Acta Solum 4, Number 2 (March 2026), 110–120. DOI: 10.20527/actasolum.v4i2.3608
http://jtam.ulm.ac.id/index.php/actasolum e-ISSN: 2987-514

Integrating Geopedology and Land Evaluation to Diagnose Soil Constraints for Maize in Tropical Riparian Landscapes

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Article Information

Received December 31st 2025
Accepted March 18th 2026
Published March 28th 2026
Online March 28th 2026

Keywords:

Landform-based assessment; Limiting factors analysis; Riparian agroecosystems; Soil fertility constraints; Spatial land evaluation

Abstract

Maize (*Zea mays* L.) production in tropical riparian landscapes is strongly governed by spatial variability in soil–landscape interactions that control drainage conditions, rooting depth, and nutrient availability. This study aims to delineate geopedological landforms, evaluate maize suitability using a limiting-factor approach, and diagnose key landform-specific soil constraints. A GIS-supported geopedological framework with land suitability evaluation to spatially diagnose soil constraints affecting maize cultivation along the Kelinjau River, East Kalimantan, Indonesia. The study area was stratified into two geopedological landform units (permanently waterlogged peaty floodplains and undulating sandy terraces) using terrain analysis derived from digital elevation model (DEM) data, high-resolution satellite imagery, and field surveys. Climatic, soil physical and chemical, hydrological, and terrain characteristics were quantified using field observations, laboratory analyses, and geospatial datasets, and maize suitability was assessed using a land-characteristic–crop-requirement matching approach based on the principle of limiting factors. The results indicate that climatic and topographic conditions are spatially uniform and generally favorable for maize cultivation, whereas soil-related variables exert dominant control on suitability outcomes. Both landform units were classified as marginally suitable (S3). On peaty floodplains, low nutrient availability (particularly phosphorus) constitutes the primary limitation, while sandy terraces are constrained by impeded drainage, shallow effective soil depth, and nutrient deficiencies. These findings highlight the importance of landform-based spatial stratification in revealing process-driven soil limitations and demonstrate that integrating geopedology with spatial land evaluation enhances the diagnosis of constraints on maize suitability, thereby supporting targeted and sustainable land management in heterogeneous riparian landscapes.

1. Introduction

Maize (*Zea mays* L.) is one of the most widely cultivated cereal crops worldwide and plays a critical role in food security, rural livelihoods, and livestock feed systems, particularly in tropical and subtropical regions dominated by smallholder agricultural systems. The productivity and sustainability of maize cultivation are strongly governed by the interactions among soil properties, climate, and topography, making landscape characteristics a fundamental determinant of crop performance (FAO, 1976; Awoonor et al., 2023; Karapetsas et al., 2024). In this context, land suitability assessment (LSA) serves as a systematic framework to evaluate whether specific land units meet crop requirements, thereby supporting sustainable agricultural planning and optimal land resource allocation. Previous studies have applied LSA using diverse approaches, ranging from GIS-based multi-criteria decision analysis (MCDA) to physically based soil–climate matching, to identify suitable areas for maize cultivation in

environments such as East Java, Indonesia and the Marvdasht Plain, Iran (Tashayo et al., 2020; Habibie et al., 2021).

Most land evaluation studies are grounded in the FAO land evaluation framework, which emphasizes the matching of land characteristics with crop-specific requirements to derive suitability classes from highly suitable (S1) to not suitable (N), based on the type and severity of limiting factors (FAO, 1976; Indonesian Center for Agricultural Land Resources Research and Development, 2016; Nugroho et al., 2025). The strength of the FAO framework lies in its holistic consideration of soil, climatic, topographic, and hydrological constraints, allowing a comprehensive assessment of land performance potential (FAO, 1976). Recent applications in Europe and Africa have demonstrated the utility of this framework for evaluating maize suitability under current and future climate scenarios and identifying key soil fertility limitations that affect yield potential (Awoonor et al., 2023; Karapetsas et al., 2024).

Beyond classical matching approaches, recent LSA research has increasingly incorporated spatial analysis and decision-support models to enhance the quantification of biophysical constraints. Techniques such as the analytic hierarchy process (AHP) integrated with GIS have been widely used to weight environmental variables relevant to maize cultivation, including soil texture, slope, and soil reaction, often revealing soil physical properties as dominant limiting factors (Tashayo et al., 2020). Similar GIS–AHP applications in West Africa and Nigeria further highlight the importance of integrating climatic, physicochemical, and terrain data to delineate the spatial patterns of maize suitability and guide land management interventions (Bwadi et al., 2025).

Despite these methodological advances, many conventional LSA approaches remain outcome-oriented, focusing primarily on suitability classes without explicitly linking them to the soil–landscape processes that generate spatial variability in land quality (FAO, 1976; Tashayo et al., 2020; Bwadi et al., 2025). To address this limitation, the geopedological approach integrates geomorphology and pedology to stratify landscapes into landform units that reflect differences in soil genesis, drainage conditions, effective soil depth, and nutrient dynamics. Previous applications of geopedological frameworks to crops, such as rice and mixed cropping systems, have demonstrated that landscape position and soil development pathways exert strong controls on land suitability beyond what can be captured by overlay-based GIS techniques alone (Han et al., 2021). This process-based perspective is particularly relevant to maize, which is sensitive to oxygen availability and to root-zone physical constraints that vary with landform position, drainage regime, and soil water dynamics.

Tropical riparian landscapes are characterised by pronounced spatial heterogeneity driven by fluvial processes that produce contrasting landforms, including floodplains and terraces, each associated with distinct soil properties relevant to maize growth (De Feudis et al., 2021; Samiei-Fard et al., 2024). Within such environments, drainage conditions, organic matter accumulation, and effective rooting depth can vary over short distances, necessitating a land suitability framework that explicitly integrates pedological and geomorphological controls. By combining geopedology with land evaluation, it becomes possible to diagnose dominant and landform-specific soil constraints rather than merely classifying suitability levels. Accordingly, this study aims to evaluate maize suitability in a tropical riparian landscape in East Kalimantan, Indonesia, by linking soil and landform attributes to maize-specific requirements, thereby providing a process-based diagnosis of soil constraints to support sustainable land-use planning and targeted management interventions.

2. Research Methods

2.1. Research Location

The research was conducted in Kelinjau Village, Muara Ancalong Subdistrict, East Kutai Regency, East Kalimantan Province, Indonesia, situated within a tropical riparian landscape shaped by the Kelinjau River system (Figure 1). As illustrated in Fig. 1a and 1b, the study site is located in eastern Kalimantan and represents a lowland fluvial landscape influenced by ongoing riverine processes. The Area of Interest (AOI), delineated along the Kelinjau River corridor (Figure 1c), encompasses two principal riparian landform units: permanently waterlogged peaty floodplains covering 36.17 ha and undulating sandy terraces occupying 426.70 ha. These landforms exhibit pronounced contrasts in relative elevation, drainage regimes, and soil properties, which play a critical role in controlling land suitability for agricultural use. The spatial arrangement of floodplain units adjacent to the active river channel underscores the importance of fluvial dynamics and shallow groundwater conditions in shaping soil and landscape characteristics within the riparian zone.

To characterize soil conditions within each landform, one representative observation point was selected per landform unit based on field reconnaissance and geomorphological homogeneity, resulting in a total of two observation points. At each location, soil morphological descriptions were conducted to assess key land characteristics relevant to maize suitability, including drainage conditions, effective soil depth, texture, and peat properties. Soil samples were collected for laboratory analysis of selected physical and chemical properties, specifically those required for land suitability evaluation. This approach was designed to represent dominant soil–

landscape conditions within each geopedological unit and to support a land characteristic–based evaluation framework, rather than to capture fine-scale spatial variability within landforms.

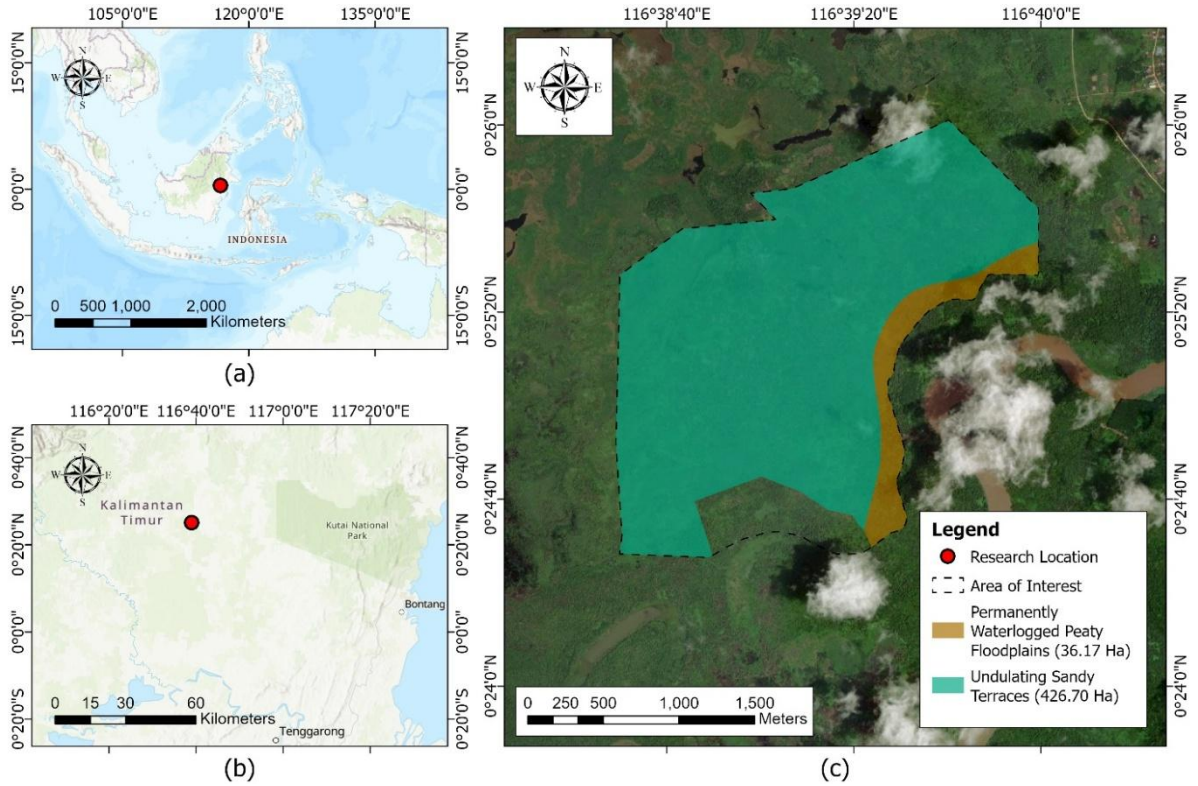

Figure 1. Location of the study area along the Kelinjau River, East Kalimantan, Indonesia: (a) national context, (b) provincial context, and (c) Area of Interest (AOI).

2.2. Geopedological Landform Delineation

Geopedological landform delineation in this study was implemented to generate a landscape stratification framework that directly associates geomorphological units with underlying soil development processes that influence maize growth in riparian environments, recognizing that terrain morphology and landform position exert first-order controls on drainage, soil depth, and nutrient distribution (Irawan et al., 2022). The procedure integrated high-resolution satellite image interpretation, systematic field reconnaissance, and analysis of elevation and derivative terrain data from the Indonesian National Digital Elevation Model (DEMNAS), which has been extensively utilized for terrain and landform analyses in Indonesian agricultural and geomorphological research (Geospatial Information Agency of Indonesia, 2018; Julzarika and Harintaka, 2019; De Feudis et al., 2021). Using DEM-derived attributes such as relative relief and positional context alongside surface morphology and hydrological indicators, the Area of Interest was partitioned into two dominant riparian landform units illustrated in Figure 1c: (i) permanently waterlogged peaty floodplains, occupying lower elevations adjacent to the river with frequent saturation and accumulation of organic matter, and (ii) undulating sandy terraces, located at modestly higher positions with improved surface drainage and coarser parent material expression. These landforms manifest contrasting pedological and hydrological regimes that are critical to maize suitability because they govern key limiting factors, such as oxygen availability, rooting depth, and water/nutrient dynamics, which are not readily captured by conventional land use overlays without explicit terrain stratification (Irawan et al., 2022; Samiei-Fard et al., 2024). Thus, the delineation of geopedological units provides a process-driven framework for subsequent land suitability evaluation by ensuring that soil variability and its mechanistic links to landscape processes are represented in the assessment of crop-specific requirements.

2.3. Land Characteristics Data and Analysis

Land suitability evaluation for maize was carried out using a suite of key land characteristics that collectively influence crop performance, including climatic, soil physical and chemical, hydrological, and terrain attributes, following integrated land evaluation frameworks that emphasize the combined effects of these variables on crop potential (FAO, 1976; Indonesian Center for Agricultural Land Resources Research and Development, 2016; Moisa et al., 2022; Karapetsas et al., 2024; Umeugokwe et al., 2025). Climatic conditions, specifically annual rainfall, the number of months with significant precipitation, and mean temperature, were quantified using long-

term CHIRPS climate data to capture moisture and thermal regimes relevant to maize growth and development, a practice commonly adopted in regional suitability studies (Moisa et al., 2022; Awoonor et al., 2023; Climate Hazards Center, 2025). Terrain slope, extracted from DEMNAS, was used to assess potential erosion hazard and its implications for soil conservation and water retention, factors known to constrain maize production when excessive (Geospatial Information Agency of Indonesia, 2018; Julzarika and Harintaka, 2019; Tashayo et al., 2020; Riza et al., 2022; Karapetsas et al., 2024). Soil physical properties, such as texture, coarse fragments, and effective depth, were determined through systematic field surveys and laboratory analyses (e.g., the sieve–hydrometer method), while drainage class and hydrological conditions were documented through soil morphological descriptions to evaluate rooting conditions and oxygen availability in the root zone. Standard laboratory procedures were employed to analyze key soil chemical properties, including cation exchange capacity (CEC), base saturation, soil pH, organic carbon, and available macronutrients (total nitrogen, P_2O_5, and K_2O), using ammonium acetate extraction, Kjeldahl digestion, and Bray I colorimetry to assess nutrient retention and supply potential, consistent with soil fertility evaluation protocols used in maize suitability research (Awoonor et al., 2023). Additionally, field evidence of sheet and rill erosion was systematically recorded to supplement DEM-derived erosion indicators. All data sources, measurement techniques, and analytical procedures are detailed in Table 1, ensuring that environmental gradients relevant to maize productivity are robustly captured across the delineated geopedological landform units.

Table 1. Land characteristics, data sources, and detailed analytical methods used for maize suitability evaluation

Land Use Requirement / Land Characteristic	Data source	Detailed analytical method
Temperature (tc)		
Annual mean temperature (°C)	CHIRPS climate data	Gridded climate data extraction and monthly–annual averaging (Climate Hazards Center, 2025)
Water availability (wa)		
Annual Rainfall (mm year^{-1})	CHIRPS climate data	Annual rainfall analysis (Climate Hazards Center, 2025)
Number of wet months (>200 mm month^{-1})	CHIRPS climate data	Monthly rainfall threshold analysis (Climate Hazards Center, 2025)
Oxygen Availability (oa)		
Drainage	Field survey	Soil morphological description (Soil Science Division Staff, 2017)
Rooting conditions (rc)		
Soil texture	Soil samples	Particle size distribution (sieve–hydrometer method) (Gee and Bauder, 2018)
Coarse fragments (%)	Field survey	Visual estimation and point count (Soil Science Division Staff, 2017)
Effective soil depth (cm)	Field survey	Measurement to lithic or restrictive layer (Soil Science Division Staff, 2017)
Peat		
Thickness (cm)	Field survey	Peat probing and stratigraphic description (Soil Science Division Staff, 2017)
Decomposition (maturity)	Field survey	Von Post scale classification (Zaccone et al., 2018)
Nutrient retention (nr)		
CEC (cmol(+) kg^{-1})	Soil samples	Ammonium acetate extraction (Blakemore et al., 1987; Carter and Gregorich, 2007)
Base saturation (%)	Soil samples	Exchangeable bases determination and percentage calculation (Blakemore et al., 1987)
Soil pH (H_2O)	Soil samples	pH meter in soil–water suspension (Blakemore et al., 1987)
Organic C (%)	Soil samples	Walkley–Black wet oxidation

Table 1. Continued

Land Use Requirement / Land Characteristic	Data source	Detailed analytical method
Available nutrients (na)		
Total N (%)	Soil samples	Kjeldahl digestion (Blakemore et al., 1987)
P_2O_5 (mg 100 g^{-1})	Soil samples	Bray I extraction and colorimetry (Bray and Kurtz, 1945; Blakemore et al., 1987)
K_2O (mg 100 g^{-1})	Soil samples	Ammonium acetate extraction and flame photometry (Blakemore et al., 1987)
Erosion hazard (eh)		
Slope (%)	DEMNAS Indonesia	DEM-derived slope computation (Geospatial Information Agency of Indonesia, 2018)
Erosion hazard	Field survey	Field evidence of sheet and rill erosion (Soil Science Division Staff, 2017)

2.4. Land Suitability Evaluation

Land suitability evaluation for maize in this study was carried out using a matching approach grounded in the principle of limiting factors, in which measured land characteristics were systematically compared with crop-specific requirements to assign land suitability classes ranging from highly suitable (S1) to not suitable (N). This approach ensures that the performance potential of maize is assessed conservatively by recognizing that the most restrictive limiting factor governs the overall suitability rating, a principle widely adopted in land evaluation research (FAO, 1976; Indonesian Center for Agricultural Land Resources Research and Development, 2016). Suitability thresholds for biophysical variables including climatic conditions (temperature and rainfall regime), soil physical and chemical properties (texture, depth, pH, nutrient status), rooting and oxygen availability (drainage class), and terrain attributes (slope and erosion hazard) were derived from established land evaluation frameworks and adapted to the specific ecological requirements of maize (Table 2), consistent with semi-detailed evaluation guidelines applied at comparable scales (FAO, 1976; Umeugokwe et al., 2025). The criteria and thresholds used in this study were informed by the FAO land evaluation principles, regional suitability studies for maize that emphasize integrated consideration of soil, climate, and topography (Tashayo et al., 2020; Karapetsas et al., 2024), and national-level technical guidance for agricultural land assessment adapted to tropical conditions (Indonesian Center for Agricultural Land Resources Research and Development, 2016). For each land characteristic listed in Table 2, the attribute value from field observation and laboratory analysis was compared with the defined suitability classes, and the maximum limitation principle was applied to determine the final suitability subclass, resulting in a management-oriented evaluation that highlights key biophysical constraints affecting maize cultivation potential across the delineated geopedological landforms.

Table 2. Land suitability criteria for maize based on land characteristics

Land Use Requirement / Land Characteristic	Land Suitability Classes			
	S1	**S2**	**S3**	**N**
Temperature (tc)				
Annual mean temperature (°C)	21–26	>26–29; 20–<21	>29–33; 18–<20	>33; <18
Water availability (wa)				
Annual Rainfall (mm $year^{-1}$)	1,200–1,500	1,000–<1,200; >1,500–1,900	800–<1,000; >1,900–2,300	<800; >2,300
Number of wet months (>200 mm $month^{-1}$)	3–5	<3; >5–7	>7–8	>8
Oxygen Availability (oa)				
Drainage	good, moderately good	moderately rapid, somewhat impeded	impeded	very impeded, rapid
Rooting conditions (rc)				
Soil texture	fine, moderately fine, medium	fine, moderately fine, medium	moderately coarse	coarse
Coarse fragments (%)	<15	15–35	35–55	>55
Effective soil depth (cm)	>60	40–60	25–40	<25

Table 2. Continued

Land Use Requirement / Land Characteristic	Land Suitability Classes			
	S1	S2	S3	S4
Peat				
Thickness (cm)	<50	50–100	100–150	>150
Decomposition (maturity)	sapric	sapric–hemic	hemic	fibric
Nutrient retention (nr)				
CEC (cmol(+) kg^{-1})	>16	5–16	<5	–
Base saturation (%)	>50	35–50	<35	–
Soil pH (H_2O)	5.5–7.0	5.0–5.5; 7.0–8.0	<5.0; >8.0	–
Organic C (%)	>1.2	0.8–1.2	<0.8	–
Available nutrients (na)				
Total N (%)	medium	low	very low	–
P_2O_5 (mg 100 g^{-1})	high	medium	low	–
K_2O (mg 100 g^{-1})	medium–high	low	very low	–
Erosion hazard (eh)				
Slope (%)	<8	8–15	15–25	>25
Erosion hazard	–	very low	low–medium	medium–very high

3. Results and Discussion

3.1. Land Characteristics of Geopedological Landform Units

The geopedological landform units in the Kelinjau River riparian landscape exhibit relatively uniform climatic conditions but distinct contrasts in soil physical, chemical, and hydrological characteristics that are critical for maize cultivation (Table 3). Both permanently waterlogged peaty floodplains and undulating sandy terraces experience comparable thermal and rainfall regimes, with annual mean temperatures of 27–28 °C, annual rainfall of 1,800–1,900 mm, and four wet months per year, indicating that climate is not a major differentiating factor between the landforms. In contrast, soil hydrological and physical properties vary markedly, particularly those related to oxygen availability and rooting conditions. The floodplains are characterized by somewhat impeded drainage, fine-textured soils, and very deep effective soil depth (147 cm). In contrast, the terraces exhibit more severely impeded drainage, medium-textured soils, and shallower effective depth (50 cm), reflecting differences in landscape position and pedogenetic development. Peat thickness is greater on floodplains (38 cm) than on terraces (9 cm), with both landforms showing hemic peat decomposition. Soil chemical properties are broadly similar across landforms, with moderate cation exchange capacity, low base saturation (35%), and acidic soil reaction, particularly on terraces (pH 4.5), conditions that constrain nutrient availability. Available nutrients constitute a major limitation on both landforms, as total nitrogen, phosphorus, and potassium are consistently low, despite relatively high organic carbon contents. Terrain-related constraints are minimal, with flat to gentle slopes (0–3%) and no evidence of erosion on either landform. These results indicate that maize suitability in the study area is primarily governed by landform-controlled soil properties rather than by climatic or topographic factors, underscoring the relevance of geopedological stratification in land suitability assessment.

Table 3. Land characteristics of geopedological landform units in the Kelinjau River riparian landscape

Land Characteristics	Landform Unit	
	Permanently Waterlogged Peaty Floodplains	Undulating Sandy Terraces
Temperature (tc)		
Annual mean temperature (°C)	27	28
Water availability (wa)		
Annual Rainfall (mm $year^{-1}$)	1,900	1,800
Number of wet months (>200 mm $month^{-1}$)	4	4
Oxygen Availability (oa)		
Drainage	somewhat impeded	impeded
Rooting conditions (rc)		
Soil texture	fine (clay–sandy clay)	medium (dusty loam)
Coarse fragments (%)	3	5

Table 3. Continued

Land Characteristics	Landform Unit	
	Permanently Waterlogged Peaty Floodplains	Undulating Sandy Terraces
Effective soil depth (cm)	147	50
Peat		
Thickness (cm)	38	9
Decomposition (maturity)	hemic	hemic
Nutrient retention (nr)		
CEC (cmol(+) kg^{-1})	10.5	11.1
Base saturation (%)	35	35
Soil pH (H_2O)	5.3	4.5
Organic C (%)	1.5	1.3
Available nutrients (na)		
Total N (%)	0.2 (low)	0.1 (very low)
P_2O_5 (mg 100 g^{-1})	15.1 (low)	15.3 (low)
K_2O (mg 100 g^{-1})	14.9 (low)	15.1 (low)
Erosion hazard (eh)		
Slope (%)	0–3	0–3
Erosion hazard	none	none

3.2. Land Suitability for Maize across Geopedological Landforms

Land suitability evaluation indicates that both geopedological landform units are classified as marginally suitable (S3) for maize cultivation, although the dominant limiting factors differ between landforms (Table 4). Under the matching approach and the maximum limitation principle, climatic parameters such as temperature, annual rainfall, and the number of wet months generally fall within the suitable-to-moderately suitable classes (S1–S2) for maize on both landforms, confirming that climate is not the primary constraint in the study area. Terrain-related factors, including slope and erosion hazard, are also rated as highly suitable (S1), reflecting the flat riparian setting and absence of observable erosion processes. Consequently, land suitability differentiation is primarily governed by soil-related constraints rather than by climatic or topographic limitations.

On the permanently waterlogged peaty floodplains, the final suitability class of S3 is mainly controlled by nutrient availability (na), particularly low phosphorus status, which is consistently rated as S3 despite otherwise favorable rooting depth and soil texture conditions. Moderate limitations related to drainage and soil chemical properties (CEC, base saturation, and pH) further constrain nutrient dynamics but do not independently determine the final suitability class. In contrast, the undulating sandy terraces are classified as S3 due to a combination of oxygen availability (oa) and nutrient availability (na) constraints. More severely impeded drainage on the terraces reduces soil aeration, while a shallow effective soil depth and very low nitrogen availability exacerbate root-zone stress and limit maize growth potential. These results demonstrate that although both landforms share the same overall suitability class, the mechanisms underlying land limitation differ markedly, highlighting the importance of landform-based evaluation for diagnosing maize suitability constraints in tropical riparian landscapes.

Table 4. Land suitability classes for maize across geopedological landform units

Land Characteristics	Landform Unit	
	Permanently Waterlogged Peaty Floodplains	Undulating Sandy Terraces
Temperature (tc)		
Annual mean temperature (°C)	S2	S2
Water availability (wa)		
Annual Rainfall (mm $year^{-1}$)	S2	S2
Number of wet months (>200 mm $month^{-1}$)	S1	S1
Oxygen Availability (oa)		
Drainage	S2	S3
Rooting conditions (rc)		
Soil texture	S1	S1
Coarse fragments (%)	S1	S1
Effective soil depth (cm)	S1	S2

Table 4. Continued

Land Characteristics	Landform Unit	
	Permanently Waterlogged Peaty Floodplains	Undulating Sandy Terraces
Peat		
Thickness (cm)	S1	S1
Decomposition (maturity)	S2	S2
Nutrient retention (nr)		
CEC (cmol(+) kg^{-1})	S2	S2
Base saturation (%)	S2	S2
Soil pH (H_2O)	S2	S2
Organic C (%)	S1	S1
Available nutrients (na)		
Total N (%)	S2	S3
P_2O_5 (mg 100 g^{-1})	S3	S3
K_2O (mg 100 g^{-1})	S2	S2
Erosion hazard (eh)		
Slope (%)	S1	S1
Erosion hazard	S1	S1
Suitability Class	**S3**	**S3**
Suitability Sub-Class	**S3 na**	**S3 oa,na**

3.3. Geopedological Controls on Soil Properties Relevant to Maize

The marked contrasts in soil properties between the permanently waterlogged peaty floodplains and the undulating sandy terraces reflect the fundamental influence of geopedological processes on land suitability for maize cultivation. In riparian environments, geomorphic position, sedimentary history, and hydrological regimes interact to shape soil texture, depth, drainage, and nutrient dynamics, which are critical determinants of maize performance. The fine-textured, deep soils with higher organic matter on the floodplains arise from sediment deposition and prolonged waterlogging, which enhance soil moisture retention but reduce oxygen availability and alter nutrient cycling, conditions that can suppress nutrient mineralization and root penetration in crops such as maize that require well-aerated root zones. Conversely, terrace soils, though formed under relatively better drainage, remain impeded and shallower with coarser texture, which are generally associated with lower water and nutrient retention capacity and reduced effective rooting volume (Brady and Weil, 2016; Karapetsas et al., 2024), hereby limiting the soil's ability to support maize growth (Table 3).

These landscape-driven soil characteristics are consistent with findings from maize land suitability studies showing that soil physical and chemical constraints are often the dominant factors limiting maize growth in heterogeneous environments (Awoonor et al., 2023; Karapetsas et al., 2024). Research in smallholder maize systems has demonstrated that combinations of soil texture, depth, and fertility status explain much of the spatial variability in suitability classes, often outweighing climatic controls in regions with adequate rainfall and temperature regimes. The contrasting pedogenetic pathways observed in this study's landform units thus provide a mechanistic basis for understanding why similar overall suitability classifications (e.g., S3) can arise from different limiting processes, highlighting the value of geopedological stratification in revealing how landscape evolution influences the fundamental soil constraints experienced by maize in tropical riparian landscapes.

3.4. Dominant and Landform-Specific Soil Constraints

The land suitability classification results indicate that both geopedological landform units are marginally suitable (S3) for maize, but the underlying limiting factors differ between landform units, underscoring the need to distinguish dominant constraints rather than treating all marginal classes as homogeneous. On the permanently waterlogged peaty floodplains, nutrient availability emerges as the principal constraint, particularly low phosphorus levels, which aligns with findings from other maize land suitability studies where soil fertility limitations, such as low available nitrogen and phosphorus are frequently identified as major factors limiting maize production potential (Nurdin et al., 2023; Nusi et al., 2024). Although the floodplain soils have deep effective depths and fine textures that could otherwise support robust root systems, the low status of essential macronutrients and moderate base saturation restrict root uptake and crop growth, consistent with evidence that nutrient limitations often override favorable physical soil attributes in maize suitability assessments (e.g., nutrient and chemical constraints in smallholder maize systems).

In contrast, the undulating sandy terraces exhibit a combination of oxygen availability (drainage) and nutrient constraints, in which impeded drainage and a shallower effective depth contribute to suboptimal aeration and

limited rooting volume for maize. The dual limitation by oxygen availability and nutrient status reflects conditions documented in other upland maize suitability studies, in which drainage characteristics and soil chemical parameters, such as pH and base saturation, interact to shape limiting factors for crop growth (Kenzong et al., 2022). While climatic and topographic conditions remain generally non-limiting in both units, these soil-specific constraints illustrate how similar suitability classes (S3) can arise through distinct mechanistic pathways driven by landscape position and soil development. Recognizing these landform-specific limitation mechanisms is essential for targeted soil and nutrient management strategies, such as ameliorating drainage in terrace positions and enhancing nutrient inputs on floodplain soils, thereby improving the functional suitability of each landform unit for maize cultivation.

3.5. Implications for Maize Land Management and Sustainable Cultivation

The identification of distinct limiting factors across geopedological landform units has clear implications for site-specific management strategies to enhance maize production potential. On permanently waterlogged peaty floodplains where nutrient deficiencies are the primary constraints, targeted soil fertility improvement is essential. Studies on maize suitability have shown that addressing soil fertility through judicious application of balanced fertilizers, organic amendments, and micronutrient supplementation can improve nutrient availability and crop performance, especially in soils with moderate to low base saturation and acidic pH conditions similar to those observed here (Awoonor et al., 2023; Gani and Usman, 2024). Integrating organic matter inputs and practices that increase cation exchange capacity can also contribute to longer-term soil fertility resilience, thereby reducing the severity of nutrient constraints that lead to marginal suitability classifications.

For undulating sandy terraces, where oxygen availability and shallow effective depth accentuate root zone limitations in addition to nutrient scarcity, management interventions should aim to improve both soil aeration and nutrient availability. Techniques such as controlled drainage, shallow tillage to improve soil structure, and incorporation of organic residues can enhance soil porosity and rooting conditions. In contrast, nutrient management through balanced fertilization and organic amendments is essential to address low nitrogen and phosphorus availability. These approaches have been recommended in maize land suitability research to mitigate impeded drainage, texture constraints, and soil fertility limitations (Tashayo et al., 2020; Moisa et al., 2022). Moreover, matching maize genotypes with tolerance to periodic waterlogging or moderate soil acidity may improve adaptation on terrace units that experience combined physical and chemical limitations. These tailored strategies, grounded in the geopedological diagnosis of limiting factors, allow for site-specific agronomic interventions rather than one-size-fits-all prescriptions, thereby supporting sustainable maize cultivation in heterogeneous tropical riparian landscapes and aligning with broader goals of optimized land use planning and resource efficiency (Moisa et al., 2022; Umeugokwe et al., 2025).

4. Conclusion

This study demonstrates that integrating a geopedological framework with land suitability evaluation provides a robust, process-based approach for diagnosing soil constraints affecting maize cultivation in tropical riparian landscapes. Although climatic and topographic conditions in the Kelinjau River riparian zone are generally favorable for maize, both permanently waterlogged peaty floodplains and undulating sandy terraces were classified as marginally suitable (S3) due to soil-related limitations. The results reveal that similar suitability classes can arise from distinct landform-specific mechanisms: nutrient availability, particularly phosphorus deficiency, constitutes the dominant constraint on floodplain soils, whereas a combination of oxygen availability constraints, shallow effective soil depth, and nutrient limitations governs maize suitability on sandy terraces. These findings highlight that landform position and associated soil properties, particularly those related to drainage, rooting conditions, and nutrient availability, play a key role in controlling maize suitability, underscoring the value of geopedological stratification beyond conventional, overlay-based land evaluation approaches. The principal strength of this research lies in its ability to move beyond suitability classification toward diagnosing the underlying soil–landscape processes that limit maize performance, thereby enhancing the interpretability and practical relevance of land suitability results. However, the analysis is constrained by its reliance on landform-level soil representation, which may not fully capture fine-scale variability within each unit, and by the absence of yield or crop response data to validate suitability classes directly. Despite these limitations, the integrated geopedological–land evaluation framework offers clear potential applications for site-specific land use planning and sustainable maize management in heterogeneous riparian environments. By identifying landform-specific constraints, the approach supports targeted interventions, such as fertility enhancement on floodplains and drainage and rooting-condition improvement on terraces, to enhance the functional suitability of land for maize cultivation. More broadly, this framework can be applied to other crops and tropical landscapes where soil variability is strongly governed by geomorphological processes, contributing to more informed and sustainable agricultural development strategies.

Acknowledgements

The authors gratefully acknowledge the local community groups and residents of Kelinjau Ilir Village for their valuable support, cooperation, and assistance during field data collection and site access. Their local knowledge and willingness to facilitate research activities were essential to the successful completion of this study.

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