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Integrated Land Degradation Assessment through Geographic Information Systems and Soil Biophysical Evaluation in Kalibeluk Village, Batang Regency

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Abstract

Land degradation is a major environmental issue that reduces soil productivity and impairs ecological functions. Kalibeluk Village, Batang Regency, has diverse biophysical characteristics that may result in varying levels of land degradation. This study assessed land degradation potential and the corresponding degradation status in Kalibeluk Village, using GIS-based spatial analysis supported by field verification and laboratory assessment. Spatial analysis was conducted using soil type, slope gradient, rainfall, and land use parameters through an overlay technique to determine land degradation potential. Field verification and laboratory analyses were subsequently performed for each Land Mapping Unit (LMU) to evaluate land degradation status based on Government Regulation of the Republic of Indonesia Number 150 of 2000 and Regulation of the State Minister of Environment Number 07 of 2006. The results classified land degradation potential into three categories: low (71.481 ha; 39.8%), moderate (104.167 ha; 57.9%), and high (4.137 ha; 2.3%). Evaluation of land degradation status indicated that LMUs with low and moderate degradation potential were categorized as Slightly Degraded (R.I), whereas LMUs with high degradation potential were categorized as Moderately Degraded (R.II). The main limiting factors were soil fraction composition, water permeability, redox conditions, and surface rockiness. The findings demonstrate that GIS is an effective tool for identifying land degradation levels and supporting land management planning. Recommended rehabilitation measures include agroforestry, cover crops, terracing, the application of organic matter and soil amendments, and conservation drainage systems to improve soil quality and reduce land degradation risks sustainably.

1. Introduction

Land is a natural resource that plays a strategic role in supporting agricultural production, maintaining environmental stability, and sustaining human livelihoods (Viana et al., 2022). The availability of healthy and productive soil is a key factor in ensuring food security, conserving water resources, and maintaining ecosystem balance (Țopa et al., 2025). However, increasing pressure on land resources resulting from population growth, agricultural expansion, and land-use intensification often leads to land degradation. Land degradation is characterized by the decline in soil physical, chemical, and biological properties, ultimately reducing the land's capacity to perform its productive functions effectively (Gao et al., 2025). Several measurable indicators, including deterioration of soil structure and texture, increased soil compaction, reduced permeability and water infiltration, low organic matter content, nutrient depletion, changes in soil pH, poor redox conditions, and increased surface rockiness commonly reflect the characteristics of degraded land. These indicators collectively reduce soil fertility, restrict root development, decrease water retention and infiltration capacity, and impair nutrient cycling, ultimately diminishing agricultural productivity and ecosystem resilience. This issue has become a global environmental concern due to its adverse impacts on agricultural productivity, ecosystem sustainability, and the well-being of communities that depend on land resources (AbdelRahman, 2023; Symeonakis, 2022).

Soil degradation may occur as a result of interactions between natural and anthropogenic factors. Natural factors, such as high rainfall, steep slopes, and specific soil characteristics, can increase land susceptibility to degradation (Chalise et al., 2019; Nofrizal et al., 2025). Meanwhile, human activities, including intensive tillage practices, land-use change, vegetation removal, and inadequate implementation of soil and water conservation measures, can accelerate the degradation process (Bhattacharyya et al., 2023; Chaudhuri et al., 2023). The resulting impacts include increased erosion, reduced organic matter content, soil compaction, decreased infiltration capacity, and disruption of soil biological activity. The accumulation of these processes leads to declining land productivity and an increased risk of long-term environmental degradation (Haregeweyn et al., 2023; Mason et al., 2023). Therefore, the identification and evaluation of soil degradation levels are essential for supporting sustainable land management.

Advances in Geographic Information System (GIS) technology have created broader opportunities for land resource inventory, land suitability assessment, and land degradation evaluation (Nugroho et al., 2026; Nurhutami et al., 2025; Rahman et al., 2025). GIS enables the integration of various spatial parameters influencing soil degradation, including soil type, slope gradient, rainfall, and land use, thereby providing more accurate and comprehensive information regarding the vulnerability of a particular area to land degradation. In addition to identifying the potential for soil degradation, GIS can support land management planning through the presentation of spatial information in an accessible and interpretable format. Numerous studies have demonstrated that GIS-based spatial approaches are effective for soil degradation assessment because they can accurately represent the spatial distribution of degradation levels in a detailed and systematic manner (Filchev and Kolev, 2021; Kartini et al., 2023; Nurhutami et al., 2025). Nevertheless, spatial analysis results become more reliable when supported by field verification and laboratory analyses of soil characteristics within the study area.

Kalibeluk Village, located in Batang Regency, is predominantly characterized by agricultural land use, diverse topographic conditions, and relatively intensive land management practices (Raharjo et al., 2015). These conditions may increase the susceptibility of land to degradation processes if not accompanied by adequate conservation measures. Numerous studies on land degradation have been conducted in Indonesia and other countries. However, most have focused primarily on mapping land degradation potential using spatial parameters or assessing soil biophysical conditions separately. Studies integrating GIS-based land degradation potential assessment with field verification and laboratory analyses according to the soil degradation criteria established in Government Regulation of the Republic of Indonesia Number 150 (2000) and Regulation of the State Minister of Environment Number 07 (2006) remain limited, particularly at the village scale. Consequently, there is insufficient local-level data on actual soil degradation to support land management decisions. This study addresses this limitation by integrating GIS-based spatial analysis with field verification and laboratory soil analyses to provide a more comprehensive and reliable assessment of land degradation at the village scale. The integration of these complementary approaches contributes to improving the accuracy of land degradation assessment and provides a stronger scientific basis for developing evidence-based land management and soil conservation strategies. Therefore, this study aimed to analyze land degradation potential and determine soil degradation status in Kalibeluk Village, Batang Regency, using a combination of GIS-based analysis, field verification, and laboratory soil analysis.

2. Research Methods

2.1. Research Location

This land degradation assessment was conducted from April to August 2025 in Kalibeluk Village, Batang Regency, utilizing field surveys, laboratory and geospatial analyses. The study area was selected because it is predominantly characterized by agricultural land use and exhibits diverse biophysical conditions in terms of land use, rainfall, soil type, and slope gradient. These variations may influence the susceptibility of land to degradation and soil damage resulting from continuous land utilization activities. Laboratory analyses of soil samples collected from the field were carried out at the Agrotechnology Laboratory, University of Pekalongan, to support the determination of soil degradation status according to the applicable soil degradation criteria.

2.2. Research Implementation

The implementation of this research involved collecting and integrating datasets from field investigations, laboratory analyses, and spatial data analyses to support the assessment of land degradation conditions in the study area. Both primary and secondary sources of information were utilized to provide comprehensive data for evaluating land degradation potential and soil degradation status. Primary data consisted of soil biophysical characteristics collected through field observations and laboratory testing of soil samples from each designated land unit. Secondary data consisted of spatial information related to soil type, slope, rainfall, and land use across Kalibeluk Village. These datasets were processed and converted into thematic spatial layers using Geographic Information System (GIS) tools. Each thematic layer represented a specific parameter influencing land degradation potential and was subsequently combined through an overlay procedure to generate a land degradation potential map. The resulting map served as the basis for identifying areas with different levels of susceptibility to land degradation. The equipment used in this study included a Global Positioning System (GPS), soil auger, soil sampling rings, measuring tape, pH meter, soil oven, analytical balance, soil sieve set, and QGIS 3.22.14 software for spatial data processing and analysis.

The study was conducted through several stages, including spatial data collection, soil degradation potential analysis, delineation of Land Mapping Units (LMUs), field verification involving soil sampling and laboratory analyses, and determination of soil degradation status. The collected spatial data were first processed using QGIS 3.22.14 to generate information on soil degradation potential based on the characteristics of the study area. The results of the spatial analysis were subsequently used as the basis for selecting observation sites and soil sampling locations in the field. Data obtained from field surveys and laboratory analyses were then evaluated according to the soil degradation criteria established in Government Regulation of the Republic of Indonesia Number 150 (2000) and Regulation of the State Minister of Environment Number 07 (2006) to determine the soil degradation status of each Land Mapping Unit (LMU) in Kalibeluk Village, Batang Regency.

2.3. Spatial analysis of Soil Degradation Potential

Soil degradation potential was determined using a spatial analysis approach by integrating several parameters that influence land vulnerability. The parameters included land use, rainfall, soil type, and slope gradient. Each parameter was assigned a score according to its sensitivity to soil degradation. All parameters were then analyzed using an overlay method to generate cumulative values representing the level of soil degradation potential within the study area. The interpretation and classification of soil degradation potential were carried out using the evaluation framework established in Government Regulation of the Republic of Indonesia Number 150 (2000) and Regulation of the State Minister of Environment Number 07 (2006). Under this framework, the cumulative scores derived from the integration of soil type, slope gradient, rainfall, and land use parameters were utilized to determine the degree of land vulnerability to degradation. The resulting classification provides a standardized basis for assessing spatial variations in degradation potential and serves as an important reference for subsequent land evaluation and conservation planning. The soil degradation potential classes used in this study are presented in Table 1.

Table 1. Classification criteria for soil degradation potential assessment

Symbol	Soil Degradation Potential Class	Weighted Score
PR.I	Very Low	< 15.00
PR.II	Low	15.00 – 24.00
PR.III	Moderate	25.00 – 34.00
PR.IV	High	35.00 – 44.00
PR.V	Very High	45.00 – 50.00

The overlay of all spatial parameters produced a soil degradation potential map showing the spatial distribution of land vulnerability to degradation across the study area. Subsequently, LMUs with homogeneous characteristics were delineated using this map based on the combined parameters. Each LMU served as the basis for field surveys and soil sampling activities conducted to determine soil degradation status. Therefore, the spatially derived information generated from the integration and evaluation of multiple environmental parameters not only illustrated the distribution of land susceptibility to degradation throughout the study area but also provided a scientific basis for conducting more detailed field investigations and comprehensive assessments of actual soil conditions.

2.4. Soil Degradation Status Evaluation Based on Field and Laboratory Analyses

Soil degradation status was determined through field verification and laboratory analyses of samples representing each LMU identified during the degradation potential assessment. Soil samples were collected using a purposive sampling approach based on relatively homogeneous land characteristics within each LMU to ensure that the samples adequately represented actual field conditions (Ardyansyah et al., 2025). These samples were analyzed for physical, chemical, and biological degradation indicators. The observed parameters included solum thickness, surface rockiness, soil fraction composition, bulk density, total porosity, water permeability, pH (H_2O), electrical conductivity, redox potential, and soil microbial population. The measured values were compared against the critical threshold presented in Table 2.

Table 2. Critical threshold values for evaluating soil degradation indicators

No	Parameter	Critical Threshold
1	Solum Thickness (s)	< 20.00 cm
2	Surface Rock Fragments (b)	> 40%
3	Soil Fraction Composition (f)	< 18% Colloids; > 80% Quartz Sand
4	Bulk Density (d)	> 1.40 g cm^{-3}
5	Total Porosity (v)	< 30%; > 70%
6	Permeability Rate (p)	< 0.70 cm $hour^{-1}$; > 8.00 cm $hour^{-1}$
7	pH (H_2O) (a)	< 4.50; > 8.50
8	Electrical Conductivity (e)	> 4.00 mS cm^{-1}
9	Redox Potential (r)	< 200 mV
10	Total Microbial Population (m)	< 10^2 cfu g^{-1} soil

Parameters were classified as degraded or non-degraded based on these critical thresholds. Those exceeding the limits were identified as limiting factors contributing to soil degradation. Relative frequency analysis was then performed to determine the dominance of each limiting factor within a particular land unit. The relative frequency values were subsequently converted into soil degradation scores representing the severity level of degradation for each parameter. The classification of scores based on the relative frequency of soil degradation is presented in Table 3.

Table 3. Soil degradation scores based on the relative frequency of soil degradation parameters

Relative Frequency of Soil Degradation (%)	Score	Weighted Score Classification
0.00 – 10.00	0	Non-Degraded
11.00 – 25.00	1	Slightly Degraded
26.00 – 50.00	2	Moderately Degraded
51.00 – 75.00	3	Severely Degraded
76.00 – 100.00	4	Very Severely Degraded

The degradation scores from all parameters were summed to obtain a cumulative soil degradation score for each LMU. This cumulative value determined the final soil degradation status, which reflected the overall level of soil degradation within each land unit. Higher cumulative scores indicated more severe soil degradation. The resulting soil degradation status classification was then used to develop a soil degradation status map and identify the dominant limiting factors affecting land conditions within the study area. The classification of soil degradation status based on cumulative scores is presented in Table 4.

Table 4. Soil degradation scores based on the accumulated soil degradation score values

Symbol	Soil Degradation Status	Accumulated Soil Degradation Score
N	Non-Degraded	0.00
R.I	Slightly Degraded	1.00 – 12.00
R.II	Moderately Degraded	13.00 – 21.00
R.III	Severely Degraded	22.00 – 30.00
R.IV	Very Severely Degraded	31.00 – 36.00

3. Results and Discussion

3.1. GIS-Based Analysis of Land Degradation Potential

Kalibeluk Village covers an area of approximately 179.785 ha and features diverse biophysical conditions, including variations in soil type, slope gradient, rainfall, and land use. These parameters are important factors influencing land vulnerability to degradation and soil damage processes (Liu et al., 2021). Variations in biophysical conditions across a landscape can affect the ability of soil to maintain both its productive and ecological functions (Romero et al., 2025). Therefore, the identification of the spatial characteristics of the study area constitutes an essential initial step in assessing land degradation potential. The spatial characteristics of the study area are visualized in Figure 1, which depicts the distribution of soil type, slope gradient, rainfall patterns, and land use across Kalibeluk Village and highlights the heterogeneity of environmental conditions that may contribute to differences in land degradation potential.

As shown in Figure 1, Ultisols and Inceptisols dominate Kalibeluk Village, covering approximately 141.359 ha and 38.426 ha, respectively. Although these soils exhibit different levels of profile development, both require careful management to sustain land quality. Ultisols generally exhibit low fertility due to intensive leaching (Ebido et al., 2025; Putri et al., 2023), while Inceptisols are relatively young soils with less developed physical characteristics (Riry and Tetelepta, 2023; Saricaoglu et al., 2021). These characteristics make both soil types relatively sensitive to land-use changes and disturbances of the soil surface. Consequently, soil type represents an important factor in determining land vulnerability to degradation processes. In addition to soil type, topographic characteristics also influence the potential for land degradation within the study area (Talib et al., 2026).

Slope conditions in Kalibeluk Village range from flat to very steep classes, with flat slopes (0–8%) and gently sloping areas (8–15%) being the dominant categories. This indicates that most parts of the study area have a relatively low susceptibility to erosion, although areas with slopes exceeding 15% remain vulnerable to greater soil loss (Fadl et al., 2025). Annual rainfall in Kalibeluk Village ranges from 2,000 to 3,000 mm year^{-1} and is classified as moderate according to the land degradation potential classification. Rainfall within this range can support plant growth but may also increase surface runoff and nutrient leaching if not accompanied by appropriate land management practices (Li et al., 2024). Land use in Kalibeluk Village is dominated by paddy fields covering 104.382 ha, while other land-use types include settlements and activity areas covering 71.322 ha and dryland farming areas covering 4.081 ha. Differences in land-use characteristics influence land vulnerability because they are associated with vegetation cover, soil management intensity, and the ability of land to protect the soil surface from degradation processes.

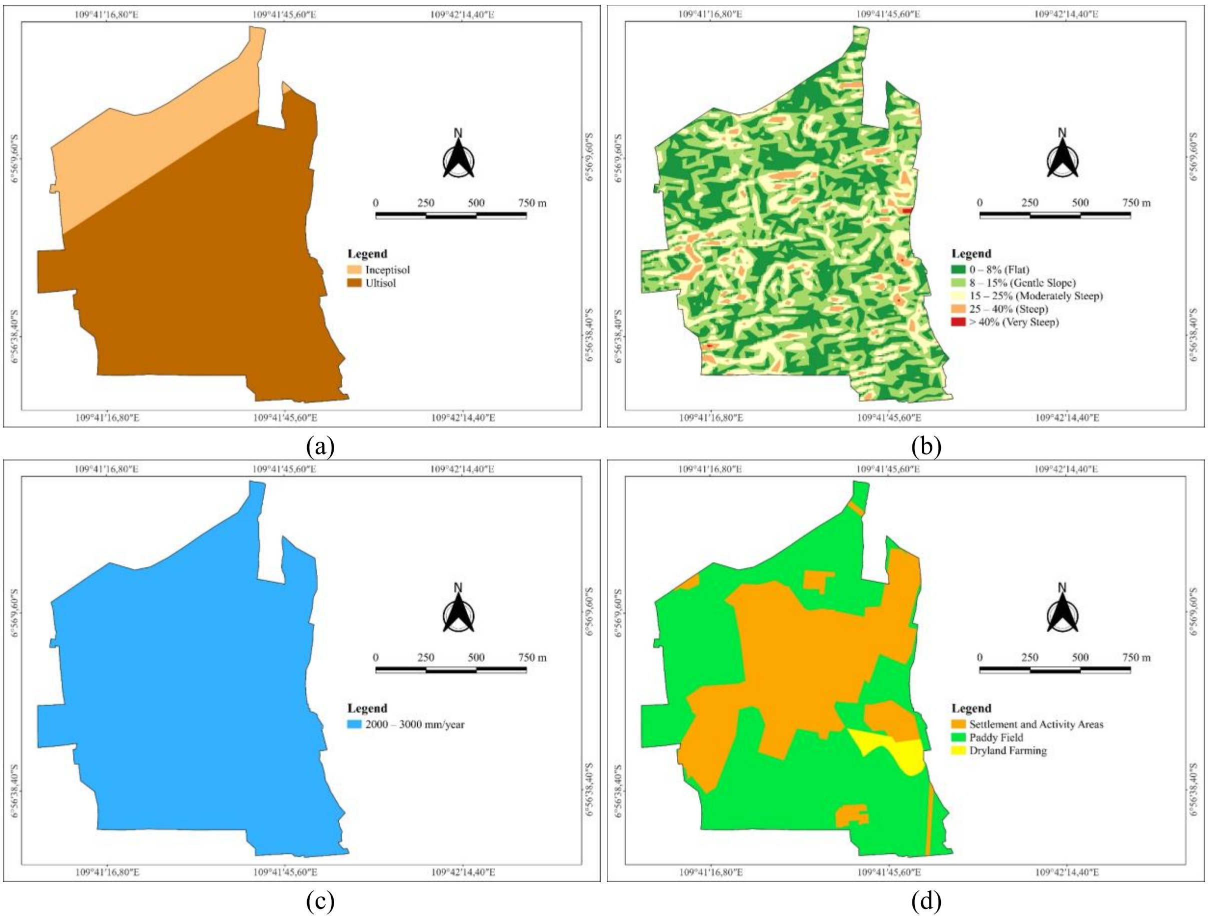

Figure 1. Spatial characteristics of Kalibeluk Village based on the distribution of (a) soil type, (b) slope gradient, (c) rainfall distribution, and (d) land use patterns.

The thematic maps derived from geospatial information on soil type, topographic slope, rainfall distribution, and land use characteristics were subsequently integrated using an overlay procedure to evaluate land degradation potential and to characterize the spatial distribution of degradation susceptibility across different parts of Kalibeluk Village, Batang Regency, based on the combined influence of these environmental factors. Each parameter was assigned a score and weight according to its susceptibility to soil degradation based on the classification established in Government Regulation of the Republic of Indonesia Number 150 (2000) and Regulation of the State Minister of Environment Number 07 (2006). The overlay analysis was performed using QGIS software to generate spatial information regarding the distribution of land degradation potential based on the combination of all analyzed parameters (Afiatan et al., 2024; Al Ramadhani et al., 2026). The resulting information was then presented as a Land Degradation Potential Map of Kalibeluk Village, as shown in Figure 2.

Based on the analysis presented in Figure 2, land degradation potential in Kalibeluk Village was classified into three categories, namely low degradation potential (PR.II), moderate degradation potential (PR.III), and high degradation potential (PR.IV). The moderate degradation potential class (PR.III) dominated the study area, covering 104.167 ha or approximately 57.9% of the total village area. The low degradation potential class (PR.II) covered approximately 71.481 ha or 39.8%, whereas the high degradation potential class (PR.IV) occupied only 4.137 ha or approximately 2.3% of the study area. The dominance of this moderate potential class indicates that much of Kalibeluk Village is vulnerable to soil degradation without proper conservation measures. The distribution of degradation potential classes is influenced by variations in soil type, topographic conditions, rainfall, and land use across different parts of the study area. These findings suggest that sustainable land management efforts should be prioritized in areas classified as having moderate and high degradation potential to prevent further soil degradation.

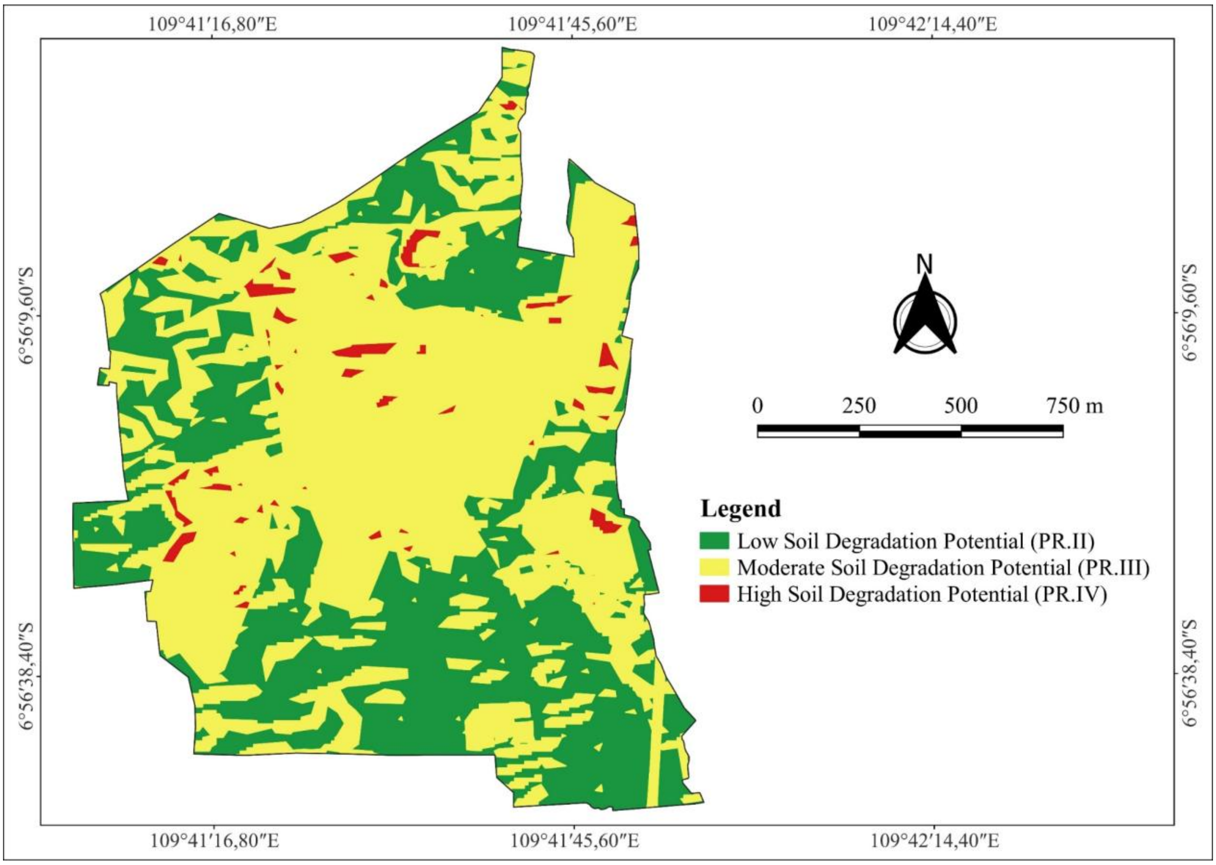

Figure 2. Land degradation potential map of Kalibeluk Village.

3.2. Field Verification and Evaluation of Land Degradation Status

Following the spatial assessment of land degradation potential, a comprehensive evaluation was conducted to determine the actual degradation status of the land and to validate the spatial analysis results through field-based observations and measurements. The resulting land degradation potential map was subsequently used as the basis for delineating LMUs. The overlay analysis identified three LMU classes, namely LMU PR.II (Low Degradation Potential), LMU PR.III (Moderate Degradation Potential), and LMU PR.IV (High Degradation Potential). Each LMU was then verified through field surveys and soil sampling to obtain information on the actual soil conditions within the study area. Field investigations included the observation and measurement of ten soil biophysical parameters considered relevant for evaluating land degradation conditions and identifying dominant limiting factors within each LMU. The relative frequency values obtained for each degradation parameter within the respective LMUs were subsequently integrated to establish the overall degradation status of each land unit. This evaluation provided a basis for identifying the severity of land degradation and the dominant limiting factors affecting soil quality across the study area. The detailed results of the degradation status assessment are summarized in Table 5, whereas the spatial pattern and geographic distribution of degradation classes throughout Kalibeluk Village are illustrated in Figure 3.

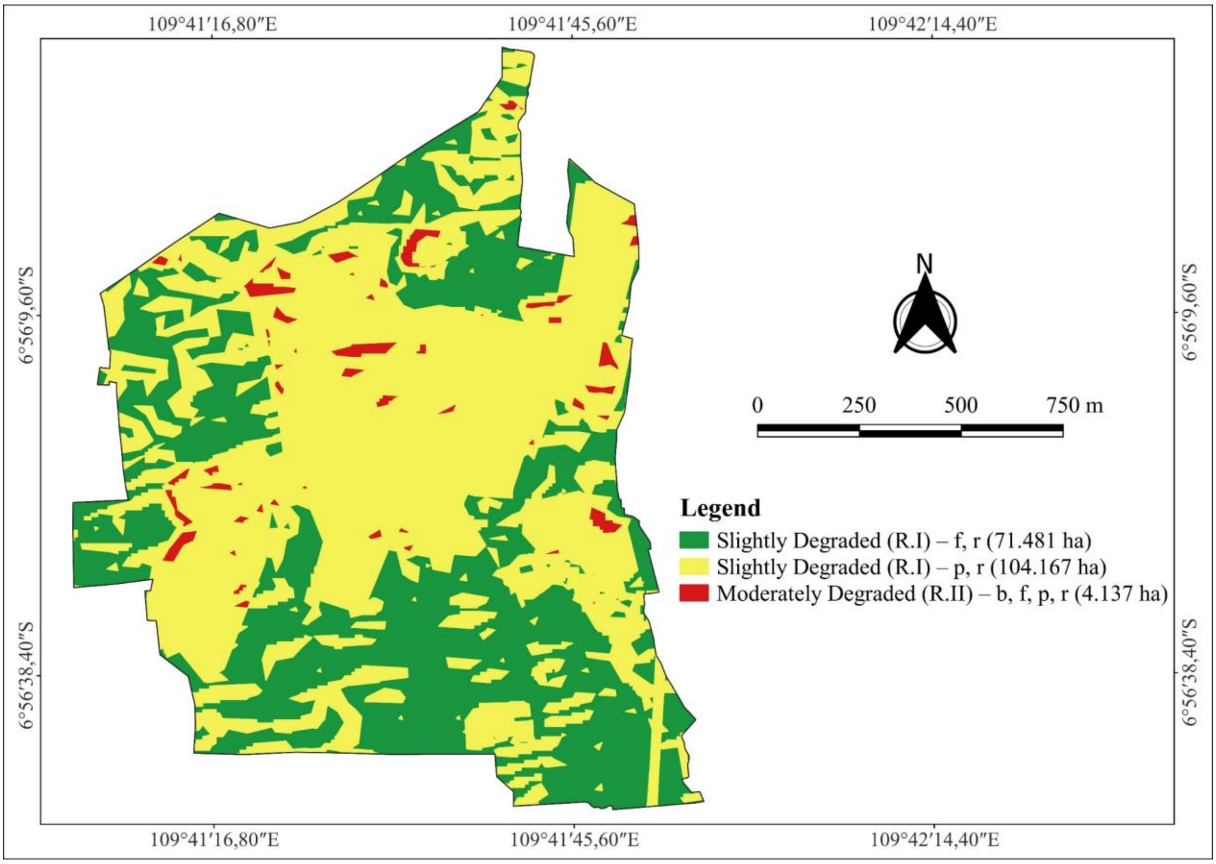

Figure 3. Land degradation status map of Kalibeluk Village.

The information summarized in Table 5 and illustrated spatially in Figure 3 indicates that LMU PR.II, which was classified as having low degradation potential, was categorized as Slightly Degraded (R.I) with a total degradation score of 6 and an area of approximately 71.481 ha. The limiting factors identified in this land unit were soil fraction composition (f) and redox potential (r). Colloidal fraction values below the critical threshold indicate a reduced capacity of the soil to retain water and nutrients, thereby lowering its productive capacity. This condition is commonly associated with the loss of fine particles due to erosion and long-term leaching processes (He et al., 2023). Low redox values indicate limited oxygen availability within the soil, resulting in less efficient decomposition processes and nutrient cycling (Das et al., 2025; Schlüter et al., 2025). Conservation measures that can be implemented in this land unit include the application of organic matter, mulching, the use of cover crops, and proper drainage management to improve soil aeration and enhance soil physical properties (Matisic et al., 2024).

LMU PR.III, which represented the moderate degradation potential class, was also classified as Slightly Degraded (R.I) with a total degradation score of 7 and an area of 104.167 ha. The primary limiting factors identified in this land unit were water permeability (p) and redox potential (r). Water permeability values outside the critical threshold indicate disturbances in the soil's ability to transmit water, which may result from soil compaction, structural degradation, or reduced organic matter content. Such conditions can increase surface runoff while reducing the effectiveness of water infiltration into the soil profile (Jarvis et al., 2024). Low redox values further indicate that a portion of the soil pores remains under poorly aerated conditions, limiting gas exchange processes within the soil (Dorau et al., 2022). Land conditions can be improved by adding organic matter, the implementation of biopore systems or infiltration wells, the reduction of excessive tillage, and the enhancement of vegetation cover to maintain soil structural stability and increase infiltration capacity (Blanchy et al., 2023).

Table 5. Relative frequency and soil degradation status in Kalibeluk Village

LMU	Sample	s (cm)	b (%)	f (%) Colloids	f (%) Quartzitic Sand	d (g cm^{-3})	v (%)	p (cm hour^{-1})	a	e (mS cm^{-1})	r (mV)	m (10^2 cfu g^{-1})	Total Score	Land Degradation Status	Limiting Factor
PR.II (Low Degradation Potential)	1	38	7.25	19.81	39.41	0.92	53.3	6.05	6.6	0.19	**130.00**	2.60 x 10^5	6	R.I	f, r
	2	26	11.50	38.24	12.25	0.91	57.84	0.82	6.4	0.11	**76.80**	6.20 x 10^6			
	3	40	15.63	**1.71**	1.75	0.93	54.48	3.43	7.0	0.18	**49.60**	1.33 x 10^7			
	RF (%)	0	0	33.3		0	0	0	0	0	100	0			
	Score	0	0	2		0	0	0	0	0	4	0			
PR.III (Moderate Degradation Potential)	1	35	13.50	32.38	30.15	1.19	47.33	**10.70**	6.6	0.17	**68.60**	3.60 x 10^5	7	R.I	p, r
	2	34	17.75	40.76	8.95	1.16	49.12	**8.08**	6.4	0.16	**88.20**	1.35 x 10^6			
	3	36	28.13	33.74	37.05	1.05	47.59	7.07	6.5	0.09	**58.70**	1.49 x 10^7			
	RF (%)	0	0	0		0	0	66.7	0	0	100	0			
	Score	0	0	0		0	0	3	0	0	4	0			
PR.IV (High Degradation Potential)	1	33	**57.25**	41.62	17.58	1.18	46.38	**15.34**	6.1	0.15	**51.90**	2.40 x 10^5	14	R.II	b, f, p, r
	2	34	**42.75**	37.24	12.21	1.17	44.06	**0.06**	5.4	0.14	**36.30**	5.90 x 10^5			
	3	43	**50.00**	**2.36**	5.40	1.18	45.69	**10.00**	6.0	0.09	**78.40**	2.75 x 10^6			
	RF (%)	0	100	33.3		0	0	100	0	0	100	0			
	Score	0	4	2		0	0	4	0	0	4	0			

Note: Values shown in bold indicate parameters classified as degraded, as they exceed the standard criteria for soil degradation. PR.II = Low Degradation Potential, PR.III = Moderate Degradation Potential, PR.IV = High Degradation Potential, RF = Relative Frequency, s = Solum Thickness, b = Surface Rock Fragments, f = Soil Fraction Composition, d = Bulk Density, v = Total Porosity, p = Permeability Rate, a = pH (H_2O), e = Electrical Conductivity, r = Redox Potential, m = Total Microbial Population, R.I = Slightly Degraded, R.II = Moderately Degraded.

LMU PR.IV, which was classified as having high degradation potential, exhibited more severe conditions than the other land units, with a total degradation score of 14 and a Moderate Degradation status (R.II) over an area of approximately 4.137 ha. The identified limiting factors included surface rockiness (b), soil fraction composition (f), water permeability (p), and redox potential (r). A high percentage of surface rockiness indicates limited soil development and a shallower effective soil depth available for root growth (Morandage et al., 2021). This condition is further aggravated by the low colloidal fraction content, which reduces the soil's capacity to retain water and nutrients (He et al., 2023). In addition, impaired water permeability and low redox values indicate a decline in soil hydrological functions (Basak et al., 2022). The spatial distribution shown in Figure 3 reveals that areas classified as Moderately Degraded are concentrated in locations characterized by the most complex combination of limiting factors. Consequently, these areas require more intensive conservation measures, including terracing on sloping land, the establishment of conservation vegetation, regular application of organic matter, and surface runoff control to minimize the risk of further soil degradation (Chalise et al., 2019; Girma et al., 2023). Furthermore, the integrated implementation of agroforestry systems, cover crops, conservation drainage channels, minimum tillage practices, and land rehabilitation through the application of organic amendments and balanced fertilization is necessary to improve soil physical, chemical, and biological properties and enhance land resilience to future degradation processes (Daryanto et al., 2018; Fahad et al., 2022).

The results revealed a consistent relationship between land degradation potential classes and the actual land degradation status in Kalibeluk Village. Areas classified as having low and moderate degradation potential were generally categorized as Slightly Degraded (R.I), whereas areas with high degradation potential were classified as Moderately Degraded (R.II) due to the accumulation of more complex limiting factors. These findings indicate that the spatial approach employed in this study was capable of providing a reliable representation of land vulnerability prior to field verification. Nevertheless, the differences observed between degradation potential classes and actual degradation status suggest that land conditions are influenced not only by biophysical factors (Lestariningsih et al., 2018; Qi et al., 2025; Taye et al., 2023), but also by land management practices implemented by local communities (Dakeso, 2024; Kgaphola et al., 2023; Solomon et al., 2024). Therefore, the integration of spatial analysis and field verification represents an essential step in generating more representative and accurate information on land degradation conditions (Kartini et al., 2023; Riva et al., 2017; Workie and Teku, 2025). The strong agreement between the land degradation potential mapping results and field verification findings demonstrates that the GIS-based approach can serve as an effective tool for the early identification of areas vulnerable to land degradation. Such information is essential for supporting more targeted land management policies, particularly in areas experiencing intensive land-use pressure and biophysical conditions that are highly susceptible to degradation.

3.3. Implications for Land Resource Management

Based on the land degradation assessment, integrated land resource management strategies are essential to prevent further degradation and ensure long-term land sustainability. The results of this study indicate that most areas of Kalibeluk Village remain within a degradation level that can still be restored through appropriate land management interventions. Therefore, conservation strategies should be implemented according to the dominant limiting factors identified in each Land Mapping Unit (LMU). Vegetative conservation measures, including agroforestry systems and permanent vegetation cover, should be prioritized to improve soil stability, enhance biodiversity, and strengthen ecosystem resilience. Agronomic practices, such as the application of organic matter, balanced fertilization, cover crops, and minimum tillage, are recommended to improve soil fertility, restore soil structure, and enhance infiltration capacity in areas affected by poor soil fraction composition and reduced permeability. In areas with high surface rockiness and greater runoff potential, mechanical conservation measures such as terracing, contour farming, and conservation drainage channels should be prioritized to reduce erosion and enhance water infiltration.

Geographic Information Systems (GIS) provide an effective platform for supporting long-term land resource management by identifying priority areas for conservation, monitoring changes in land degradation over time, and facilitating evidence-based spatial decision-making (Kochanek et al., 2025; Kunberger et al., 2025). The land degradation maps generated in this study can be integrated into regional spatial planning, land rehabilitation programs, and sustainable agricultural development policies. Furthermore, periodic monitoring that combines GIS, field verification, and laboratory analysis is recommended to evaluate the effectiveness of conservation measures and support adaptive land management under changing environmental conditions. The implementation of these integrated land resource management strategies is expected to maintain land productivity, preserve ecosystem functions, and reduce future land degradation risks in a sustainable manner.

4. Conclusion

This study demonstrates that an integrated land degradation assessment through Geographic Information Systems (GIS) and soil biophysical evaluation, supported by field verification and laboratory analysis, provides a comprehensive and reliable framework for assessing land degradation at the village scale. The assessment identified moderate land degradation potential as the dominant condition in Kalibeluk Village, while field verification and laboratory analysis confirmed that most Land Mapping Units (LMUs) were classified as Slightly Degraded, with localized areas categorized as Moderately Degraded due to soil fraction composition, water permeability, redox conditions, and surface rockiness. The integration of GIS-based spatial analysis with field verification and laboratory analysis improves the identification of degradation status and its limiting factors, thereby strengthening the scientific basis for land degradation assessment. The findings provide valuable information for prioritizing land management interventions and support evidence-based soil conservation planning and regional land management policies. The implementation of appropriate conservation practices, including agroforestry, cover crops, terracing, organic matter application, conservation drainage systems, and surface runoff control, can contribute to reducing land degradation risks while maintaining long-term land productivity and environmental sustainability.

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