hevea brassiliensis* L.) because no other crops could grow in the area or the soils became secondary forest. The secondary forest was formed from the native rubber plantation, or alang-alang and shrubs. The rubber trees took about 5 to 10 years until the rubber trees covered the soil. They were harvested over 6 years and produced latex for 25 years or more (Xu, 2024; Vanolli et al., 2023). The landscapes were formed by several cycles of erosion and young coastal movements (the first sediment). In that time, the soils forming processes occurred (Abdel Rahman et al., 2020; Abijith & Saravanan, 2021). The second sediments are recognized as sediments of quaternary acid tuff (15,000 years ago) called Lampung tuffs (Armanto, 2019a; 2019b). These quaternary sediments consist of young acid tuff and young andesite; their mineralogy consists of 30% quartz (turbid and transparent quartz), 20% Na, Ca-Feldspars, 22% K-feldspars, 15% mica and 13% Fe-, Mg-minerals (hypersthene, ilmenite, magnetite, zirconite, amphibole, andalusite, sanidine and biotite) and acid volcanic glass (Bhunia et al., 2018).

Relationships between Morphology and Soil Characters

The soil system is categorized as a "open system" since the landscape does not exhibit redeposition of eroded components. The Lampung tuff is highly porous and well-drained, particularly on hilltops, which helps explain how

this system formed. This location has an extremely high degree of penetration. Because there are numerous flat places on the hilltops, the groundwater table is deep there and flows laterally as inter or underflow. This water runs constantly after heavy rains until it reaches the relatively impermeable krosos layers. In addition to the deep leaching of many soil nutrients, groundwater also rises to the surface on middle to lower slopes and erodes topsoil particles laterally to surrounding rivers. Tropaquepts are created at the lower slopes and depressions by an excess of water in addition to severe downslope erosion. Large landscapes with homogeneous but stratified parent materials, such as Lampung tuffs, host these hydrologic sequences. Open systems are created as a result of these procedures. These conditions create unbalanced ecosystems, making land more susceptible to soil erosion and degradation. As rainfall increases, so does the risk for water-induced soil erosion. Relief variables play a major role in establishing soil taxa. Erosion effects drive the distribution of soil taxa throughout the landscape. According to erosion phenomena and the groundwater table, there are soil subgroups: Plinthic Kanhapludult for hilltops and upper slopes, Oxic Dystropept, Aquic Dystropept for middle slopes, and Typic Tropaquept, Plinthic Tropaquept for lower slopes. These slopes have been caused basically by geomorphological factors during the tertiary and quaternary periods of sedimentation (including the incorporation of volcanic ashes). After deforestation and during cultivation, recent relocation processes (runoff and erosion) overformed the apparent relief depending on the spatial distribution of soils. Excessive subsurface flux of water may presently induce chemical degradation (Cherubin et al., 2020).

Very high transport energy by runoff water takes nearly all materials from the surface into the rivers (shown by the color of rivers). Very few materials would be colluviated except gravel fractions, which are deposited in lower slopes due to their resistance to runoff. As a result, the landscape balance could not be fully achieved. Although little colluvium was formed, this could not be analyzed because the morphological properties do not fulfill the criteria of colluvium formed under temperate humid conditions.

Firstly, these soils are too low in CEC to absorb soil nutrients, have a high Al-saturation, and are rich in caolinitic clay minerals. Secondly, the colluvial sediment was derived from parent materials that were already highly weathered, thin, and contained a high proportion of quartz. Thirdly, there is a very rapid mineralization and destruction of organic matter. Such colluvium may be called "tropical colluvium". It is rich in quartz and has low reserves of weatherable minerals (Armanto, 2019b).

CONCLUSION

The relationships between soil morphology and soil characters result from intensive leaching and erosion. All profiles are increasingly leached from the hilltop to the lower slopes. The lowest boundaries of the leaching process are impermeable hard iron layers between the tertiary and quaternary sediments (krokos layers) found in the BC or B₃ horizons (depths of 70-120 cm). This phenomenon tends to form the open system in the sugarcane landscape; however, the forest system is closed. All soil characteristics are presented as depth functions to facilitate analysis. Fertilisation and dolomite application on the sugarcane soils increased only pH, P content, base saturation, and exchanged bases, decreasing exchanged Al and Al saturation in topsoils, and these characteristics are relatively constant for all subsoils. Other soil properties are relatively constant. Soil compaction due to mechanization was a serious problem of soil degradation and fertility reduction, and became more serious due to decreasing infiltration rates from hilltop to lower slopes.

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