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Pedology and its relationship to cropping decisions in Kamuli District, Uganda

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Abstract

Kamuli District offers an opportunity to understand pedology and cropping decisions in an area that has been underdocumented. Broad, flat summits and narrow convex shoulders are composed of residuum formed from Precambrian granite. Valleys mirror the summits, that is, broad flats composed of alluvium that are rimmed by narrow concave toeslopes. The alluvial landscape is a mix of Holocene terraces and modern floodplains. Gentle, linear backslopes gently merge into footslopes connecting the summits and valleys. These positions are composed of residuum-derived colluvium. These geologic and geomorphic differences create a systematic soil landscape pattern with Oxisols predominating on summits and shoulders, Ultisols predominating on the backslopes and footslopes, and Alfisols predominating across the valleys. The backslopes are more intensively cultivated compared to the summits and valleys. A comparison between cultivated and uncultivated areas revealed a dynamic relationship dependent on landscape position and human impacts. Critical human impacts include upland erosion, declining soil organic matter content, available phosphorus, total nitrogen, and exchangeable bases. Each of these appears to be gradually diminishing soil function, which has dire implications for future food security in Kamuli District.

Plain Language Summary

This study examined the relationship between soils and cropping decisions in Kamuli District, eastern Uganda. The soils in this area vary depending on their location within the landscape. Older soils formed in place on the basement rock are found on the upland hilltops. At the same time, eroded sediment from the hilltops accumulates on the middle slopes, and newer river sediment from the River Nile and local streams settles in the lowlands. Tied to this pattern, the soils on the

Abbreviations: CEC, cation exchange capacity; SOM, soil organic matter; TN, total nitrogen.

upland flats were primarily Oxisols, while Ultisols dominated the middle slopes, and lowland soils were majorly Alfisols. The middle slopes were the most cropped compared to the upland flats and lowlands. A comparison between cultivated and uncultivated pedons showed that cropping decisions alter soil conditions depending on location. Soil erosion, especially in the uplands, is associated with lower soil organic matter, total nitrogen, available phosphorus, and exchangeable bases in cultivated pedons.

1 | INTRODUCTION

Uganda lies within a region regarded as the "original" center of tropical pedology. Milne, 1935a, 1935b, 1936, 1947) developed the catena concept in the 1930s, in part, from his time in Uganda. Independently, Ollier and Ruhe published groundbreaking studies in soil geomorphology from their respective time in Uganda (Ollier, 1959; Ollier et al., 1969; Ollier & Harrop, 1959; Ruhe, 1954). In fact, Ollier's (1959) theory of a two-cycle process for landscape evolution via dissolution surfaces remains as important in tropical pedology as Milne's original work with catenas. Other pedological studies from that era in Uganda include Pallister (1956), Pidgeon (1976), and Radwanski (1960). These studies laid the foundation for understanding landscape evolution, soil formation, and land use, especially on the Buganda catena, a classical soil sequence in central Uganda (Borden et al., 2019 2020; Rhem & Grashey-Jansen, 2016).

The current rates of progress in pedological knowledge across Uganda are slow when compared to the tempo that characterized its heyday (Karuma et al., 2021). Some areas have been studied in detail (Brown, 2002; Brown et al., 2003; Brown et al., 2004; Brunner et al., 2004; Fungo et al., 2011; Rhem & Grashey-Jansen, 2016; Kyebogola et al., 2020). Most areas, though, have not been studied beyond the fieldwork in the 1940s and 1950s that was needed to create the nation's 1:250,000 pedological map (CIFOR-ICRAF, 2013; Semalulu & Mubiru, 2024). As a result, the connections between soils knowledge and cropping suitability are poorly understood across much of Uganda (Ebanyat et al., 2010; Minai, 2015; Bouma et al., 2022). Uganda's National Agricultural Research Organization is striving to remedy this shortcoming by creating a 1:50,000 pedological map; however, this project is only 40% complete (Semalulu & Mubiru, 2024).

Recent studies have documented pedology (Rehm & Grashey-Jansen, 2016; Kyebogola et al., 2020), soil property variation (Bamutaze et al., 2021; Ivanova et al., 2021), and soil fertility (Goettsch et al., 2017; Kyebogola et al., 2021; Musinguzi et al., 2016) across Uganda. Kyalo et al. (2024, 2025) have conducted a series of nationally relevant studies; however, the majority of their sampling uses composite epipedons (0- to 30-cm depth). As a result, the application of their results to advancing pedological understanding is limited.

Veenstra et al. (2015) was the only study that focused on the pedology of Kamuli District. The nearest soil surveyed area with updates is Jinja District (Semalulu & Mubiru, 2024). Jinja District is located 75 km south of Kamuli, leaving a critical gap in soil information in between. According to the 1950s national soil map, Kamuli District largely consisted of the "Buruli Catena" (Isabirye et al., 2004). It is characterized by upland lateritic soils formed from Precambrian granites (Ollier & Harrop, 1959; Radwanski, 1960). The predominant color and texture of the Buruli Catena are reddish-brown sandy loams and/or loams. Brown and colleagues (Brown, 2002;Brown et al., 2003; Brown et al., 2004) revisited the Buruli catena, providing detailed interpretations of the soil-landscape relationships. Their work was conducted in the Nakasongola-Luweero area, about 100 km west of Kamuli District. Google Earth imagery indicates that the two areas are different in terms of pronounced landscape patterns. Ruhe (1954) showed that Kamuli District sits on an end-Tertiary erosion surface. Granites of Precambrian age are prevalent and typically associated with weathered zones, as noted by Batte et al. (2008). Kamuli's natural vegetation comprises savanna with scattered trees and shrubs. In remote and rarely cultivated areas, there is a trend toward forest regrowth, leading to the invasion of thicket or young secondary forests (Radwanski & Ollier, 1959).

Cropping practices often lead to soil degradation due to erosion, nutrient depletion, and loss of organic matter (Ikendi et al., 2024; Lal, 2012; Richter, 2019). In Uganda, agriculture primarily relies on the soils' inherent fertility, making soil degradation a significant problem (Nkonya et al., 2008). In addition, smallholder farmers in Kamuli District contend with dwindling field sizes (Mukadasi, 2010) and climate change (Opio, 2023). Land-use decisions are typically guided by local experience and visual cues rather than formal soil information, since detailed soil maps are not readily accessible (Okullo et al., 2022; Wendiro et al., 2019). Yet studies have shown that soil-informed land use planning improves sustainability and reduces degradation risks (Bouma, 2001; Lehmann & Stahr, 2010; Nziguheba et al., 2022; Tefera et al., 2024). Better crop selection and suitable conservation measures are informed by insights gathered in pedological studies. In Kamuli District, understanding the relationship between cropping decisions and soil properties becomes both a scientific and practical necessity in order to ensure long-term soil stewardship and productivity.

This paper aims to (i) characterize the pedology of Kamuli district and (ii) assess the relationship between pedology and cropping decisions. We formulated two working hypotheses. The first hypothesis is that soil patterns in Kamuli are linked to parent material types and local hydrology that vary systematically with landscape positions. The second hypothesis is that soils with higher inherent productivity are more likely to be allocated to active cropland, including annual and perennial crops (cultivated), while less productive and more constrained soils are left under shrubs and pastures (uncultivated).

Core Ideas

- The pedology of Kamuli is interpretable using a geology-landscape relationship.
- Four landscape positions predominate: broad, flat summits and narrow shoulders are granite-derived residuum; gently sloping, linear backslopes are residuum-derived colluvium; concave footslopes are colluvium with alluvium; and broad, flat valleys (including toeslopes) are alluvium.
- Summits and shoulders are predominantly Oxisols.
- Backslope and footslope pedons are predominantly Ultisols.
- Valley pedons are predominately Alfisols.
- Backslopes are intensively cultivated compared to summits and valleys.
- Pedon evolution is continuing through a feedback loop driven by long-term cropping decisions.

2 | MATERIALS AND METHODS

2.1 | Study area and soil sampling

Kamuli District lies at an average of 1083 m above sea level and has a total area of 1622 km^2 (Figure 1). Kamuli's landscape, as shown in Figure 1, consists of flat topped ridges, sloping hillsides, and narrow valleys that drain to Nile River in the west and Lake Kyoga to the north. The valley pattern observed in Figure 1 can be tied to stream evolution. The studied pedons are within the Lake Kyoga catchment (Babaousmail & Ojara, 2025), approximately 100 km north of Lake Victoria. The study covered eight villages: Buyomba (Kamuli Municipality); Nakanyonyi and Kiwungu (Butansi sub-county); and Kabalira, Kikonko, Bususwa, Kisaikye, and Malugulya (Namasagali sub-county).

The district's climate is classified as tropical savanna (Köppen Aw), with consistently warm temperatures and a bimodal rainfall pattern (Komutunga & Musitwa, 2001; Peel et al., 2007). Average annual temperatures range between 19˚C and 25˚C, and average annual rainfall ranges between 1000 and 1200 mm. Rainfall is received in two main seasons: the first rainy season from March to May, and the second from August to November. Peak rainfall for the first (long rains) and second (short rains) rainy seasons is received in May and October, respectively (Babaousmail & Ojara, 2025). The district's dry seasons, typically lasting from December to March and June to July, receive minimal to no rain at all. However, over the past 20 years, a notable shift in the weather pattern has been observed (Babaousmail & Ojara, 2025).

Three criteria were used to select locations of the pedon pits: (a) a review of the landscape from Google Earth, (b) field reconnaissance, and (c) field-based observational discussions with farmers. These discussions aided our field interpretation while ensuring better understanding of the project by the farmers. No attempt was made to record any personal information about individual farms. Once pit locations were identified, the existing land use was noted, locations were georeferenced, and topographic characteristics such as slope gradients and landscape position were determined (Schoeneberger et al., 2012). Our study also leveraged Google Earth's images to longitudinally assess land use since March 2014.

Nineteen pedon pits were excavated. Each pedon was described according to methods outlined in Schoeneberger et al. (2012). Horizons, depth of each horizon, rock fragments, structure, consistency, presence of clay coatings, and root abundance were determined visually. Soil texture was initially estimated in the field using the feel method (Thien, 1979). Soil color was determined by comparison to a Munsell soil color chart. The target depth of 1 m or more was often unattainable due to water seepage from a shallow water table or thick plinthic strata. In a few cases, digging ceased when no further changes in subsoil color and structure were observed.

2.2 | Laboratory analysis

A 500 g sample from each horizon was delivered to the Plant and Soil Analysis Laboratory at Makerere University. Following air-drying, each sample was ground to pass through a 2-mm sieve. The analytical procedures followed the routine protocols outlined by Okalebo et al. (2002), with "original" methodologies shown in Table 1.

Using the morphological and laboratory data, pedons were classified to the family level of the USDA Soil Taxonomy using *Keys to soil taxonomy*, 12th edition (Soil Survey Staff, 2022), and the Reference Soil Group level of the World Ref-

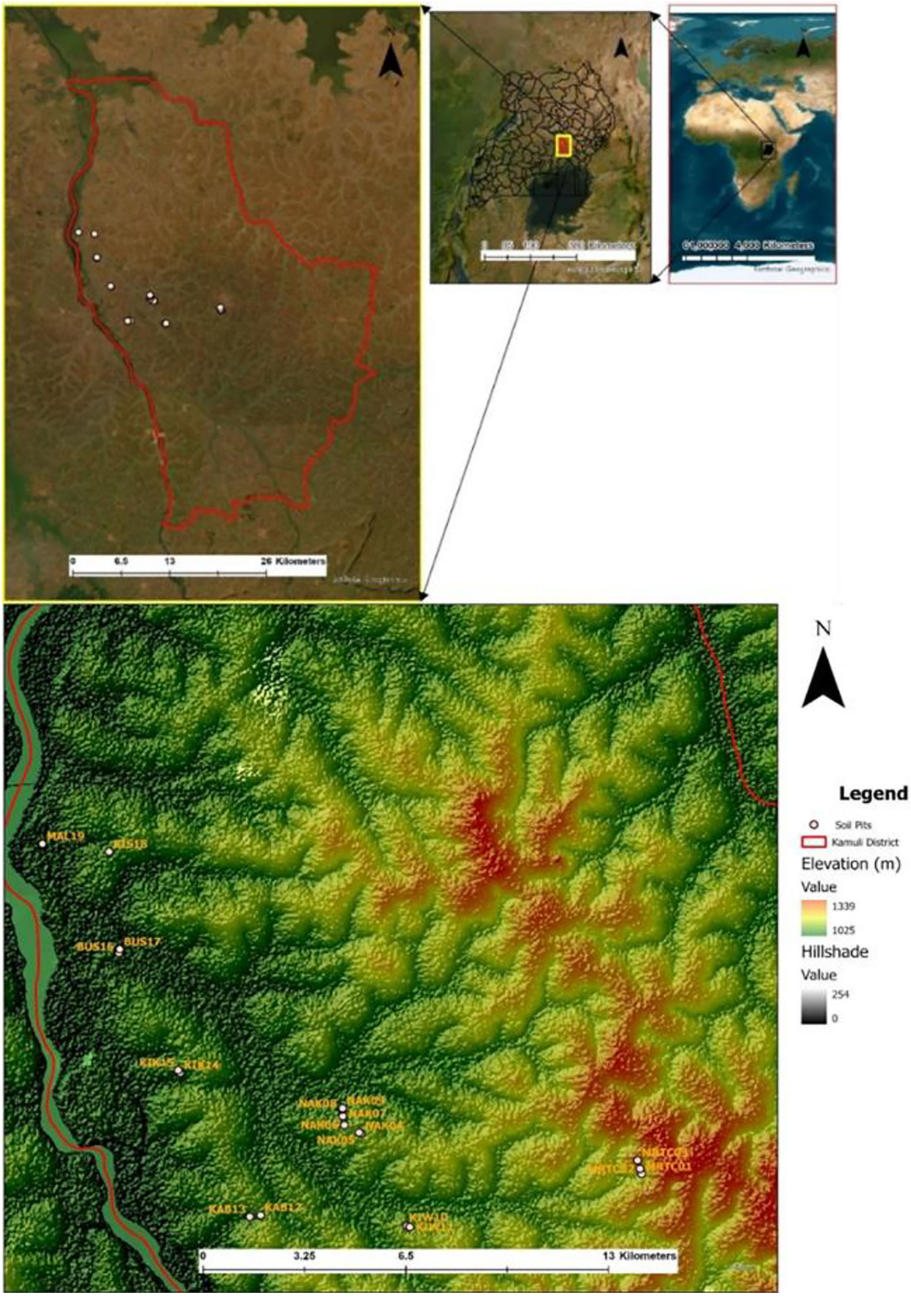

FIGURE 1 The location of Kamuli District, highlighting the detailed elevation variations and sites of the studied pedons.

erence Base (WRB) for soil resources (IUSS Working Group WRB, 2022).

2.3 | Data handling and statistical analysis

2.3.1 | Pedological assessment

Differences between surface (0–40 cm) and subsurface (40 cm+) horizons across the soils categorized by parent material types were evaluated. The depth break at 40 cm was chosen to provide a consistent basis for comparison across the soils with non-uniform horizon boundaries. This approach facilitated the analysis of surface-subsurface changes in key soil properties. The basis for grouping pedons was parent material types, whose distribution closely aligned with landscape positions. Within each parent material group, independent sample *t*-tests were performed to assess statistical significance of surface-subsurface differences. All analyses were conducted using the T.TEST function in Microsoft Excel, and significance determined at a 95% confidence level ($p < 0.05$).

TABLE 1 Summary of the soil sample laboratory methods used by Plant and Soil Analysis Laboratory (Okalebo et al., 2002).

Soil property	Method
pH (soil:water)	Water extraction (1:2.5) (Rhoades, 1982)
Soil organic matter (SOM) (%)	Potassium dichromate wet oxidation (Nelson & Sommers, 1996). Organic carbon converted to SOM using a conversion factor of 1.72 (Okalebo et al., 2002)
Total nitrogen (%)	Kjeldhal digestion and distillation (Bremner & Mulvaney, 1983)
Available phosphorus (ppm)	Bray 1 (Murphy & Riley, 1962)
Potassium, sodium ($Cmol_c kg^{-1}$)	Ammonium acetate extraction, flame photometry (Thomas, 1983)
Calcium, magnesium ($Cmol_c kg^{-1}$)	Ammonium acetate extraction, read on an atomic absorption spectrophotometer (Thomas, 1983)
Soil texture	Hydrometer (Bouyoucos, 1951)
Cation exchange capacity ($Cmol_c kg^{-1}$)	Nuetral 1 M ammonium acetate (Chapman, 1965)
Percent base saturation	Dividing sum of the exchangeable bases by the derived CEC

Abbreviation: CEC, cation exchange capacity.

To assess the degree of weathering among the different parent material types, a silt-to-clay ratio by depths (0–20, 20–40, 40–60, and 60+ cm) was calculated. This ratio has been used as a proxy for soil development in tropical pedology (Eswaran & Bin, 1978; Srivastava & Pal, 2024; Wambeke, 1962), where decreasing value correspond to highly weathered and more developed soils.

2.3.2 | Pedology and cropping decisions

For statistical purposes, cultivated and uncultivated soils were grouped by landscape position, that is, upland and lowland. Uplands included pedons located on the summits and backslopes. The lowlands included pedons on the footslope and valley positions. Morphological properties such as depth of mollic colors, depth to plinthite, depth to contrasting texture, and depth to redoximorphic features were treated as profile indicators. Chemical properties were assessed on a whole profile basis as well as a depth-by-depth basis. Depths were standardized across pedons into fixed 10-cm depth increments from the surface to 60 cm. A depth of 60 cm was chosen because farmers, who have no formal pedological training, assess soils based on observable surface features (Kyebogola et al., 2020). This depth ensures that chemical assessment captures the layer relevant to farmer-led land evaluations. A weighted average approach was used to consider the proportional contribution of each sub-depth. This approach ensured that the representation was accurate, especially in cases where the depth increments did not precisely match the field morphological descriptions.

Welch's *t*-test was used to evaluate differences between cultivated and uncultivated soils. Upland and lowland pedons were analyzed separately on both a depth-by-depth as well as profile basis. All analyses were performed using R software (R Core Team, 2022). *p* values are reported, and results are considered significant at $\alpha = 0.1$.

3 | RESULTS AND DISCUSSION

3.1 | Site characteristics and soil morphology

The site characteristics are shown in Table 2. Kamuli's landscape is best described as a Precambrian grantic residuum plateau dissected over time by young, nearly level alluvial valleys. Connecting the uplands with the valleys are long linear, gently sloping colluvial backslopes. The valleys, likely of Holocene or even modern age, are filled with sediment from backflooding of the River Nile and local stream deposition. As a result, the parent materials vary systematically from residuum on the broad, flat summits and narrow shoulders, to colluvium accumulated on the long linear backslopes. The concave footslopes have a mix of colluvium and alluvium, ultimately leading to the valleys filled with alluvium (Figure 2).

Compared to Brown's (Brown et al., 2004) interpretation of the Buruli catena, the landscape of Kamuli District showed distinct geomorphic and morphological differences. The summits were flat rather than convex, and features such as a stoneline and a saprolite were absent. Instead of a stoneline, a thick horizon that we interpreted as "locked colluvium" was often encountered. The locked colluvium was dominated by angular quartz fragments embedded within a fine matrix, with clay films coating the surfaces and bridging the quartz stones (Figure 3a). This feature, which differs significantly from a stoneline, suggests slope-derived deposition rather than relicit erosional surfaces. Iron-rich cemented zones, which Brown (2004) described as ferricrete layers, were interpreted as plinthite in this study (Figure 3b). Ferricrete and plinthite describe iron-rich indurated horizons, but plinthite is the current term used in modern soil classification (Soil Survey Staff, 2022). Plinthite, majorly in residual summits and backslopes, suggests pedogenic iron accumulation under alternating wetting and drying conditions, which drive iron mobilization,

TABLE 2 Site settings highlighting the parent material, position, slope, land use, location, and elevation of the studied pedons.

Pedon ID	Parent material	Physiographic position	Slope (%)	Land use (at time of description)	Land use over the last 6 years	UTM coordinates	Elevation (m.a.s.l)
MRTC01	Alluvium	Stream terrace	2.0	Swamp vegetation and grasses left in place	Consistently left under pasture	0°55′49.37″ N, 33°7′10.16″ E	1074
BUS17	Alluvium	Stream terrace	1.0	Pasture with native grasses	Forest in 2014, bush burnt in 2015, grassland in 2016 to 2019	0°59′52.65″ N, 32°58′9.23″ E	1035
BUS16	Alluvium	Stream terrace	1.0	Bananas and maize	Forest in 2014, bush burning in 2015, grassland in 2016 to 2018, and then cropped	0°59′48.98″ N, 32°58′8.40″ E	1038
MAL19	Alluvium	Stream terrace	1.00	Pasture with native grasses	Pasture with trees	1°1′46.95″ N, 32°56′49.02″ E	1018
NAK08	Alluvium	Stream terrace	4.5	Pasture with native grasses and creeping plants	Cropped 2014–2016 and then put under sugarcane in 2017	0°56′59.24″ N, 33°1′59.48″ E	1043
NAK09	Alluvium	Stream terrace	1.0	Pasture with native grasses and a water pond about 10 m from the site	Cropped 2014–2016 and then put under sugarcane in 2017	0°57′0.46″ N, 33°2′0.24″ E	1042
KAB13	Alluvial-colluvium	Footslope	1.0	Sugarcane garden	Grassland in 2014–2016 and then put under sugarcane in 2017	0°55′2.78″ N, 33°0′24.01″ E	1041
KIK14	Alluvial-colluvium	Footslope	1.0	Maize cultivation	Consistently cropped	0°57′38.88″ N, 32°59′11.65″ E	1045
KIK15	Alluvial-colluvium	Footslope	1.0	Native grasses left in place	Cropped until 2018	0°57′41.61″ N, 32°59′9.68″ E	1043
MRTC02	Colluvium	Gentle linear backslope	2.5	Coffee, cacao, and banana cultivation	Under plantation with coffee	0°55′54.88″ N, 33°7′8.54″ E	1082
KIW10	Colluvium	Gentle linear backslope	3.0	Pasture with native grasses	Cropped 2014–2017 and left under grass	0°54′52.84″ N, 33°3′6.73″ E	1063
KIW11	Colluvium	Gentle linear backslope	2.5	Maize cultivation	Consistently cropped	0°54′51.77″ N, 33°3′9.94″ E	1063
KAB12	Colluvium	Backslope	2.5	Sweet potatoes	Consistently cropped	0°55′4.62″ N, 33°0′35.10″ E	1044
NAK04	Colluvium	Backslope	2.0	Soybean and amaranth cultivation	Consistently cropped	0°56′33.18″ N, 33°2′19.42″ E	1064
MRTC03	Residuum	Shoulder	4.0	Casava and maize cultivation	Consistently cropped	0°56′4.13″ N, 33°7′6.13″ E	1090
NAK05	Residuum	Summit	1.0	Papaya and guava orchards with a lot of grassy weeds	Cropped until 2017	0°56′34.08″ N, 33°2′17.23″ E	1065
NAK06	Residuum	Summit	1.0	Pasture with native grasses and creeping plants	Consistently cropped	0°56′42.25″ N, 33°2′1.96″ E	1050
NAK07	Residuum	Shoulder	3.5	Bananas and sweet potatoes	Consistently cropped until 2018	0°56′51.75″ N, 33°2′0.42″ E	1055
KIS18	Residuum	Summit	2.00	Jackfruit, orange trees, mangoes, coffee, bananas, sweet potatoes	Forested area until 2018	1°1′38.42″ N, 32°57′58.03″ E	1042

Abbreviation: UTM, Universal Transverse Mercator.

Soil Science Society of America Journal

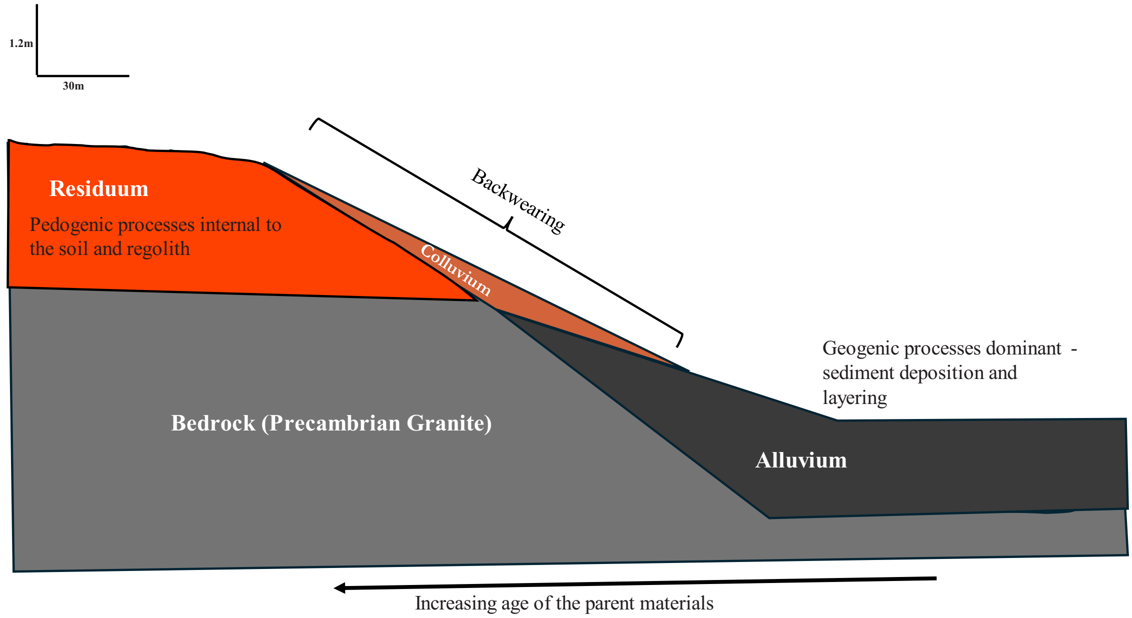

FIGURE 2 A cross-section of the Kamuli landscape with a relief of 12 m showing the distribution of parent materials and processes governing pedogenesis.

oxidation, and accumulation (Eze et al., 2014; McFarlane, 1991).

Furthermore, termite mounds, often prominent indicators of biological pedoturbation, were sparse on the summits, where plinthite was shallow. Termite mound density increased downslope in colluvium and alluvium (Figure 3c,d), where plinthite was encountered at depth or absent, respectively. Termite mound distribution along the landscape suggests that shallow plinthic layers form a physical barrier that restricts termite excavation and mound building. This observation aligns with Beauvais (2009), who showed termite colonization in an area where the ferricrete layers were degrading in Central African Republic. This suggests that degradation of these plinthic layers made soil turnover easier for the termites to build their mounds.

The morphological characteristics of the pedons are summarized in Table S1. Upland soils in residuum and colluvium exhibit 7.5YR, 5YR, and 2.5YR hues, with surface horizons frequently meeting the criteria for mollic colors with moist value and chroma less than or equal to 3/3. Due to their low base saturation, they were classified as umbric epipedons (Soil Survey Staff, 2022). With increasing depth, colors gradually transitioned to higher values and chromas. Lowland soils were predominated by 2.5Y and 10YR hues with a depth relationship similar to the upland soils. The transition from reddish and reddish brown in the uplands to very dark and grayish colors in the lowlands shows a clear drainage-related soil pattern from well-drained soils dominated by hematite (Schwetmann, 1993) to poorly drained soils in the valleys. This drainage-based transition embodies the ideals of Milne's original catena concept in which soil colors are embedded in topographic and hydrologic variation (Borden et al., 2019). The differences in morphology between pedons and the different parent materials are shown in Figure S1.

Field observations revealed a progressive increase in clay with depth, assessed via field texture across both upland and lowland profiles. Additionally, clay coatings along the peds in the B horizons indicate that clay illuviation is an active pedogenic process (Pal, 2019). Seasonal rainfall in Kamuli facilitates clay translocation through percolation along root channels and pores (Khomo et al., 2011; Pal, 2019). Also noted were frequent occurrences of animal burrows and termite activity, pointing to the significance of bioturbation in influencing the profile morphology (Sauzet et al., 2022). Particle size data plotted in Figure 4 shows an increase in clay content from the surface to the subsurface horizons in upland and lowland soils. Sandy loams and sandy clay loams make up the majority of upland surface textures, whereas sandy clays and sandy clay loams predominate in subsurface samples. Lowland profiles exhibited wider textural variability, with surface horizons ranging from loamy sands to sandy loams. These sandier textural classes indicate the influence of depositional and fluvial sorting in the surface horizons of the lowland soils. The subsurface horizons of these soils have finer sandy clay loam, sandy clay loam, and clay textures, evidence of clay translocation.

3.2 | Chemical properties

The chemical properties in the pedons across the different parent materials are summarized in Table 3. Grouping by parent material reveals distinct trends across the landscape from residuum to alluvium. On average, the highest pH,

TABLE 3 Chemical properties across the different pedons in Kamuli District, aggregated by parent materials and depth into surface (0–40 cm) and subsurface (40+ cm).

Parent material	Depth	pH (H_20)	SOM (%)	TN (%)	P (ppm)	Sum of exchangeable bases (Cmolc kg^{-1})	CEC (Cmolc kg^{-1})	Base saturation (%)
Residuum	Surface (0–40 cm)	5.8 ± 0.6	2.6 ± 0.7*	0.17 ± 0.03	12.3 ± 3.7	9.3 ± 1.3	26.1 ± 5.3	36.2 ± 6.6
	Subsurface (40+ cm)	5.5 ± 0.6	1.9 ± 0.7	0.15 ± 0.02	10.2 ± 1.1	10.5 ± 1.6	27.5 ± 5.9	38.0 ± 5.3
Colluvium	Surface (0–40 cm)	6.2 ± 0.4	2.4 ± 0.5	0.16 ± 0.02*	11.8 ± 2.3	8.7 ± 1.2*	23.7 ± 4.2	36.7 ± 8.0
	Subsurface (40+ cm)	6.1 ± 0.6	2.0 ± 0.8	0.14 ± 0.01	11.2 ± 2.4	9.9 ± 0.7	25.5 ± 3.5	39.4 ± 5.8
Alluvial-colluvium	Surface (0–40 cm)	6.05 ± 0.3	2.6 ± 0.6*	0.16 ± 0.02*	12.9 ± 1.8*	7.2 ± 1.5	20.1 ± 4.2	36.5 ± 10.8
	Subsurface (40+ cm)	5.6 ± 0.5	1.6 ± 0.5	0.12 ± 0.01	10.6 ± 1.3	8.1 ± 1.2	20.9 ± 5.0	40.1 ± 9.8
Alluvium	Surface (0–40 cm)	6.3 ± 0.3	4.1 ± 2.2*	0.19 ± 0.03*	12.6 ± 2.5*	15.1 ± 13.3	25.3 ± 2.3	45 ± 10.8
	Subsurface (40+ cm)	6.5 ± 0.7	1.6 ± 0.5	0.13 ± 0.02	9.17 ± 1.9	13.6 ± 8.6	24.7 ± 5.6	54 ± 10.5

Note: Values show mean ± standard deviation in the different parent materials. Values followed by symbol "*" showed significant differences between surface and subsurface values in the respective parent material.

Abbreviations: CEC, cation exchange capacity; SOM, soil organic matter; TN, total nitrogen.

soil organic matter (SOM), total nitrogen (TN), P, exchangeable bases, and base saturation are recorded in alluvium. Considering the trends down the profile (surface and subsurface trends), soil pH generally decreases down the profile in residuum, colluvium, and alluvial-colluvium (Table 3). The increased surface soil pH is attributed to soil management. In Kamuli District, where lime applications are minimal or absent, increased soil pH is associated with periodic residue burning, which deposits ash on the surface (Mandal et al., 2004). As shown in Table 2, burning was noted at two sites. However, farmers often burn crop residues as quick strategy to clear fields for the next season (Nankya et al., 2019). In alluvium, a reverse pattern is observed with increase in pH in the subsurface in Table 3, attributed to seasonal fluctuation of the shallow groundwater table (Kawalko et al., 2021). This fluctuation is primarily in the subsurface, leading to localized salt accumulation and higher pH. Notably, the only effervescence (using hydrochloric acid) was recorded in an examined termite mound in alluvium, implying possible carbonate accumulation. According to Hazelton and Murphy (2016), the pH ranges across all pedons are strongly acidic to slightly alkaline.

SOM, TN, and P showed similar depth trends across all the parent materials (Table 3). Higher SOM in surface horizons reflects the accumulation of residues that become incorporated into the surface, and its subsequent mineralization releases nitrogen and P. These trends are consistent with the findings of Dourado-Neto et al. (2010), showing the role of organic matter in nutrient cycling in the tropics and low-input systems. Significant differences in TN between surface and subsurface horizons in colluvium can be attributed to the deposition of fine sediment during runoff and erosion events from the residual summits on top of sediment that has been mineralized. Slope-driven sedimentation also explains significant depth differences we see further downslope for both TN and P in both alluvial-colluvium and alluvium. Denitrification (Rasiah et al., 2010; Rodrigues et al., 2024; Wang et al., 2015) and redox-driven leaching of P (Rodrigues et al., 2024), intensified by poor drainage in alluvial-colluvium and alluvium, may explain the significant differences between surface and subsurface TN and P values. SOM and TN ranged from very low to very high and low to medium, respectively, while available phosphorus ranged from low to moderate (Hazelton & Murphy, 2016).

Sum of exchangeable bases, cation exchange capacity (CEC), and base saturation generally increase in the subsurface compared to the surface in residuum, colluvium, and alluvial-colluvium. In alluvium, exchangeable bases and CEC are higher on the surface, while base saturation is higher in the subsurface. Leaching driven by rainfall and consistently warm conditions (Nawaz et al., 2010), combined with continuous crop uptake and limited nutrient replenishment, especially in small-scale agriculture, explain the higher base cations in subsurface layers. Candra et al. (2021) and Mtama et al. (2018) also noted higher exchangeable bases in the subsoil, highlighting leaching as a pedogenic process. In alluvium, the surface horizons showing higher exchangeable bases are due to periodic flooding and deposition of sediment rich in exchangeable bases over the subsurface materials that exhibit higher exchangeable bases in comparison to upland counterparts. Flooding frequency in Kamuli District over the last 10 years has increased (Opio, 2023), possibly increasing the deposition of fresh sediments. Exchangeable bases are generally above their critical limits across all parent materials (Landon, 1991; Okalebo et al., 2002). CEC values ranged from moderate to high with low to moderate base saturation (Hazelton & Murphy, 2016). Kyalo et al. (2024) also reported high CEC values in this region of the country.

The variation in CEC across the soils shows the influence of SOM and clay in tropical soils (Buol et al., 2011;

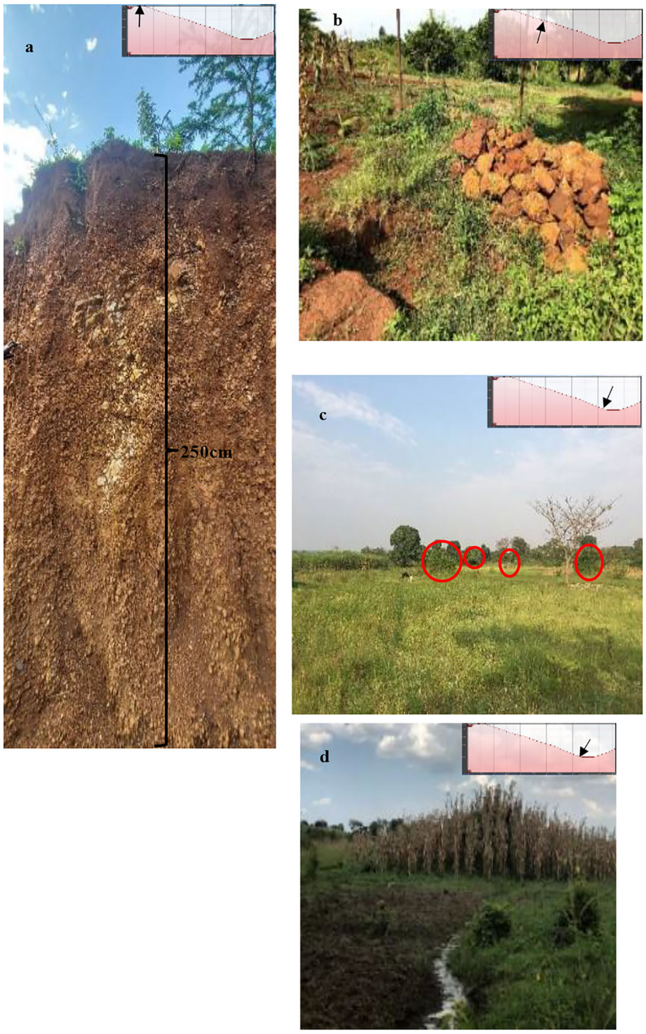

FIGURE 3 Features commonly observed along the Kamuli catena; landscape position of each feature noted in the upper right-hand corner. (a) slope cut showing the locked colluvium lacking a distinct stone line (b) massive plinthite extracted from a maize field (c) stream terrace with visible termite mounds (circled) (d) maize grown on a termite mound in an alluvial setting.

Mtama et al., 2018; Weil & Brady, 2017). CEC on the surface varies significantly, indicating the influence of SOM. The increase in CEC in the subsurface in residuum, colluvium, and alluvial-colluvium suggests the influence of clay. In alluvium, the surface horizons showed higher CEC despite these being highly sandy horizons compared to the subsurface. The soils in alluvium had the highest SOM on the surface, highlighting them as a major source of exchange sites. Wokibula et al. (2024), a study on the CEC of soils in this region, demonstrated that possible variations in clay mineralogy also play a role. The study suggests that 1:1 and 2:1 clay minerals may be dominant in the uplands and lowlands, respectively. While effective CEC was not measured in this study, variable charge likely plays a role, particularly in the red upland soils with iron oxide clays (Al-Shamare & Salman, 2021; Candra et al., 2021; Gomes de Albuquerque et al., 2024; Hall & Huang, 2017; Kong et al., 2021).

3.3 | Soil classification

Based on the soil morphology and physicochemical data, diagnostic epipedons and subsurface horizons were defined, and pedons were classified according to the USDA soil taxonomy and WRB, as shown in Table 4. The diagnostic criteria for classifying the soils according to the USDA Soil Taxonomy (Soil Survey Staff, 2022) include a ustic moisture regime with udic properties in the lowlands and a thermic soil temperature regime.

The soils in alluvium were classified as Alfisols (67%), Inceptisols (16%), and Ultisols (17%). In alluvial-colluvial zones, the soils transition to Entisols (33%) and Ultisols (67%). In colluvial backslopes, the soils were classified as Alfisols (20%) and Ultisols (80%). The residual summits were majorly Oxisols (80%) and Ultisols (20%). The respective WRB reference soil groups are shown in Table 4. Despite the overlap in soil orders across the landscape (related to parent material), a distinct pedogenic gradient emerges. In this case, from highly weathered residual uplands to colluvial backslopes and finally more recent alluvial lowlands. This variation is also evident in chemical properties. The highly weathered upland soils (residuum and colluvium) exhibit lower values for chemical properties compared to the lowland soils in alluvium (Table 3).

The upland pedons in residuum and colluvium exhibited a lower average silt-to-clay ratio compared to the lowland counterparts (Figure 5). This variation indicates that the upland pedons are highly weathered and more developed, while the lowlands are influenced by more recent geogenic and deposition processes. Plinthite has often been associated with highly weathered conditions (McFarlane, 1991; Idowu & Oluwatosin, 2008; Oluwatosin et al., 2019). Its predominance in upland residual and colluvial soils provides additional evidence of the greater degree of weathering in these soils when compared to the lowland soils.

Kamuli District's pedology is highly variable, albeit understandable within the framework of a catena. Soil variation in Kamuli shows the influence of landscape position, drainage, and parent material. Consistent with Milne's (1936) concept, the soil-landscape relationship is a sequence from well-drained (reddish-brown soils) uplands to poorly drained lowlands. This pattern is further reinforced by a systematic variation in morphological properties (Figure 6), parent materials, chemical properties (Table 3), and even degree of weathering (Figure 5). These insights support the initial hypothesis that soil properties vary systematically with

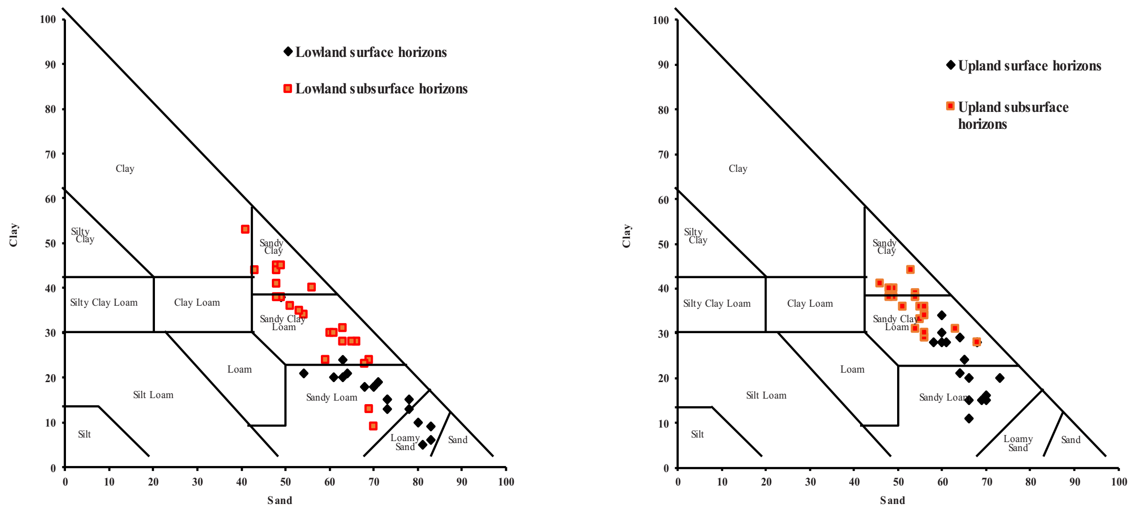

FIGURE 4 Textural triangles showing particle size distribution in lowland and upland soils of Kamuli District. Also highlighted in the figure are textural contrasts between surface and subsurface horizons in the upland and lowland soils.

TABLE 4 Classification of the pedons studied in Kamuli District grouped by parent material using both USDA soil Taxonomy and World Reference Base (WRB).

Alluvium		
Pedon ID	**USDA soil taxonomy**	**WRB**
MRTC01	Sandy over clayey fine, mixed, active, thermic Vertic Endoaqualf	Haplic Endostagnic Vertisol (Mollic, Hypereutric, Gilgaic)
BUS16	Fine-loamy, subactive, thermic Typic Endoaquult	Endostagnic Acrisol (Loamic, Cutanic, Profondic)
BUS17	Fine, mixed, active, thermic Vertic Endoaqualf	Haplic Endostagnic Vertisol (Mollic, Hypereutric, Gleyic)
MAL19	Fine, mixed, thermic, Umbric Endoaqualf	Mollic Gleyic Umbrisol (Loamic, Abruptic, Pachic)
NAK08	Loamy, mixed, semi-active, thermic Arenic Hapludalf	Haplic Mollic Umbrisol (Loamic, Abruptic, Pachic)
NAK09	Sandy, mixed, thermic, Typic Dystrudept	Stagnic Dystric Cambisol (Arenic, Humic)
Alluvial-colluvium		
KAB13	Sandy, mixed, thermic Typic Endoaquent	Eutric Arenosol (Ochric, Stagnic)
KIK14	Fine-loamy, mixed, thermic Typic Haplustult	Abruptic Haplic Acrisol (Loamic, Cutanic, Humic)
KIK15	Shallow, Sandy over loamy, mixed, thermic Typic Plinthustult	Haplic Umbric Plinthosol (Loamic, Dystric, Humic)
Colluvium		
MRTC02	Fine-loamy, kaolinitic, thermic, Typic Plinthustalf	Haplic Mollic Plinthosol (Loamic, Dystric, Ochric)
KIW10	Shallow, Fine-loamy, Kaolinitic, thermic, Typic Plinthustult	Haplic Umbric Plinthosol (Loamic, Dystric, Humic)
KIW11	Shallow, Fine-loamy, Kaolinitic, thermic, Typic Plinthustult	Haplic Umbric Plinthosol (Loamic, Dystric, Humic)
KAB12	Fine-loamy, mixed, active, thermic Typic Haplustult	Haplic Rhodic Acrisol (Loamic, Cutanic, Humic)
NAK04	Fine-loamy, mixed, subactive, thermic Typic Haplustustult	Haplic Rhodic Acrisol (Cutanic, Humic)
Residuum		
MRTC03	Loamy-skeletal, Kaolinitic, thermic Plinthic Haplustox	Haplic Petric Plinthosol (Loamic, Dystric, Ochric)
NAK05	Shallow, Coarse-Loamy, Kaolinitic, thermic Plinthic Haplustox	Haplic Petric Plinthosol (Loamic, Dystric, Humic)
NAK06	Shallow, loamy, Kaolinitic, thermic Plinthic Haplustox	Umbric Petric Plinthosol (Loamic, Dystric, Humic)
NAK07	Shallow, Fine-loamy, mixed, thermic Plinthic Eutrustox	Umbric Petric Plinthosol (Loamic, Dystric, Humic)
KIS18	Coarse-loamy, sub-active, acid, Typic Haplustult	Haplic Ferralic Acrisol (Ochric, Oxyaquic)

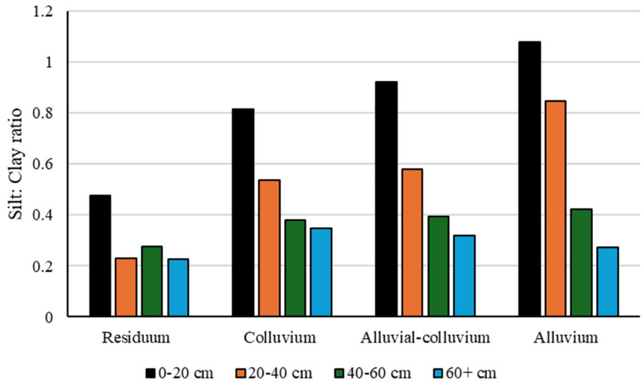

FIGURE 5 Variation in silt-to-clay ratio with depth across the different parent materials in Kamuli District.

landscape position. Soil formation and variation in Kamuli District are related to landscape positions, ultimately capturing the ideals of a catena.

As earlier noted, Kamuli District's soil-landscape is mapped as the Buruli catena, but our findings reveal not only the similarities but also the differences. Brown (2004), the most recent study on this catena with a pedological perspective, classified the soils in the upland as a mix of Ultisols, Oxisols, and Inceptisols. This study shows a mix of Ultisols, Alfisols, and Oxisols. Classifications in the lowland areas, which were not included in Brown's classification, revealed a mix of Alfisols, Inceptisols, and Ultisols. Morphologically, the flat summits and absence of a stoneline also add to the differences noted between Kamuli District and Brown's landscape. Such distinctions, together with Isabirye et al.'s (2004) finding that the Buruli catena occupies a smaller spatial extent than originally mapped, underscore the need for updated interpretations of catena systems in this region.

3.4 | Pedology and cropping decisions in Kamuli District

It is acknowledged that socio-economic factors, including access to inputs and cultural preferences, influence land use (Ahimbisibwe et al., 2019; Kalanzi et al., 2021). This study focused solely on pedology and cropping patterns; therefore, any interpretations presented are limited to the observed patterns during field work and farmer interactions. Twenty percent of sites in residuum were left to fallow. Forty percent had woodlots and fruit orchards established. Anecdotally, farmers planted trees with the expectation that their roots would penetrate the plinthic layer. The other 40% of the sites had perennial crops, such as coffee and cacao, often intercropped with cassava. However, coffee and cacao exhibit poor establishment during the seedling stage, but mature trees persist when established (Wokibula et al., 2025). Cassava, due to its ability to withstand marginal soils and resilience (Borku et al., 2025), is commonly intercropped with these perennials to ensure food security.

The backslopes are more intensively cropped (80%) with annual crops, including beans, soybeans, grain amaranth, sweet potatoes, and bananas, with some sites also featuring coffee and cacao. These crops are supported by relatively deeper soils (considering plinthite) compared to residual summits and have higher available water. In the lowlands in alluvial colluvium and alluvium, only 33% of the sites were cropped due to poor drainage. The cultivated areas are majorly under sugar cane and rice, which are tolerant to water saturation. Additional adaptation strategies such as mounding, raised beds, and even planting on termite mounds (Figure 3d) are also used to manage poor drainage.

Based on these field observations, a comparison was made between cultivated and uncultivated sites. There was evidence of differences in morphological properties in both upland and lowland positions (Figure 7).

In the upland soils, three of the four morphological properties were shallower in the cultivated pedons. However, only the depth of contrasting texture showed a significant difference, suggesting the impact of erosion (Veenstra & Burras, 2015). Water and wind-driven erosion are significant in Kamuli District, as often observed in the field. Figure 8a shows that runoff-driven erosion was pronounced, especially after rainfall. The runoff leads to rill formation (Figure 8b), particularly early in the season before crop cover is established. Sedimentation after rainfall events (Figure 8c) reflects the episodic pulsed nature of sediment transport described by Chen et al. (2019). Collectively, these observations show how surface runoff and sediment redistribution alter the morphology of soils, especially in the upland sloping areas. Compared to uncultivated areas, these processes are exacerbated in cultivated areas.

Although they showed no significant differences, the shallow depth to plinthite and red redox features (majorly associated with plinthite) can also be attributed to erosion and surface soil truncation. Idowu and Oluwatosin (2008) and Oluwatosin et al. (2019) have demonstrated that erosion due to management practices exposes plinthite. Depth of mollic colors was deeper for cultivated pedons compared to uncultivated pedons (despite non-significance), contrary to what would be expected with erosion thinning. Deeper mollic colors for cultivated pedons suggest the influence of frequent tillage, which mixes organic matter-rich sediment deeper into the profile (Veenstra & Burras, 2015).

In the lowland areas, depth of mollic colors was shallower in cultivated pedons, which can be attributed to accelerated organic matter decomposition due to improved aeration (Veenstra & Burras, 2015). However, SOM contents do not differ significantly between cultivated and uncultivated sites in the lowland (Figure 9). The greater depth of mollic

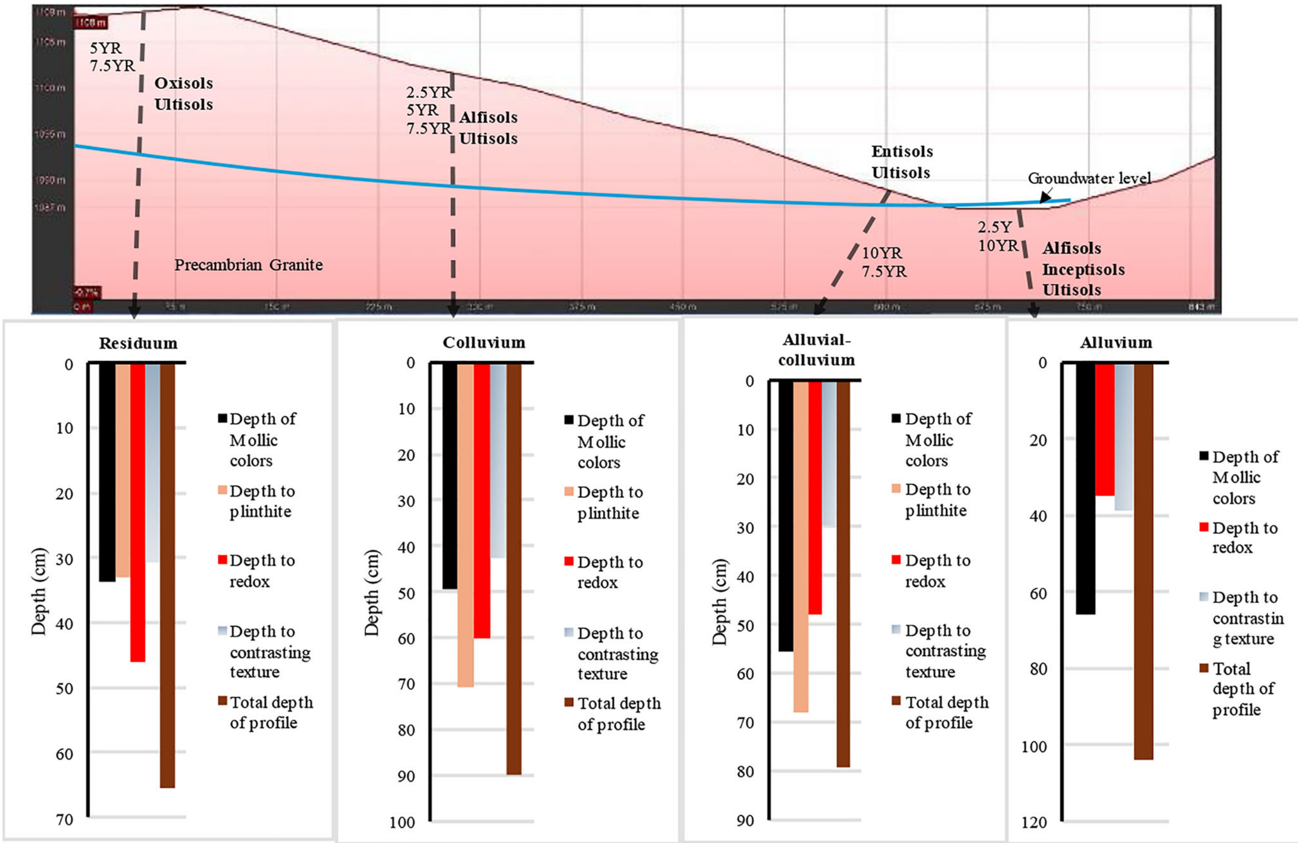

FIGURE 6 Conceptual diagram showing differences in morphological properties and classifications along the Kamuli catena.

colors in uncultivated pedons suggests deeper organic matter inputs from root turnover and below-ground biomass. In cultivated pedons subject to frequent tillage, there is a tendency to concentrate organic inputs near the surface. In Kamuli, majority of the farmers rely primarily on hoes for tillage, which results in consistent mixing of crop residues within the surface 30 cm. As a result, there is a shallower mollic-colored layer despite comparable SOM. Depth to contrasting texture being shallower in uncultivated pedons suggests a pattern tied to sediment enrichment in the cultivated sites. Cultivated lowland areas likely receive a higher pulse of sediment from the upland cultivated fields, creating a deeper and more homogeneous surface horizon. The uncultivated pedons, which experience minimal disturbance and limited sediment input, retain a shallower transition between the surface and subsurface textures. Although statistically not significant, depth to redoximorphic features was shallower in uncultivated pedons. This variation is likely tied to selective land use, where farmers are more likely to cultivate somewhat better-drained locations (El Abd & El Osta, 2014; Veenstra & Burras, 2015; West et al., 1998). The uncultivated, poorly drained soils experience frequent waterlogging, hence the shallow expression of redoximorphic features.

The depth-by-depth variation in soil chemical properties, aggregated by land use and landscape position, is shown in Table S2. On a whole profile basis, differences between cultivated and uncultivated pedons are shown in Figures 9 and 10. SOM, TN, carbon: nitrogen ratio, and P varied with landscape position and land use (Figure 9). In the uplands, on a whole profile basis, SOM and TN were significantly higher in uncultivated pedons compared to cultivated pedons. This pattern suggests organic matter depletion and nutrient depletion due to continuous tillage, surface erosion, and reduced residue return (Veenstra & Burras, 2015). The lower SOM and TN is also accompanied by a lower C:N ratio (although not statistically significant) in cultivated soils. In the lowland pedons, neither SOM nor TN was significantly different between cultivated and uncultivated pedons. This can be attributed to periodic sediment deposition that brings organic matter-rich sediment, offsetting the effects of cultivation.

Available phosphorus (P) showed no significant difference between cultivated and uncultivated pedons in the uplands despite SOM contents showing significant differences. This variation may be due to P-fixation by iron and aluminum oxides (Fink et al., 2016). Phosphorus fixation reduces P, irrespective of whether it is cultivated or not. In the lowlands, significant differences are observed (Figure 9), with cultivated pedons showing higher P. The lower P in uncultivated pedons can be explained by redox-driven P leaching (Rodrigues et al., 2024). In the more poorly drained, uncultivated pedons, iron

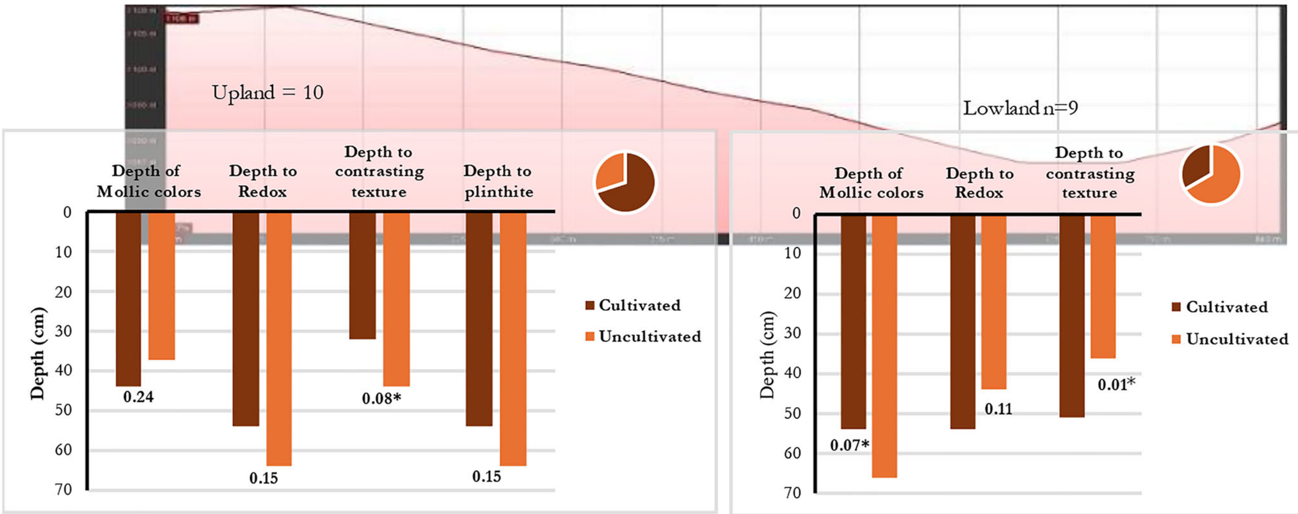

FIGURE 7 A comparative summary of morphological characteristics between cultivated and uncultivated pedons in upland ($n = 10$) and lowland ($n = 9$) landscape positions. The bars represent mean depth (cm), and the pie graphs show the proportions of cultivated and uncultivated pedons in each landscape position. The asterisks denote significance levels from Welch's t-tests with $*p < 0.1$.

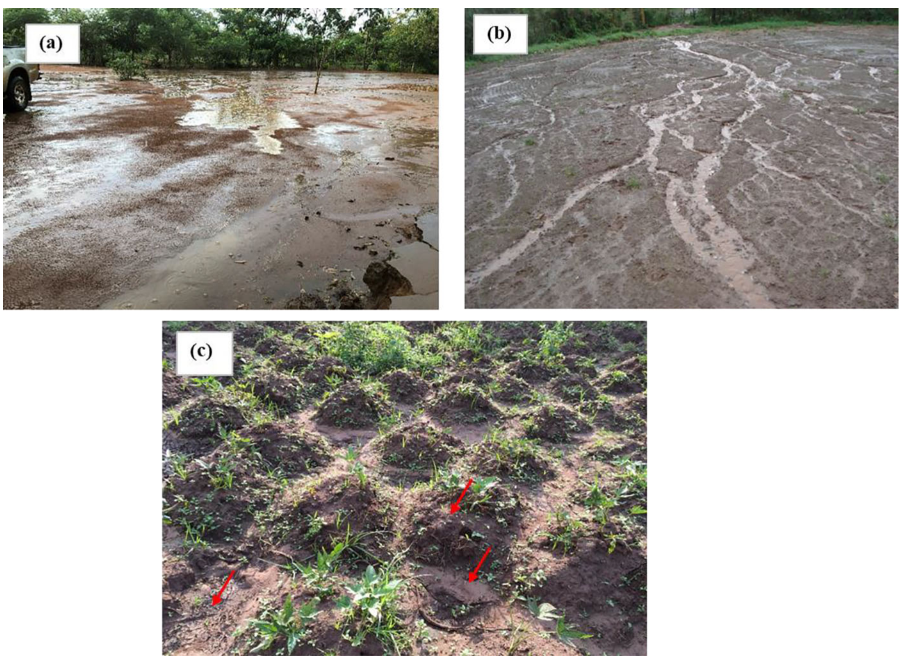

FIGURE 8 Field evidence of water-driven erosion observed in Kamuli. (a) Runoff from bare and compacted ground during a rainfall event. (b) Rill formation and active soil sediment displacement during a rainfall event in a recently cultivated field. (c) Differences highlighted by the arrows are noted in a potato garden with mounds because of sedimentation after a rainfall event pointing to erosion.

(Fe^{3+}) is reduced to Fe^{2+}, releasing the previously bound phosphate. This leaching reduces P on a whole profile basis compared to somewhat better-drained cultivated pedons.

Depth-by-depth analysis of SOM and TN showed contrasting patterns between uplands and lowland soils (Table S2). In the uplands, uncultivated pedons showed significantly higher SOM at 20- to 30-cm and 30- to 40-cm depths as well as higher TN. This pattern can be linked to the accumulation and incorporation of organic matter through continuous root turnover under undisturbed condition. In cultivated pedons, repeated tillage practices and erosion limit the subsurface SOM enrichment. In the lowlands, cultivated pedons showed higher SOM values from 30 to 60 cm, with statistically significant values at 40–50 cm. This accumulation of SOM at

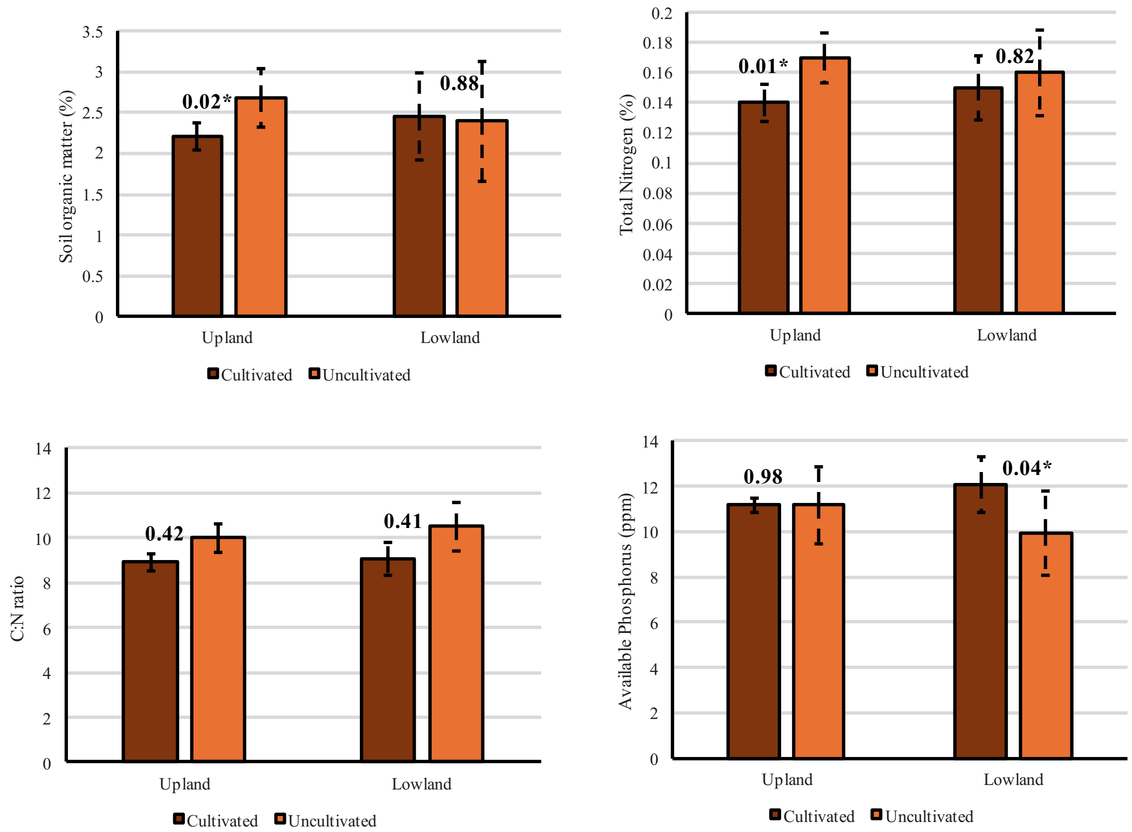

FIGURE 9 Variation in soil organic matter, total nitrogen, C:N ratio, and available phosphorus between cultivated and uncultivated pedons in upland and lowland positions on a whole profile basis with associated *p*-values for which *significance at $\alpha = 0.1$.

depth mirrors the findings of Veenstra and Burras (2015), who attributed it to dissolution and translocation of surface SOM into deeper horizons. Available P was generally higher for cultivated pedons at 20 to 60 cm, with significant differences recorded at 30–40 cm and 50–60 cm in the uplands. Despite having relatively higher SOM, they had lower P, which we can attribute to higher P-fixation. The plinthite, with iron oxides (Soil Survey Staff, 2022) and generally low pH (Figure 10a), facilitates P-fixation in the uncultivated pedons. In the lowlands, cultivated pedons exhibited statistically higher P across all depths, emphasizing the influence of drainage on P dynamics in this landscape position.

The dyamics of SOM and P observed in Kamuli District have important agronomic implication. In both uplands and lowlands, SOM values in cultivated pedons were below the 3% (equivalent to 1.7% soil organic carbon) threshold considered critical for maintaining productivity in low-input tropical systems (Musinguzi et al., 2016; Okalebo et al., 2002). Similarly, P values were below the recommended 15 ppm (Bray 1) values. As a result, there is a need for conservation strategies such as no-till and residue retention to build SOM stocks in Kamuli District. Integrated soil fertility management strategies (Rware et al., 2020; Singh & Lal, 2005) and deployment of P-efficient crops offer a complementary pathway for improving nutrient acquisition and resilience.

Figure 10 shows the variation of soil pH and exchangeable base cations between cultivated and uncultivated pedons in both upland and lowland pedons on a whole profile basis. A depth-by-depth comparison is in Table S2. Soil pH was significantly higher in cultivated pedons in the uplands. The higher pH is linked to management, but farmers in Kamuli District apply minimal to no lime. The increased soil pH shows the indirect influence of residue management in cultivated areas. Practices such as incorporation and residue burning after harvest have been shown to increas soil pH (Juo & Franzluebbers, 2003; Latifah et al., 2018; Mandal et al., 2004; Trujillo-Narcia et al., 2019). What begins as a field preparation strategy carries unintended pedochemical consequences, transiently increasing soil pH. In lowland soils, where soils inherently exhibit higher pH, the influence of residue burning is dampened, hence the non-significant differences between cultivated and uncultivated pedons.

Exchangeable bases Na^{+}, K^{+}, Mg^{2+}, and Ca^{2+} were generally higher in uncultivated pedons compared to the cultivated pedons. This variation reflects the cumulative effects of crop uptake without adequate replenishment, a common occurrence in low-input, smallholder systems. The crops utilize the

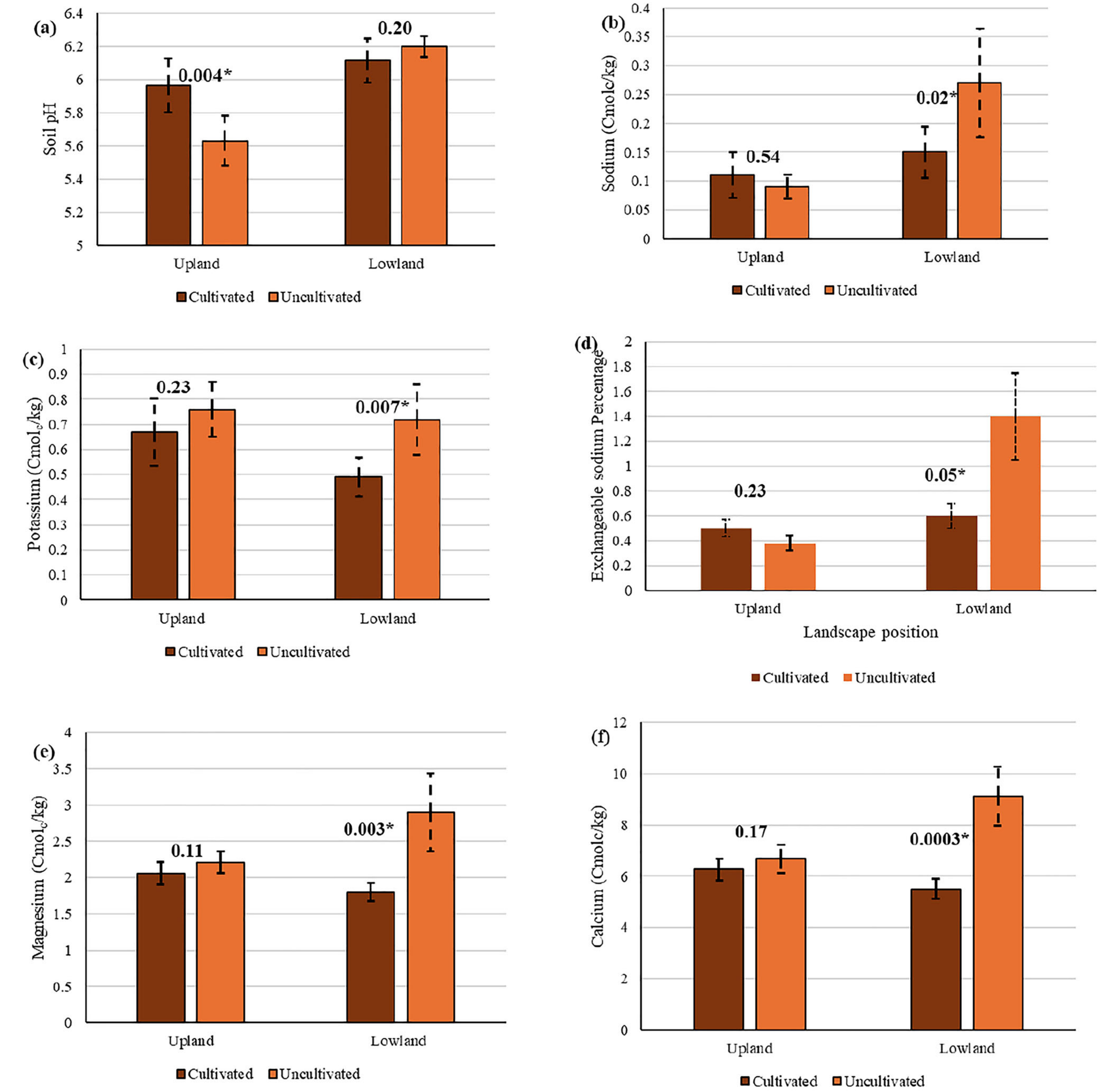

FIGURE 10 Variation in soil pH, sodium, potassium, exchangeable sodium percentage, magnesium, and calcium between cultivated and uncultivated pedons in upland and lowland positions on a whole profile basis with associated *p*-values for which *significance at $\alpha = 0.1$.

soil's reservoir of exchangeable bases, while leaching and erosion further exacerbate these losses especially in the upland. Over time, this imbalance in nutrient removal and return contributes to the gradual decline in exchangeable bases. The upland soils showed no statistically significantly different exchangeable bases compared to the lowlands. In the lowlands, periodic flooding enriches the soil with sediment rich in bases. However, in cultivated pedons, these bases are lost due to continuous crop uptake without replenishment, resulting in significantly lower exchangeable bases compared to the accumulation observed in uncultivated pedons. This difference is very distinct on a depth-by-depth basis, as shown in Table S2.

Interpretations against critical limits $0.2 Cmol_c kg^{-1}$ for Ca^{2+}, $0.5 Cmol_c kg^{-1}$ for Mg^{2+}, and $0.25 Cmol_c kg^{-1}$ for K^+ according to Landon (1991) and Okalebo et al. (2002), indicate that Ca^{2+}, Mg^{2+}, and K^+ in both cultivated and uncultivated remain well above their respective critical thresholds. Despite sufficient levels, base saturation was low, especially in the uplands, indicating the dominance of acidic cations, such as Al^{3+}, Fe^{3+}, and H^+. This imbalance hinders nutrient uptake and creates toxicity problems, constraining plant growth and productivity. The exchangeable sodium percentage (ESP) in upland and lowland soils remains below the sodicity threshold of 15% (Allison et al., 1954), as shown in Figure 10d. In the upland, cultivated pedons had higher (on average and not significant) ESP compared to the uncultivated pedons. Lowland soils show more distinct variability, with uncultivated pedons displaying substantially higher ESP compared to the cultivated ones. This is indicative of the potential accumulation of sodium under poorly drained conditions in the uncultivated lowland soils.

The relationship between pedology and cropping decisions in Kamuli District was nuanced, creating a feedback loop between the two. In the absence of formal soil maps, farmers in Uganda rely on visual cues such as vegetation vigor, drainage, and texture to guide their cropping decisions (Kyebogola et al., 2020; Okullo et al., 2022; Wendiro et al., 2019). However, Anderson et al. (2023) showed that farmers' assessments of soil productivity in Kamuli often align with pedological evaluations. The findings in this study show that colluvial backslopes with greater effective soil depth and better drainage are more intensively cultivated. This is in comparison to the shallow, plinthic summits and poorly drained lowlands. The cropping of these favored zones has driven changes in both morphological and chemical properties. Similar patterns of land use and soil change have been widely documented (Bamutaze et al., 2021; Lal, 2012; Richter, 2019; Richter & Burras, 2017; Richter et al., 2011; Suh & Tsheko, 2024; Timbas, 2021; Veenstra & Burras, 2015; Yeboah et al., 2022). Overall, these studies show how management decisions are an active driver of soil change. Changes such as reduced SOM, low base cations, low TN, low P, and shallow depth to plinthite diverge from the initial expectation that cultivated areas are covered with more fertile and crop-favorable soils. Instead, these changes are likely to be detrimental to soil function over the long term. Future work is needed to quantify the long-term trajectory of these changes and its implications for sustainable productivity.

4 | CONCLUSION

Our study shows that the pedology of Kamuli District is highly interpretable when one understands the geology across the landscape. The district lies on a Precambrian granite-derived plateau with young, nearly level alluvial valleys of the Holocene, or modern age. These valleys are filled with sediment (alluvium) from the periodic backflooding of the Nile River combined with localized stream activity. Colluvial backslopes link the residual summits with these valleys with a transitional alluvial-colluvial zone in the footslopes. Morphological properties showed a drainage gradient from well-drained uplands to poorly drained lowlands. Upland soils in residuum and colluvium are a mix of Alfisols, Ultisols, and Oxisols. Lowland alluvial soils are a mix of Alfisols, Entisols, and Inceptisols. Silt-to-clay ratio results showed a continuum from highly weathered upland soils to younger and recent alluvial soils. The differences in parent material and hydrology, which are all affected by topography, clearly illustrate how the catena concept can be used to map soil distribution in Kamuli District. However, our findings showed differences from the classical Buruli catena, which is how the District is currently mapped. These differences warrant the need for updated interpretations to capture the present soil-landscape relationships.

The relationship between pedology and cropping patterns shows a feedback loop where they influence each other. Farmers rely more on local experience and visual cues, which is captured in the differences in cultivation intensity across the landscape. A comparison between cultivated and uncultivated areas revealed apparent shifts in key properties, showing how continuous cropping alters soil chemical and morphological properties. The magnitude and direction of these changes are also dependent on the landscape position. Although these changes are largely unintended, they are likely to have long-term impact on soil function. Enhancing productivity in Kamuli District will require tailored management practices that align with the unique pedological conditions. There is a need for agronomic interventions to ensure that even lands with inherent constraints can be cultivated more effectively.

AUTHOR CONTRIBUTIONS

Francis Akitwine: Conceptualization; data curation; formal analysis; investigation; methodology; visualization; writing—original draft. **Amber D. Anderson**: Data curation; investigation; methodology; writing—original draft; writing—review and editing. **Nicola L. Timbas**: Data curation; investigation; methodology; writing—review and editing. **Matthew T. Streeter**: Investigation; methodology; writing—review and editing. **Shillah Kwikiiriza**: Investigation; writing—original draft; writing—review and editing. **Rebecca A. Wokibula**: Investigation; methodology; writing—original draft; writing—review and editing. **Johnson G. Mtama**: Investigation; methodology; writing—original draft; writing—review and editing. **Mbeiza Moureen**: Resources; software; writing—original draft; writing—review and editing. **C. Lee Burras**: Conceptualization; data curation; funding acquisition; investigation; methodology; project administration; resources; supervision; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data supporting this study's findings are available in the dryad data repository at (https://doi.org/10.5061/dryad.rjdfn2zsj).

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SUPPORTING INFORMATION

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