



Geospatial-Based Decision Framework For Mitigating Potential Soil Degradation Risks in Sustainable Agriculture Halong, South Kalimantan

Muhammad Rizky Romadhon^{1*}, Suman Georges², Abdul Hadi¹, Muchammad Bima Gegana Sakti³, Adhia Azhar Fauzan⁴, Meldia Septiana¹, Ratna¹, Aditya Dyah Utami¹, Zikra Auliyya¹, Ismi Nuari Puspitaningrum¹

¹ Department of Soil Science, Faculty of Agriculture, Lambung Mangkurat University, Banjarbaru, South Kalimantan, Indonesia

² School of Earth and Environment, The University of Western Australia, Western Australia, Australia

³ Faculty of Meteorology, Environment and Arid Land Agriculture, King Abdulaziz University, Jeddah, Saudi Arabia

⁴ The United Graduate School of Agricultural Science, Gifu University, Gifu, Japan

*Corresponding author: rizkyrom@ulm.ac.id

Received: September 12, 2025; Revised: Februari 23, 2026; Accepted: March 2, 2026

ABSTRACT

Soil degradation is a major constraint to agricultural sustainability, particularly in areas characterised by diverse environmental conditions. Halong District, Balangan Regency, South Kalimantan Province, is characterised by heterogeneous land uses, soil types, slope variations, and variable rainfall patterns, which influence soil quality and degradation risks. This research aims to assess the potential for soil degradation concerning environmental diversity and its implications for sustainable integrated agriculture. The study highlights that differences in land use, from shifting cultivation to permanent farming, combined with acidic soils, steep slopes, and uneven rainfall distribution, increase vulnerability to erosion, nutrient depletion, and declining soil fertility. The results show that the Potential Soil Degradation Risk (PSDR) in the low-risk class (PSDR.II) covers 298.22 km² (45.20%), followed by the intermediate-risk (PSDR.III) covering 335.15 km² (50.79%), and the high-risk (PSDR.IV) covering 26.48 km² (4.01%). Land use and slope are determining factors for PSDR, as indicated by ANOVA, DMRT, and correlation test results. Understanding these linkages is essential for designing site-specific land management practices that reduce degradation risks while improving agricultural productivity. The outcomes of this research are expected to provide scientific recommendations for stakeholders in developing sustainable agricultural management strategies, such as soil conservation, organic matter management, and integrated crop-livestock systems, to mitigate degradation risks and support long-term agricultural resilience in Halong District.

Keywords: agricultural land management; environmental diversity; hazardous land assessment; soil degradation; soil security

Cite this as: Romadhon, M. R., Georges, S., Hadi, A., Sakti, M. B. G., Fauzan, A. A., Septiana, M., Ratna., Utami, A. D., Auliyya, Z., Puspitaningrum, I. N. (2026). Geospatial-Based Decision Framework For Mitigating Potential Soil Degradation Risks in Sustainable Agriculture Halong, South Kalimantan. *Agrosains: Jurnal Penelitian Agronomi*, 28(1), 1-12. DOI: <http://dx.doi.org/10.20961/agsjpa.v28i1.108954>

INTRODUCTION

Soil resources are fundamental to agricultural sustainability because they provide the basis for crop production, water regulation, and nutrient cycling (Telo da Gama, 2023). However, soils are also highly vulnerable to degradation when subjected to inappropriate land management and increasing environmental pressures (AbdelRahman, 2023). Soil degradation, defined as the decline in soil's physical, chemical, and biological functions, can manifest in several forms, including erosion, nutrient depletion, compaction, salinisation, and loss of organic matter (Polanía-Hincapié et al., 2021). These processes threaten agricultural productivity, ecological stability, and rural livelihoods if left unmanaged. The challenge becomes more pronounced in areas with high environmental diversity, where variations in land use, soil types, slope gradients, and rainfall patterns interact to create spatially heterogeneous degradation risks (He et al., 2023).

Halong District, located in Balangan Regency, South Kalimantan Province, is a region where environmental heterogeneity significantly shapes agricultural opportunities and challenges (Nasrullah et al., 2024). The district is characterised by a mix of upland and lowland areas, with diverse land uses ranging from shifting cultivation, mixed gardens, and dryland cropping to plantation systems. Such varied land-use practices exert uneven soil resource pressures (Samsudin et al., 2021). For instance, continuous cropping without adequate nutrient replenishment can lead to a decline in fertility. At the same time, expanding the cultivation of plantation crops on fragile soils may increase the risk of erosion and soil compaction. These dynamics indicate that land-use intensity and management practices are key drivers of degradation risks in Halong (Liu et al., 2025).

Soil types in Halong District also present intrinsic vulnerabilities. The dominant soils, such as Ultisols and

Inceptisols, generally exhibit low base saturation, high acidity, and limited nutrient reserves (Giao et al., 2023). Without proper soil amendments, these soils are susceptible to accelerated fertility decline under cultivation (Ichsan et al., 2023). In acidic soils, the availability of toxic elements, such as aluminium and iron, may also limit crop growth. In contrast, deficiencies in essential nutrients such as phosphorus and potassium further exacerbate productivity constraints (Gemada, 2021). When managed unsustainably, these inherent limitations contribute to the long-term decline of soil quality and resilience.

Slope variation further complicates soil management in Halong District. Steep slopes, common in upland areas, are highly prone to water erosion, particularly when vegetation cover is removed for cultivation (Nyairo, 2024). Erosion on such slopes reduces topsoil depth, organic matter content, and water-holding capacity, leading to the progressive decline of land productivity. Conversely, lower-lying areas may face risks of poor drainage, compaction, and nutrient leaching during periods of excessive rainfall (Dhanapriya et al., 2025). These contrasting risks highlight the importance of slope as a critical factor in determining soil degradation potential.

Rainfall distribution is another important determinant of soil degradation risks in Halong. The district experiences high and uneven rainfall, with intense precipitation events capable of triggering severe soil erosion, nutrient leaching, and surface runoff (Simelane et al., 2024). Periods of water surplus can also contribute to gully formation and flooding in poorly managed landscapes. Meanwhile, soil surface crusting and reduced biological activity may reduce infiltration and crop resilience during dry spells (Saco et al., 2021). The interaction between rainfall variability, sensitive soils, and steep slopes intensifies the risk of soil degradation if land management practices are not adapted to local conditions (Kumar et al., 2023).

Given these interacting factors, the potential for soil degradation in Halong District poses a significant threat to agricultural sustainability. If left unaddressed, degradation processes may compromise food security, reduce farmer income, and undermine ecosystem functions (Dewi et al., 2022). This study aims to systematically evaluate the potential risk of soil degradation in Halong District, Balangan Regency, by examining how variations in land use, soil type, slope gradient, and rainfall patterns influence soil quality and vulnerability. Specifically, the research seeks to map the spatial distribution of degradation indicators across different land-use systems, assess the inherent susceptibility of dominant soils, such as Ultisols and Inceptisols, to degradation, and analyse the roles of topography and rainfall variability in accelerating degradation. Furthermore, the study intends to identify the most influential environmental and management factors driving degradation and to develop site-specific recommendations for sustainable integrated agriculture. It is hypothesised that the combined effects of land use, soil characteristics, slope, and rainfall variability significantly influence soil degradation risk in Halong District. Areas subjected to more intensive land use, steeper slopes, and higher rainfall variability are

expected to exhibit greater degradation indicators. At the same time, the interaction among these factors is presumed to exert a more decisive influence than any single factor operating independently.

Therefore, it is crucial to systematically assess degradation risks, considering the role of environmental diversity in shaping soil vulnerability. This research aims to provide scientific evidence on the links between land use, soil type, slope, rainfall, and their contribution to soil degradation risks in Halong. The ultimate goal is to recommend best management practices to reduce degradation, enhance soil resilience, and support sustainable integrated agriculture. Such recommendations will serve as a valuable reference for policymakers, local communities, and stakeholders in Balangan Regency in ensuring that agricultural development is environmentally sound and economically viable.

MATERIALS AND METHODS

Research Time and Place

This research was initiated in June 2025 and is scheduled for completion by September 2025. The field observations focus on Halong District, Balangan Regency, South Kalimantan Province, Indonesia, a region representing diverse agroecological and geological characteristics. Geographically, Halong District is approximately 194 kilometres from Banjarbaru, the provincial capital, and 25 kilometres from Paringin, the capital of Balangan Regency. The district spans 659.84 km², making it one of the largest administrative regions within the regency. Aniungan Village represents the largest administrative unit within this area, accounting for 10.46% of the district's land area. Sumber Agung Village is the smallest, covering only 4.57 km², or 0.69% of the total area.

Topographically, Halong District is approximately 284 meters above sea level, with its highest point located along the border of Puyun Village and Karya Village. The district's landscape is strongly influenced by its underlying geology, which comprises formations such as the Birang and Dahor Formations, both of which contribute to the region's diverse soil types and mineral compositions. A distinctive geomorphological feature of Halong is its karst landscape, exemplified by Balawaian Hill and Sidabong Cave, which play a role in soil formation processes and possess high value for biodiversity conservation and ecotourism development.

In terms of agricultural production, Halong District has been actively cultivating various horticultural crops, with vegetables playing a key role in the local farming system. Data from 2023 reveal that cayenne pepper dominated the vegetable cropping area, with a harvested area of 21 hectares yielding approximately 1,063 quintals. This was followed by tomatoes, which covered 17 hectares and produced 932 quintals. These figures highlight the importance of vegetable farming to the local economy and underscore the need to maintain soil health to sustain and enhance productivity (Indonesian Central Bureau of Statistics, 2023).

Given this environmental and agricultural context, Halong District provides an ideal case study for assessing the potential risks of soil degradation under varying land uses, soil types, slopes, and rainfall

patterns. The combination of diverse geological formations, varied slope, and intensive agricultural practices presents opportunities and challenges for sustainable land management. Understanding these conditions is crucial for recommending appropriate agricultural strategies to mitigate degradation, conserve soil resources, and support long-term regional agricultural sustainability.

Research Materials and Tools

This study employed a series of thematic maps (Figure 1)—including land use patterns, slope gradients, soil classifications, and rainfall distribution—as the primary sources of spatial information. A quantitative analytical framework was applied, using a matching and

scoring technique, to evaluate and categorise the potential for land degradation across the study area. This scoring system integrated the cumulative values obtained from the overlay of different thematic layers to generate a comprehensive assessment. Following the matching process, the observed degradation field data were normalised to ensure comparability across variables. Among the various influencing factors, the intrinsic properties of the soil were identified as the most critical elements directly associated with degradation potential. This relationship is reflected in the soil degradation determinant coefficient, a measure derived from a correlation analysis that indicates the degree of association between soil attributes and PSDR.

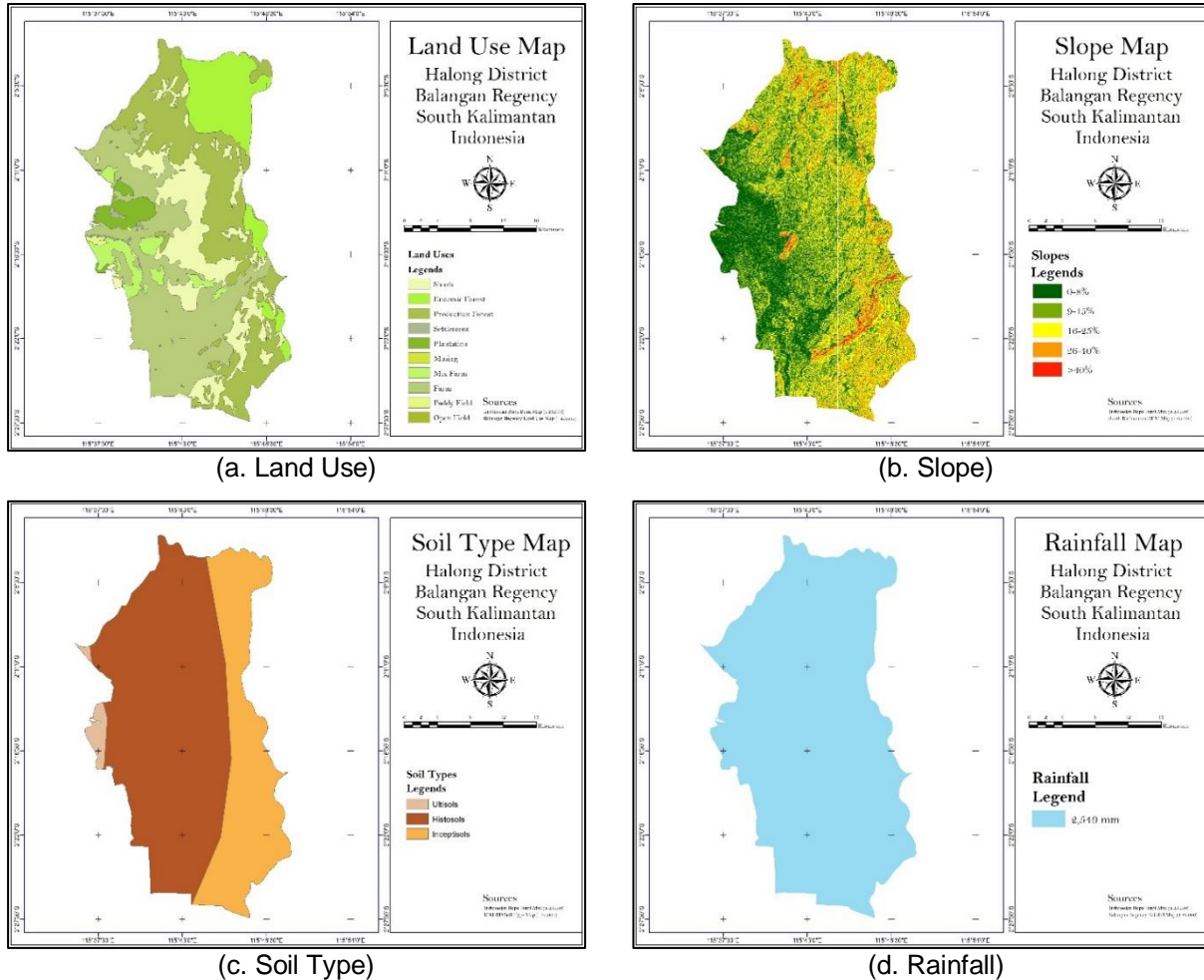


Figure 1. Thematic map of environmental diversity sources

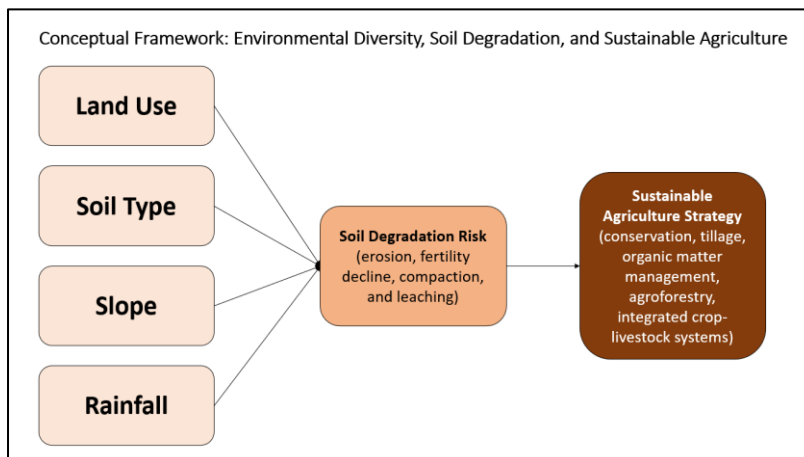


Figure 2. PSDR conceptual framework

Potential Soil Degradation Risk (PSDR) and Data Analysis

Preparation of the Potential Soil Degradation Risk (PSDR) map for Halong District was guided by the provisions of Indonesian Government Regulation No. 150 of 2000, along with relevant guidelines from the Indonesian Minister of Environment Regulation No. 17 of 2009 and Regulation No. 7 of 2006 (Tables 1 and 2). The working map produced in this study depicts the spatial distribution of PSDR status across different land-use categories within Halong District, Balangan Regency. This map was developed by integrating multiple thematic layers, including land use distribution, slope gradients, rainfall variability, and soil type characteristics (Figure 2). The following formula was used to calculate the PSDR.

$$PSDR = \sum_{i=1}^n (Wi \times Xi)$$

- PSDR = Potential Soil Degradation Risk
- Wi = weight for-i parameters
- Xi = score for ...-i parameters
- n = amount of data

The analysis used the Land Mapping Unit (LMU) approach, which overlapped four environmental diversity source maps (Figure 3). Overlaying is a key step in generating a PSDR status map and represents a fundamental procedure in GIS analysis. It refers to superimposing multiple map layers and displaying the integrated results on a screen or printout (Herdiansyah et al., 2024). This technique combines digital maps and their attributes to produce a new map containing

information from each input layer. In other words, overlaying merges data from several layers into a single layer, functioning as a visual operation that requires integrating more than one spatial layer (Romadhon et al., 2023).

The overlay process produced 21 LMUs. From each LMU with similar environmental diversity characteristics, 6 sample points from each LMU were selected, resulting in 126 observation samples. Replicating the sampling was intended to improve the validity and reliability of the findings, provide more accurate and representative data, reduce potential errors, and enable replication of the study for scientific verification. Repetition also enables researchers to assess result consistency, control variability, and strengthen confidence that the outcomes are not due to random factors or unacceptable errors (β errors).

Data on environmental diversity (including land use, slope, soil type, and rainfall) were compiled to assess PSDR status and analysed using Analysis of Variance (ANOVA). This analysis aimed to determine whether these environmental factors had a significant effect on PSDR. When ANOVA indicated a significant difference (p < 0.05), further testing was carried out using Duncan’s Multiple Range Test (DMRT). This post hoc test helped pinpoint which categories of environmental diversity accounted for variations in mean PSDR values, thereby clarifying the extent and direction of their influence. A Pearson correlation analysis was also conducted to examine the reciprocal relationship between sources of environmental diversity and PSDR.

Table 1. The weighting and score index for PSDR*

Environmental diversity sources	Class	Wi	Si	Wi x Si
Land Use				
Endemic forest and paddy field	Very Low	2	1	2
Savana, shrubs, and mixed farm	Low	2	2	4
Farm, plantation, and production forest	Moderate	2	3	6
Dryland	High	2	4	8
Open field, settlement, and mining	Very high	2	5	10
Slope (%)				
0-8	Very low	3	1	3
9-15	Low	3	2	6
16-25	Moderate	3	3	9
26-40	High	3	4	12
>40	Very high	3	5	15
Soil Type				
Vertisols	Very Low	2	1	2
Oxisols	Low	2	2	4
Alfisols, Mollisols, and Ultisols	Moderate	2	3	6
Entisols, Histosols, and Inceptisols	High	2	4	8
Andisols and Spodosol	Very high	2	5	10
Rainfall				
<1,000	Very low	3	1	3
1,000-2,000	Low	3	2	6
2,001-3,000	Moderate	3	3	9
3,001-4000	High	3	4	12
>4,000	Very high	3	5	15

Note: Wi = Weighting index; Si = Score index. * = Government Regulation No. 150, 2000; Minister of Environment Regulation No. 17, 2009; Minister of Environment Regulation No. 7, 2006.

Table 2. PSDR status

Status	Total weighting index	Symbol
Very low	< 15	PSDR.I
Low	15-24	PSDR.II
Intermediate	25-34	PSDR.III
High	35-44	PSDR.IV
Very high	> 45	PSDR.V

Note: Wi = Weighting index; Si = Score index

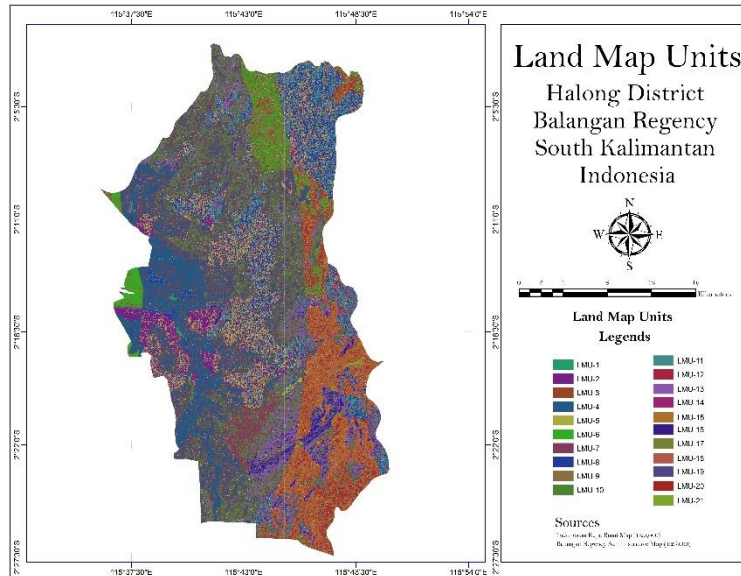


Figure 3. Halong LMU to assess PSDR

RESULT AND DISCUSSION

The PSDR Analysis

The spatial analysis of PSDR in Halong District, Balangan Regency, South Kalimantan, revealed three main classes of degradation vulnerability (Table 3). The most significant proportion of the study area falls into the intermediate-risk category (PSDR.III), covering 335.15 km², or 50.79% of the district. This is followed by the low-risk category (PSDR.II), occupying 298.22 km² or 45.20%, while the high-risk category (PSDR.IV) represents the smallest share, covering only 26.48 km² or 4.01% of the total area. These results indicate that while most of the district experiences moderate soil degradation risks, a relatively small portion is already in critical condition and requires immediate intervention (Figure 4).

The predominance of intermediate soil degradation risk suggests that agricultural land in Halong District is under pressure from environmental diversity and land

management practices, but has not yet reached severe levels of degradation across most areas. The moderate risk zones are generally associated with cultivated lands on gently sloping areas. Continuous cropping, limited organic input use, and rainfall variability contribute to gradual soil fertility decline and erosion. Without corrective measures, these areas may shift toward higher degradation classes.

The low-risk zones comprise nearly half of the district and are typically found in areas with favourable soil conditions, stable slopes, or sustainable land-use practices. These areas are essential as agricultural production bases and should be prioritised for implementing preventive conservation measures to maintain their current status and prevent degradation (Molossi et al., 2023). In contrast, the high-risk areas, though relatively small in extent (4.01%), represent critical hotspots where steep slopes, fragile soils (Ultisols and Inceptisols), and high rainfall intensity intersect.

Table 3. Analysis of PSDR Levels on Various Sources of Environmental Diversity in Halong District, Balangan Regency

PSDR	Score and Symbol	Area	
		ha	%
Low	17-24 (PSDR.II)	298.22	45.20
Intermediate	25-34 (PSDR.III)	335.15	50.79
High	35-38 (PSDR.IV)	26.48	4.01
Total		659.84	100.00

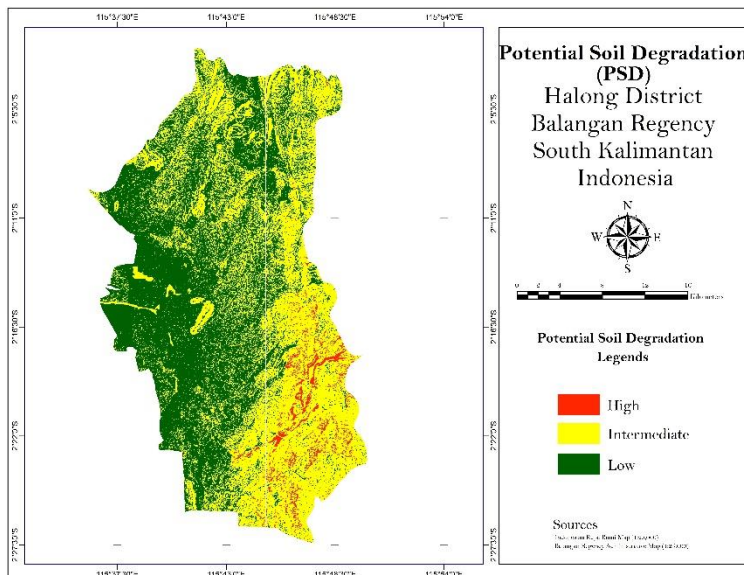


Figure 4. PSDR Levels

These conditions make such areas highly vulnerable to severe erosion, nutrient leaching, and loss of soil productivity. If not addressed promptly, these high-risk zones could experience irreversible land degradation (del Barrio et al., 2021), reducing agricultural viability and threatening local livelihoods (Solomon et al., 2024).

The spatial distribution of PSDR classes underscores the importance of site-specific land management strategies (Samiei-Fard et al., 2024). For low-risk zones, conservation farming practices such as mulching, crop rotation, and cover cropping are recommended to sustain soil quality (Wilczewski et al., 2024). In intermediate-risk zones, more intensive interventions such as contour farming, agroforestry, and organic amendments are necessary to slow degradation (Tiwari et al., 2024). Meanwhile, high-risk zones require strict soil conservation measures, such as terracing, reforestation, or conversion to less intensive land uses, to stabilise slopes and reduce erosion hazards (Maximus et al., 2025). These findings align with the research objectives, confirming that soil degradation potential in Halong District is directly influenced by environmental diversity and land management. The PSDR map produced by this study can serve as a decision-support tool for stakeholders to guide agricultural planning, land-use regulation, and targeted soil conservation programs. Moreover, these results highlight the urgent need for integrated and adaptive management approaches that balance agricultural productivity with long-term soil sustainability.

The Influence of Environmental Diversity Sources on PSDR Values

Table 4. The ANOVA results of environmental diversity sources for PSDR

Environmental diversity sources	p-value (sig.)
LU	0.00**
SL	0.00**
ST	0.502 ^{ns}
RF	0.981 ^{ns}

Note: ** very significant; ^{ns} non significant; LU = Land Use; SL = Slope; ST = Soil Type; RF = Rainfall

The statistical analysis revealed that among the sources of environmental diversity considered in this study, land use and slope were the only factors that significantly influenced the PSDR in Halong District. The ANOVA results confirmed a strong effect of land use on PSDR values ($p = 0.00$), indicating a highly significant relationship (Table 4). This finding emphasises that variations in land use across the district are decisive in determining soil degradation risks (Diop et al., 2022). The results are logical, as land management practices directly control soil cover, organic matter input, and disturbance levels, key drivers of soil erosion and fertility decline (Musa et al., 2024). Similarly, slope was shown to be a significant factor, reflecting its role in governing runoff intensity, erosion processes, and soil stability (Chen et al., 2022).

The follow-up DMRT analysis provided more detailed insights, highlighting that open fields, settlements, and mining areas significantly impacted PSDR and were statistically distinct from other land uses (Figure 5). These land uses are characterised by minimal vegetation cover, extensive soil disturbance, and limited conservation practices. Open fields, often left bare or used seasonally, expose soils to rainfall and runoff, accelerating erosion (Ke and Zhang, 2021). Settlements contribute to soil degradation through land compaction, reduced infiltration, and localised pollution. Mining activities, on the other hand, cause severe disruption of soil profiles, strip topsoil layers, and leave the land highly vulnerable to erosion and chemical degradation (Punia and Bharti, 2023). These results confirm that anthropogenic activities involving intensive land clearing and soil disturbance are Halong's most critical drivers of degradation.

Interestingly, the results also indicated that farmlands and plantations ranked second in their influence on PSDR, highlighting land uses that deserve closer attention. Unlike open fields and mining, which are visibly associated with degradation, agricultural and plantation areas are expected to sustain productivity but can also become significant contributors to soil degradation under unsustainable management (Tefera et al., 2024). In Halong District, farmlands are often

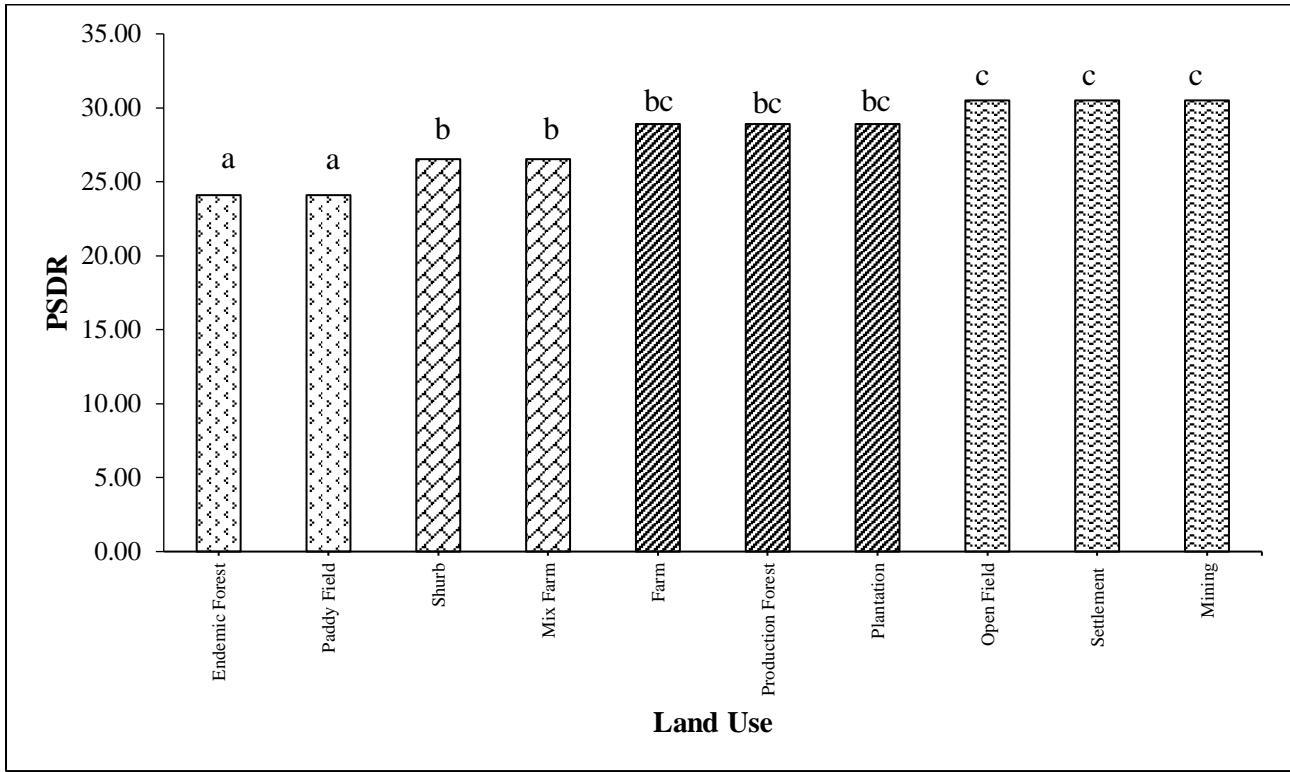


Figure 5. The DMRT of Halong land use to PSDR

Note: Different alphabet notation shows the significance of each land use

cultivated intensively, with limited crop rotation and insufficient organic inputs, leading to nutrient mining and a decline in soil structure over time (Zhang et al., 2021). Plantations, particularly those dominated by perennial crops, tend to cover large areas where tillage practices, chemical fertiliser inputs, and herbicide applications are consistently applied. If not balanced with conservation measures, these practices can exacerbate soil acidity, reduce organic matter, and weaken soil resilience (Francaviglia et al., 2023).

The mechanisms underlying plantations' influence on soil degradation are especially noteworthy. Continuous tillage in plantation systems disturbs soil aggregates, making them more susceptible to erosion, while repeated use of inorganic fertilisers—particularly nitrogen-based—enhances soil acidification and nutrient leaching (Hamidi et al., 2021). Over time, this reduces cation exchange capacity and soil fertility, increasing dependence on external inputs. Additionally, the widespread application of herbicides limits undergrowth, reducing surface cover and accelerating runoff and erosion on sloping land (Tedesse et al., 2025). These combined processes explain why plantations, despite being perceived as stable perennial systems, still contribute significantly to PSDR values. Thus, improving soil management in plantations through reduced tillage, balanced fertiliser strategies, and integrated groundcover management is essential to mitigate the risk of degradation in Halong District.

ANOVA showed a highly significant slope effect on PSDR ($p = 0.00^{**}$), confirming that slope is a primary control on soil degradation in Halong (Table 4). The DMRT test further indicates that the >40% slope class exerts the most decisive influence on PSDR and differs significantly from all gentler classes (Figure 6). Mechanistically, steep gradients amplify runoff velocity, shear stress, and detachment capacity of overland flow, which accelerates rill-gully formation, topsoil loss, and

nutrient-organic matter export (Mohamed et al., 2023). On such slopes, infiltration windows are short, rainsplash is more energetic, and shallow, stony, or acidic soils (typical in the region) are quickly stripped of fine particles and exchange sites—compounding declines in water-holding capacity and fertility (Ma et al., 2022).

Well-designed terraces interrupt slope length and convert a long energy slope into short, nearly level steps (Ertop et al., 2023). This reduces the unit stream power of runoff, increases infiltration residence time, and traps sediment and organic residues upslope. Terraces also create micro-level planting beds that support root development, retain residues, and allow precise nutrient placement, thereby reducing the risk of fertiliser loss from wash-off or leaching (Kohsaka et al., 2021). On slopes >40%, terraces must be paired with safe drainage outlets. Without them, perched water can cause saturation, riser slumps, or terrace breach during high-intensity storms (Aguilera et al., 2021).

This study suggested field-ready guidance for nature-based terrace construction and tillage on >40% slopes. Layout on an accurate contour, using an a-frame line level; keep continuous grade (0–0.2%) toward protected outlets to avoid ponding that could destabilise risers. Build narrow bench or sloping-bench terraces rather than wide cuts to minimise earth movement (Singh, 2023). Where soil is shallow, use half-moon basins or micro-terraces around individual trees. Stabilise risers and edges biologically, plant dense, deep-rooted hedges (vetiver, napier, gliricidia) on the riser crest and toe, use brushwood, bamboo, logs, or stone lines as temporary facing. At the same time, vegetation establishes (Homann-Kee Tui et al., 2023). Provide safe water disposal: stone-lined/vegetated grassed waterways, drop structures, or small spillways at intervals; place check dams in terrace drains to slow flows.

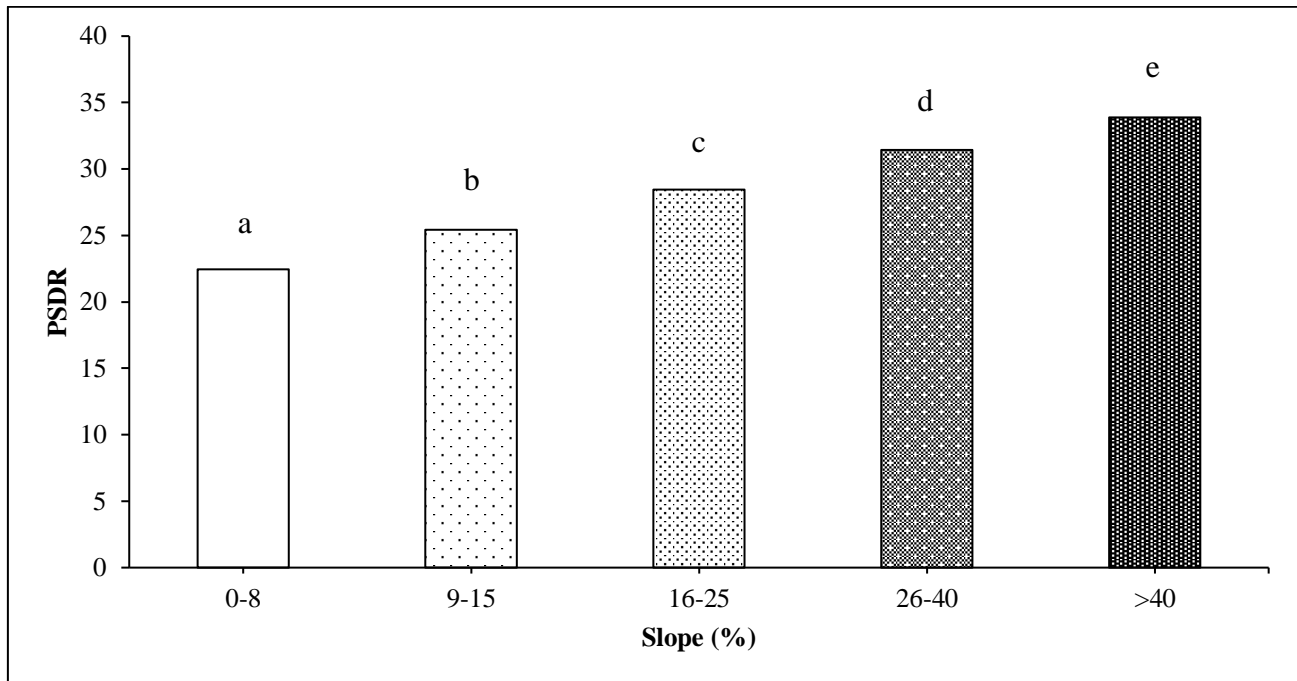


Figure 6. The DMRT of the Halong slope to PSDR

Note: Different alphabet notation shows the significance of each land use

Conservation tillage on the terrace bed: minimum soil disturbance, permanent cover (cover crops/mulch $\geq 30\%$ cover), contour strip cropping, and no up-down-slope passes. Keep traffic off risers to prevent compaction and failure (Ahuchaogu et al., 2022).

The Pearson correlation analysis (Table 5) confirmed the ANOVA and DMRT findings by showing that land use and slope are significantly positively correlated with PSDR, with coefficients of 0.405** and 0.811**, respectively. These values indicate that as land-use intensity or slope steepness increases, the risk of soil degradation also increases. The correlation for slope was particularly strong, suggesting that slope is the dominant physical factor influencing degradation risk in Halong District. In contrast, the moderate but significant correlation of land use with PSDR reflects the role of anthropogenic activities in accelerating soil degradation

through vegetation removal, land cover alteration, and intensive management practices. When these statistical findings are considered together, it becomes clear that land use and slope act synergistically in shaping soil degradation processes. For instance, steep slopes with inappropriate land uses—such as open fields, settlements, and mining—amplify the risk of degradation far more than either factor alone (Gobinath et al., 2022). Removing protective vegetation cover on steep gradients accelerates runoff velocity and soil detachment, while the absence of conservation measures exacerbates erosion and nutrient loss (Du et al., 2022). The DMRT results reinforce this interpretation by showing that land uses with the least vegetation cover and the highest disturbance (mining, settlements, open fields), and slope classes above 40%, are the most critical contributors to PSDR.

Table 5. Pearson correlation analysis

	LU	SL	ST	RF	PSDR
LU	1 126				
SL	-0.074 0.409 126	1 126			
ST	-0.229 0.01 126	-0.021 0.811 126	1 126		
RF	0.007 0.674 126	0.051 0.833 126	0.004 0.917 126	1 126	
PSDR	0.405** 0 126	0.811** 0 126	0.06 0.502 126	0.002 0.933 126	1 126

Note: ** Correlation is significant at the 0.01 level (2-tailed); LU = Land Use; SL = Slope; ST = Soil Type; RF = Rainfall; PSDR = Potential Soil Degradation Risk

An important observation is that farmland and plantation systems, while not as extreme as mining or settlements, still exhibit significant degradation risk due to the interaction between management practices and slope conditions. Intensive tillage, repeated application of inorganic fertilisers, and herbicide-based weed control reduce soil organic matter and weaken aggregate stability, especially on sloping land (Marcelino et al., 2024). The positive correlation between slope and PSDR highlights how these practices can quickly shift intermediate-risk soils into higher-degradation classes when applied on steeper terrain. Thus, the correlation analysis validates that natural (slope) and anthropogenic (land use) drivers are structurally linked in determining PSDR outcomes. From a management perspective, these results underscore the urgency of applying land-use-specific conservation practices tailored to slope gradients (Ewunetu et al., 2025). Improving soil organic matter and cover management on gentle slopes may be sufficient to maintain low-to-intermediate PSDR (Guimaraes et al., 2021). However, on slopes above 40%, terraces combined with conservation tillage, vegetative strips, and agroforestry transitions are essential to disrupt the positive correlation between slope and soil degradation risk. For plantations and farmland, adopting reduced tillage, integrating organic amendments, and maintaining living covers can significantly moderate the relationship between intensive land use and degradation risk (Chuanrum and Shrestha, 2024). Ultimately, aligning land-use planning with slope-based conservation strategies is the key to reducing PSDR and supporting sustainable integrated agriculture in Halong District.

Land Management Recommendations Based on Determinants of Environmental Diversity Sources

The findings highlight that land use is a critical determinant of soil degradation risk in Halong District. Several strategies are recommended to reduce land-use-induced degradation. Open fields and bare lands should be immediately covered with vegetation through cover crops, mulching, or reforestation to protect against direct rainfall impact (Liu et al., 2021). Mining areas must undergo reclamation, including topsoil replacement and revegetation, while settlements should integrate green infrastructure such as infiltration trenches and vegetative buffer zones (Gastauer et al., 2022). Farmlands need crop rotation, organic matter addition, and conservation tillage to maintain soil health (Farmaha et al., 2022). While plantations should reduce continuous inorganic fertiliser inputs and incorporate organic amendments, lime application, and living cover crops to control erosion and acidity (Agegnehu et al., 2021).

The role of slope as the most influential factor on PSDR suggests that soil conservation should be tailored to slopeic conditions (Xue et al., 2023). Minimum tillage and residue retention are sufficient on gentle slopes, while moderate slopes benefit from contour farming, strip cropping, and grassed waterways. Steeper slopes (25–40%) require stronger measures, such as contour bunds, vegetative barriers, and check dams to intercept runoff. On very steep slopes (>40%), intensive cultivation should be avoided and replaced with terracing supported by biological stabilisation or tree-based agroforestry systems, which are more sustainable and resilient to soil degradation (Singh,

2023). To ensure long-term effectiveness, integrated land management is essential, combining land-use planning with slope-based conservation (Workie and Teku, 2025). This includes zoning high-risk areas for rehabilitation, promoting community-based conservation initiatives, and aligning local practices with national regulations on land degradation control (Lucatello and Alcántara-Ayala, 2024). Stakeholder participation, farmer training, and incentives for sustainable practices will be key to reducing the strong positive correlation between land use, slope, and PSDR. Halong District can sustain agricultural productivity by adopting these measures while safeguarding its soil resources from further degradation.

CONCLUSION

This study revealed that the potential for soil degradation in Halong District, Balangan Regency, South Kalimantan, is primarily determined by the interactions among land-use practices, soil type, slope conditions, and rainfall distribution. Using GIS-based thematic overlays and scoring analysis enabled the identification of areas most vulnerable to erosion, nutrient depletion, compaction, and leaching. The findings confirm that intensive cultivation on fragile soils and steep slopes poses the most significant risk of degradation, while lowland areas face challenges of drainage and fertility decline. The resulting PSDR map provides a valuable framework for spatially identifying vulnerable areas and supports the development of targeted strategies for sustainable integrated agriculture. This study is constrained by data resolution, limited soil indicators, and its cross-sectional design; therefore, future research should incorporate long-term monitoring, higher-resolution spatial and biological soil assessments, socio-economic factors, and climate change scenario modelling to improve understanding and management of soil degradation. Beyond addressing the initial research objectives, this study provides a decision-support tool for land use planning, soil conservation, and agricultural development in the district, with potential for further refinement through the integration of climate variability, socio-economic dynamics, and advanced remote sensing data in future studies.

ACKNOWLEDGEMENT

The authors would like to express their sincere gratitude to all parties who contributed to the successful completion of this manuscript. Special appreciation is extended to the Indonesian Directorate of Geospatial Information Standards and Technology, the Geospatial Information Agency, the Government of Balangan Regency, BAKOSURTANAL, and the Department of Soil Science, Faculty of Agriculture, Lambung Mangkurat University, for their valuable support and assistance throughout this study.

REFERENCES

- AbdelRahman, M. A. (2023). An overview of land degradation, desertification and sustainable land management using GIS and remote sensing applications. *Rendiconti Lincei. Scienze Fisiche e Naturali*, 34(3), 767-808. <https://doi.org/10.1007/s12210-023-01155-3>

- Agegnehu, G., Amede, T., Erkossa, T., Yirga, C., Henry, C., Tyler, R., ... & Sileshi, G. W. (2021). Extent and management of acid soils for sustainable crop production system in the tropical agroecosystems: a review. *Acta Agriculturae Scandinavica, Section B—Soil & Plant Science*, 71(9), 852-869. <https://doi.org/10.1080/09064710.2021.1954239>
- Aguilera, H., Heredia Díaz, J., & de la Losa Román, A. (2021). A methodology for simulating perched conditions in multilayer aquifer systems with 2D variably saturated flow. *Vadose Zone Journal*, 20(5), e20152. <https://doi.org/10.1002/vzj2.20152>
- Ahuchaogu, I. I., Ehiomogue, P. O., & Udoumoh, U. I. (2022). Effects of soil and water conservation measures on the environment: A review. *Poljoprivredna tehnika*, 47, 42-55. <https://doi.org/10.5937/PoljTeh2203042A>
- Chen, T., Shu, J., Han, L., Tian, G., Yang, G., & Lv, J. (2022). Modeling the effects of topography and slope gradient of an artificially formed slope on runoff, sediment yield, water and soil loss of sandy soil. *Catena*, 212, 106060. <https://doi.org/10.1016/j.catena.2022.106060>
- Chuanrum, R., & Shrestha, R. P. (2024). Role of integrated farming systems in land degradation control and plant diversity enhancement: A case of northeast Thailand. *Farming System*, 2(3), 100086. <https://doi.org/10.1016/j.farsys.2024.100086>
- del Barrio, G., Sanjuán, M. E., Martínez-Valderrama, J., Ruiz, A., & Puigdefábregas, J. (2021). Land degradation means a loss of management options. *Journal of Arid Environments*, 189, 104502. <https://doi.org/10.1016/j.jaridenv.2021.104502>
- Dewi, W. S., Romadhon, M. R., Amalina, D. D., & Aziz, A. (2022). Paddy soil quality assessment to sustaining food security. In *IOP Conference Series: Earth and Environmental Science* (Vol. 1107, No. 1, p. 012051). IOP Publishing. <https://doi.org/10.1088/1755-1315/1107/1/012051>
- Dhanapriya, M., Gowtham, S., & Vigneshwari, R. (2025). Climate Change, Land Degradation and Sustainability: Insight towards Innovative Solutions from Indian Perspective. *Current Research on Geography, Earth Science and Environment Vol. 1, 1, 105-120*. <https://doi.org/10.9734/bpi/crgese/v1/5649>
- Diop, M., Chirinda, N., Beniaich, A., El Gharous, M., & El Mejahed, K. (2022). Soil and water conservation in Africa: State of play and potential role in tackling soil degradation and building soil health in agricultural lands. *Sustainability*, 14(20), 13425. <https://doi.org/10.3390/su142013425>
- Du, X., Jian, J., Du, C., & Stewart, R. D. (2022). Conservation management decreases surface runoff and soil erosion. *International soil and water conservation research*, 10(2), 188-196. <https://doi.org/10.1016/j.iswcr.2021.08.001>
- Ertop, H., Kocięcka, J., Atilgan, A., Liberacki, D., Niemiec, M., & Rolbiecki, R. (2023). The importance of rainwater harvesting and its usage possibilities: Antalya example (Turkey). *Water*, 15(12), 2194. <https://doi.org/10.3390/w15122194>
- Ewunetu, T., Selassie, Y. G., Molla, E., Admase, H., & Gezahegn, A. (2025). Soil properties under different land uses and slope gradients: Implications for sustainable land management in the Tach Karnuary watershed, Northwestern Ethiopia. *Frontiers in Environmental Science*, 13, 1518068. <https://doi.org/10.3389/fenvs.2025.1518068>
- Farmaha, B. S., Sekaran, U., & Franzluebbers, A. J. (2022). Cover cropping and conservation tillage improve soil health in the southeastern United States. *Agronomy Journal*, 114(1), 296-316. <https://doi.org/10.1002/agj2.20865>
- Francaviglia, R., Almagro, M., & Vicente-Vicente, J. L. (2023). Conservation agriculture and soil organic carbon: Principles, processes, practices and policy options. *Soil Systems*, 7(1), 17. <https://doi.org/10.3390/soilsystems7010017>
- Gastauer, M., Massante, J. C., Ramos, S. J., da Silva, R. D. S. S., Boaneres, D., Guedes, R. S., ... & Ribeiro, P. G. (2022). Revegetation on tropical steep slopes after mining and infrastructure projects: challenges and solutions. *Sustainability*, 14(24), 17003. <https://doi.org/10.3390/su142417003>
- Gemada, A. R. (2021). Soil acidity challenges to crop production in Ethiopian Highlands and management strategic options for mitigating soil acidity for enhancing crop productivity. *Agriculture, Forestry and Fisheries*, 10(6), 245-261. <https://doi.org/10.11648/j.aff.20211006.15>
- Giao, P. H., Thoang, T. T., Hiep, H., Hien, D. H., Van Long, P., Van Kieu, N., & Dung, N. T. (2023). Geological-geotechnical correlation of a deltaic subsoil profile and characterisation of its uppermost soft marine clay deposit with reference to infrastructure development in the Saigon-Dong Nai delta, Vietnam. *Bulletin of Engineering Geology and the Environment*, 82(12), 441. <https://doi.org/10.1007/s10064-023-03461-4>
- Gobinath, R., Ganapathy, G. P., Gayathiri, E., Salunkhe, A. A., & Pourghasemi, H. R. (2022). Ecoengineering practices for soil degradation protection of vulnerable hill slopes. In *Computers in earth and environmental sciences* (pp. 255-270). Elsevier. <https://doi.org/10.1016/B978-0-323-89861-4.00002-6>
- Guimaraes, D. V., Silva, M. L. N., Beniaich, A., Pio, R., Gonzaga, M. I. S., Avanzi, J. C., ... & Curi, N. (2021). Dynamics and losses of soil organic matter and nutrients by water erosion in cover crop management systems in olive groves, in tropical regions. *Soil and Tillage Research*, 209, 104863. <https://doi.org/10.1016/j.still.2020.104863>
- Hamidi, N. H., Ahmed, O. H., Omar, L., & Ch'ng, H. Y. (2021). Soil nitrogen sorption using charcoal and wood ash. *Agronomy*, 11(9), 1801. <https://doi.org/10.3390/agronomy11091801>
- He, F., Mohamadzadeh, N., Sadeghnejad, M., Ingram, B., & Ostovari, Y. (2023). Fractal features of soil particles as an index of land degradation under different land-use patterns and slope-aspects. *Land*, 12(3), 615. <https://doi.org/10.3390/land12030615>

- Herdiansyah, G., Herawati, A., Safira, R., Hardian, T., Istiqomah, N. M., Hasanah, K., & Romadhon, M. R. (2024). Analysis of potential soil degradation on agricultural land based on geographic information systems in Slogohimo District, Wonogiri Regency. In *IOP Conference Series: Earth and Environmental Science* (Vol. 1314, No. 1, p. 012108). IOP Publishing. <https://doi.org/10.1088/1755-1315/1314/1/012108>
- Homann-Kee Tui, S., Mzumara, E., Liben, F., Botoman, L., & Banda, M. (2023). Co-designing and validation of Mbili Mbili strip cropping and forage integration in mixed farming systems of Malawi. Retrieved from <https://cgspace.cgiar.org/server/api/core/bitstreams/51a62961-d02b-4550-8718-687a8768f7e9/content>
- Ichsan, C. N., Mahfira, W. S., Halim, A., & Juliawati, J. (2023, May). Mitigation of drought disaster in sorghum (*Sorghum bicolor* L. Moench) in Ultisol soil with application of soil amendments and NPK for diversification and improvement of food security. In *IOP Conference Series: Earth and Environmental Science* (Vol. 1183, No. 1, p. 012076). IOP Publishing. <https://doi.org/10.1088/1755-1315/1183/1/012076>
- Indonesian Central Bureau of Statistics. (2023). Halong Subdistrict in Number – Kecamatan Halong dalam Angka. Retrieved from <https://balangankab.bps.go.id/id/publication/2023/09/26/269536f7348f053fe8969f5d/kecamatan-halong-dalam-angka-2023.html>
- Indonesian Government Regulation. (2000). Control of Land Degradation for Biomass Production. Retrieved from <https://peraturan.bpk.go.id/Details/54039/pp-no-150-tahun-2000%23:-:text=PP%20No.%20150%20Tahun%202000%20tentang%20Pengendalian%20Kerusakan,Tahun%202000%20Pengendalian%20Kerusakan%20Tanah%20Untuk%20Produksi%20Biomassa>
- Indonesian Minister of Environment Regulation. (2006). Procedures for Measuring Standard Criteria for Soil Damage for Biomass Production. Retrieved from <https://jdih.menlhk.go.id/new2/uploads/files/PERMEN%20LH%20NO%207.pdf>
- Indonesian Minister of Environment Regulation. (2009). Guidelines for Determining Environmental Carrying Capacity in Regional Spatial Planning. Retrieved from https://komara.weebly.com/uploads/6/5/3/7/6537907/a_permen_lh_17_2009_pedoman_penentuan_daya_dukung_lh_dalam_penataan_ruang_wilayah.pdf
- Ke, Q., & Zhang, K. (2021). Patterns of runoff and erosion on bare slopes in different climate zones. *Catena*, 198, 105069. <https://doi.org/10.1016/j.catena.2020.105069>
- Kohsaka, R., Ito, K., Miyake, Y., & Uchiyama, Y. (2021). Cultural ecosystem services from the afforestation of rice terraces and farmland: Emerging services as an alternative to monoculturalisation. *Forest Ecology and Management*, 497, 119481. <https://doi.org/10.1016/j.foreco.2021.119481>
- Kumar, S., David Raj, A., Kalambukattu, J. G., & Chatterjee, U. (2023). Climate change impact on land degradation and soil erosion in hilly and mountainous landscape: sustainability issues and adaptation strategies. In *Ecological footprints of climate change: adaptive approaches and sustainability* (pp. 119-155). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-031-15501-7_5
- Liu, R., Thomas, B. W., Shi, X., Zhang, X., Wang, Z., & Zhang, Y. (2021). Effects of ground cover management on improving water and soil conservation in tree crop systems: A meta-analysis. *Catena*, 199, 105085. <https://doi.org/10.1016/j.catena.2020.105085>
- Liu, J., Hu, Y., Feng, Z., & Xiao, C. (2025). A review of land use and land cover in mainland southeast Asia over three decades (1990–2023). *Land*, 14(4), 828. <https://doi.org/10.3390/land14040828>
- Lucatello, S., & Alcántara-Ayala, I. (2024). Sustainable Synergy: Strengthening disaster risk reduction in Latin America and the Caribbean through nature-based solutions. *International Journal of Disaster Risk Reduction*, 113, 104860. <https://doi.org/10.1016/j.ijdrr.2024.104860>
- Ma, G., Li, G., Mu, X., Hou, W., Ren, Y., & Yang, M. (2022). Effect of raindrop splashes on topsoil structure and infiltration characteristics. *Catena*, 212, 106040. <https://doi.org/10.1016/j.catena.2022.106040>
- Marcelino, S. M., Gaspar, P. D., do Paço, A., Lima, T. M., Monteiro, A., Franco, J. C., ... & Lopes, C. M. (2024). Agricultural practices for biodiversity enhancement: evidence and recommendations for the viticultural sector. *AgriEngineering*, 6(2), 1175-1194. <https://doi.org/10.3390/agriengineering6020067>
- Maximus, J. K. (2025). Assessing watershed vulnerability to erosion and sedimentation: Integrating DEM and LULC data in Guyana's diverse landscapes. *HydroResearch*, 8, 178-193. <https://doi.org/10.1016/j.hydres.2024.11.002>
- Mohamed, W. W., Osman, N., & Abdullah, R. (2023). A review of bioengineering techniques for slope stability in Malaysia. *International Journal of Environmental Science and Technology*, 20(3), 3467-3482. <https://doi.org/10.1007/s13762-022-04235-3>
- Molossi, L., Hoshide, A. K., de Abreu, D. C., & de Oliveira, R. A. (2023). Agricultural support and public policies improving sustainability in Brazil's beef industry. *Sustainability*, 15(6), 4801. <https://doi.org/10.3390/su15064801>
- Musa, I. O., Samuel, J. O., Adams, M., Abdulsalam, M., Nathaniel, V., Maude, A. M., ... & Tiamiyu, A. G. T. (2024). Soil erosion, mineral depletion and regeneration. In *Prospects for soil regeneration and its impact on environmental protection* (pp. 159-172). Cham: Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-53270-2_7
- Nasrullah, N., Ahimsa-Putra, H. S., & Semedi, P. (2024). Malan: Farming Practices of the Bakumpai People in the Tidal Lands of South Kalimantan Province.

- Jurnal Socius: Journal of Sociology Research and Education*, 11(2), 61-70.
<http://dx.doi.org/10.24036/scs.v11i2.664>
- Nyairo, R. (2024). Effect of slope on water runoff and soil vulnerability in an unglaciated sub-watershed: a case study of conservation practice siting. *Environmental Systems Research*, 13(1), 50.
<https://doi.org/10.1186/s40068-024-00380-5>
- Polanía-Hincapié, K. L., Olaya-Montes, A., Cherubin, M. R., Herrera-Valencia, W., Ortiz-Morea, F. A., & Silva-Olaya, A. M. (2021). Soil physical quality responses to silvopastoral implementation in Colombian Amazon. *Geoderma*, 386, 114900.
<https://doi.org/10.1016/j.geoderma.2020.114900>
- Punia, A., & Bharti, R. (2023). Loss of soil organic matter in the mining landscape and its implication to climate change. *Arabian Journal of Geosciences*, 16(1), 86.
<https://doi.org/10.1007/s12517-023-11177-8>
- Romadhon, M. R., Mujiyo, M., Cahyono, O., Maro'Ah, S., Istiqomah, N. M., & Irmawati, V. (2023). Potential soil degradation of paddy fields through observation approaches from various sources of environmental diversity. In *IOP Conference Series: Earth and Environmental Science* (Vol. 1241, No. 1, p. 012013). IOP Publishing.
<https://doi.org/10.1088/1755-1315/1241/1/012013>
- Saco, P. M., McDonough, K. R., Rodriguez, J. F., Rivera-Zayas, J., & Sandi, S. G. (2021). The role of soils in the regulation of hazards and extreme events. *Philosophical Transactions of the Royal Society B*, 376(1834), 20200178.
<https://doi.org/10.1098/rstb.2020.0178>
- Samiei-Fard, R., Heidari, A., Drohan, P. J., Mahmoodi, S., & Ghatrehsamani, S. (2024). The Effect of Using a Geopedological Approach in Determining Land Quality Indicators, Land Degradation, and Development (Case Study: Caspian Sea Coast). *Environments*, 11(1), 20.
<https://doi.org/10.3390/environments11010020>
- Samsudin, Y. B., Adzani, T., Ramadian, M. A., Naito, D., & Baral, H. (2021). The potential of agarwood as a climateresilient livelihood option in Indonesia. Retrieved from https://www.cifor-icraf.org/publications/pdf_files/WPapers/WP271Samsudin.pdf
- Simelane, M. P. Z., Soundy, P., & Maboko, M. M. (2024). Effects of rainfall intensity and slope on infiltration rate, soil losses, runoff and nitrogen leaching from different nitrogen sources with a rainfall simulator. *Sustainability*, 16(11), 4477.
<https://doi.org/10.3390/su16114477>
- Singh, R. (2023). Terrace. In *Soil and Water Conservation Structures Design* (pp. 63-93). Singapore: Springer Nature Singapore.
https://doi.org/10.1007/978-981-19-8665-9_4
- Solomon, N., Birhane, E., Tilahun, M., Schauer, M., Gebremedhin, M. A., Gebremariam, F. T., ... & Newete, S. W. (2024). Revitalizing Ethiopia's highland soil degradation: a comprehensive review on land degradation and effective management interventions. *Discover Sustainability*, 5(1), 106.
<https://doi.org/10.1007/s43621-024-00282-7>
- Tadesse, A., Chimdi, A., & Chibsa, T. (2025). Characterisation and Assessment of Soil Acidity Status Under Different Land Use Types and Soil Depths in Lalistu Cheri Watershed, Sibu Sire District, Western Ethiopia. *American Journal of Chemical and Biochemical Engineering*, 9(1), 18-37.
<https://doi.org/10.11648/j.ajcbe.20250901.12>
- Tefera, M. L., Carletti, A., Altea, L., Rizzu, M., Migheli, Q., & Seddaiu, G. (2024). Land degradation and the upper hand of sustainable agricultural intensification in sub-Saharan Africa-A systematic review. *Journal of Agriculture and Rural Development in the Tropics and Subtropics (JARTS)*, 125(1), 63-83.
<https://doi.org/10.17170/kobra-202403129757>
- Telo da Gama, J. (2023). The role of soils in sustainability, climate change, and ecosystem services: Challenges and opportunities. *Ecologies*, 4(3), 552-567.
<https://doi.org/10.3390/ecologies4030036>
- Tiwari, A. K., Karn, N., Thakur, A., & Kumari, D. (2024). Soil Conservation and Restoration: Strategies to Combat Soil Erosion and Rehabilitate Degraded Lands. *A Comprehensive Exploration of Soil, Water, and Air Pollution in Agriculture*, 207. Retrieved from <https://books.google.co.id/books?id=tIHZEAAQBAJ&lpg=PA207&ots=JZkcmCsYuo&dq=more%20intensive%20interventions%20like%20contour%20farming%2C%20agroforestry%2C%20and%20the%20application%20of%20organic%20amendments%20are%20necessary%20to%20slow%20down%20degradation&lr&pg=PA207#v=onepage&q&f=false>
- Wilczewski, E., Jug, I., Szpunar-Krok, E., Staniak, M., & Jug, D. (2024). Shaping Soil Properties and Yield of Cereals Using Cover Crops under Conservation Soil Tillage. *Agronomy*, 14(9), 2104.
<https://doi.org/10.3390/agronomy14092104>
- Workie, M. D., & Teku, D. (2025). Assessing soil erosion hotspots and land degradation extent in Beshilo Watershed, Northeastern Ethiopia: integrating geospatial and field survey techniques, for sustainable land management. *Frontiers in Environmental Science*, 13, 1548881.
<https://doi.org/10.3389/fenvs.2025.1548881>
- Xue, C., Chen, X., Xue, L., Zhang, H., Chen, J., & Li, D. (2023). Modeling the spatially heterogeneous relationships between tradeoffs and synergies among ecosystem services and potential drivers considering geographic scale in Bairin Left Banner, China. *Science of the Total Environment*, 855, 158834.
<https://doi.org/10.1016/j.scitotenv.2022.158834>
- Zhang, Y., Tan, C., Wang, R., Li, J., & Wang, X. (2021). Conservation tillage rotation enhanced soil structure and soil nutrients in long-term dryland agriculture. *European Journal of Agronomy*, 131, 126379.
<https://doi.org/10.1016/j.eja.2021.126379>