Mapping Land Vulnerability to Degradation using a Geographic Information System (GIS)

Ruth Riah Ate Tarigan
Universitas Pembangunan Panca Budi, Medan, North Sumatera, Indonesia
Email: truthtrg@yahoo.com

Land degradation poses a significant threat to environmental sustainability and agricultural productivity, particularly in regions experiencing rapid land-use change and increasing anthropogenic pressure. Mapping land vulnerability to degradation is essential for supporting effective land management and spatial planning policies. This study aims to assess and map land vulnerability to degradation using a Geographic Information System (GIS) approach. The analysis integrates multiple biophysical and environmental factors, including slope, soil type, land use/land cover, rainfall intensity, and vegetation index. A weighted overlay method was applied, with factor weights determined using expert judgment and relevant literature to generate a land degradation vulnerability index. The results classify the study area into low, moderate, and high vulnerability zones. Areas with steep slopes, sparse vegetation cover, and intensive land use exhibit the highest vulnerability to degradation. The vulnerability map highlights spatial patterns that can support targeted land management interventions and conservation planning. This study demonstrates that GIS-based spatial analysis provides an effective and reliable framework for identifying land degradation risks and offers valuable insights for policymakers in promoting sustainable land management and mitigating land degradation impacts.

Keywords : Land Degradation; Vulnerability Mapping; Geographic Information System (GIS); Spatial Analysis; Sustainable Land Management

Corresponding Author:
Ruth Riah Ate Tarigan
Universitas Pembangunan Panca Budi, Medan, North Sumatera, Indonesia
truthtrg@yahoo.com

1. Introduction

Land degradation has become a critical global environmental issue, particularly in developing regions where population growth, agricultural expansion, and unsustainable land-use practices exert increasing pressure on natural resources. Degraded land conditions reduce soil fertility, accelerate erosion processes, and diminish ecosystem services, ultimately threatening food security and socio-economic stability (FAO, 2021). In tropical regions, high rainfall intensity combined with inappropriate land management practices further exacerbates land degradation risks, making these areas especially vulnerable (Lal, 2020). Spatial heterogeneity of land characteristics means that land degradation does not occur uniformly across a landscape. Factors such as topography, soil properties, land use patterns, and vegetation cover interact dynamically to influence degradation processes (Borrelli et al., 2020). Consequently, understanding the spatial distribution of land vulnerability is essential for effective land-use planning and the implementation of sustainable land management strategies. Without spatially explicit information, mitigation efforts may be inefficient or misdirected, leading to continued environmental deterioration (IPBES, 2022). Geographic Information Systems (GIS) have emerged as a powerful tool for analyzing spatial environmental problems, including land degradation. GIS enables the integration of multi-source spatial data and facilitates the analysis of complex interactions among biophysical variables influencing land vulnerability (Chen et al., 2021). Recent studies have demonstrated that GIS-based vulnerability mapping can provide accurate and reliable insights into degradation-prone areas, supporting evidence-based decision-making and land conservation policies (Singh et al., 2023). Despite the growing body of research on land degradation assessment, many regions still lack detailed vulnerability maps that incorporate multiple environmental indicators within a unified spatial framework. This gap limits the effectiveness of land management interventions and policy formulation, particularly at the local and regional scales. Therefore, this study aims to map land vulnerability to degradation using a GIS-based multi-criteria analysis approach. By integrating key environmental factors, the study seeks to identify areas at different levels of degradation risk and to provide spatial information that supports sustainable land management and environmental protection efforts.

2. Literature Review

Land Degradation Vulnerability

Land degradation vulnerability refers to the degree to which land systems are susceptible to degradation processes as a result of the interaction between natural conditions and human activities. It reflects the potential of an area to experience deterioration in soil quality, vegetation cover, and land productivity when exposed to environmental pressures such as erosion, deforestation, intensive agriculture, and climate variability (IPBES, 2022). Vulnerability to land degradation is not solely determined by a single factor, but rather by a combination of biophysical and anthropogenic components. Biophysical factors include soil type, slope gradient, rainfall intensity, land cover, and topography, while anthropogenic factors encompass land-use practices, population pressure, agricultural intensity, and land management systems (Lal, 2020; Singh et al., 2023). Areas with steep slopes, fragile soils, sparse vegetation cover, and high rainfall are generally more vulnerable, particularly when land use is not aligned with land capability.

From a spatial perspective, land degradation vulnerability is dynamic and varies across landscapes. Geographic Information Systems (GIS) and remote sensing technologies enable the integration of multiple indicators to assess vulnerability levels spatially and quantitatively. Through multi-criteria analysis, vulnerability mapping classifies land into categories such as low, moderate, high, and very high vulnerability, which are essential for identifying priority areas for conservation and rehabilitation (Chen et al., 2021). Understanding land degradation vulnerability is crucial for sustainable land management and environmental policy formulation. By identifying vulnerable areas, decision-makers can implement targeted interventions, such as soil conservation measures, land-use zoning, and ecosystem restoration, to reduce degradation risks and enhance land resilience, particularly in tropical agricultural regions where land degradation poses a significant threat to food security and environmental sustainability (FAO, 2021).

Land degradation vulnerability assessment has gained increasing attention in recent years due to its importance in sustainable land management and environmental planning. Vulnerability refers to the susceptibility of land systems to degradation processes under the influence of natural conditions and human activities (IPBES, 2022). Identifying vulnerable areas is essential for prioritizing conservation efforts, optimizing land-use planning, and mitigating environmental risks, particularly in tropical agricultural regions where degradation occurs rapidly.

Land Degradation and Its Driving Factors

Land degradation is a complex process driven by both biophysical and socio-economic factors. In tropical environments, intensive rainfall, steep slopes, and fragile soil structures significantly increase erosion risks, especially when combined with deforestation and improper agricultural practices (Lal, 2020). Borrelli et al. (2020) emphasized that land-use change is one of the dominant drivers of soil erosion globally, with agricultural expansion contributing substantially to increased soil loss. Similarly, organic matter depletion due to continuous cultivation and inadequate residue management has been identified as a key indicator of declining soil quality and land productivity (FAO, 2021). Several recent studies highlight that land degradation cannot be evaluated using a single indicator. Instead, it requires a multi-factor approach incorporating soil characteristics, topography, land cover, climate variables, and human interventions (Singh et al., 2023). This multidimensional nature underscores the need for spatially integrated assessment methods capable of capturing complex interactions across landscapes.

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GIS-Based Approaches for Land Vulnerability Mapping

Geographic Information Systems (GIS) have become widely used in land degradation studies due to their ability to integrate, analyze, and visualize spatial data from multiple sources. GIS-based vulnerability mapping typically employs multi-criteria decision analysis (MCDA) techniques, such as weighted overlay, analytic hierarchy process (AHP), or fuzzy logic, to assess degradation susceptibility (Chen et al., 2021). These methods allow researchers to assign relative importance to different environmental factors based on expert judgment or statistical analysis. Recent research demonstrates the effectiveness of GIS-based models in identifying high-risk degradation zones. For instance, Singh et al. (2023) successfully applied a GIS–AHP approach to map land degradation vulnerability, revealing that slope, land use, and soil texture were the most influential factors. Similarly, Pourghasemi et al. (2020) showed that integrating remote sensing data with GIS significantly improves the accuracy of land degradation assessments by providing up-to-date land cover and vegetation condition information.

Geographic Information System (GIS)-based approaches have become essential tools for mapping land vulnerability to degradation due to their ability to integrate, analyze, and visualize spatial data from multiple sources. GIS enables the combination of biophysical, climatic, and socio-economic variables to assess land vulnerability in a comprehensive and spatially explicit manner, which is critical for effective land-use planning and sustainable land management (Chen et al., 2021). One of the most commonly used GIS-based techniques for land vulnerability mapping is multi-criteria decision analysis (MCDA). This approach integrates various indicators such as slope, soil texture, rainfall intensity, land cover, and land use by assigning weights based on their relative importance in contributing to land degradation. Methods such as the Analytical Hierarchy Process (AHP) and Weighted Overlay Analysis are widely applied to produce vulnerability indices and classify land into different vulnerability levels (low, moderate, high, and very high) (Saaty, 2020; Rahman et al., 2022).

Remote sensing data play a critical role in GIS-based vulnerability assessments by providing up-to-date and spatially consistent information on land cover, vegetation condition, and surface changes. Satellite-derived indices, such as the Normalized Difference Vegetation Index (NDVI) and Land Degradation Index (LDI), are frequently used to detect degradation trends and support vulnerability mapping in tropical regions (Singh et al., 2023). The integration of remote sensing and GIS enhances the accuracy and temporal resolution of vulnerability assessments. Recent advances in GIS-based approaches also incorporate machine learning models, such as Random Forest, Support Vector Machines, and Artificial Neural Networks, to improve the prediction of land degradation vulnerability. These data-driven models can handle complex non-linear relationships between degradation drivers and have demonstrated higher predictive performance compared to conventional statistical methods (Li et al., 2021; Zhang et al., 2024). Overall, GIS-based land vulnerability mapping provides a robust scientific basis for identifying degradation-prone areas, prioritizing conservation efforts, and supporting evidence-based decision-making. By integrating spatial analysis, remote sensing, and advanced modeling techniques, GIS-based approaches contribute significantly to sustainable land management strategies, particularly in tropical agricultural landscapes that are highly susceptible to land degradation (FAO, 2021).

Application of Remote Sensing in Land Degradation Assessment

Remote sensing data, such as satellite-derived vegetation indices and land cover classifications, play a crucial role in modern land degradation studies. Vegetation indices like the Normalized Difference Vegetation Index (NDVI) are widely used to evaluate vegetation health and land surface conditions (Xue & Su, 2021). Declining NDVI values are often associated with increased degradation and reduced land resilience. Recent studies indicate that combining remote sensing with GIS enhances the temporal and spatial resolution of degradation analysis, enabling the monitoring of land condition changes over time (IPBES, 2022). This integration supports data-driven decision-making and allows policymakers to evaluate the effectiveness of land restoration and conservation initiatives.

Remote sensing has become a critical tool in land degradation assessment due to its capability to provide continuous, spatially extensive, and temporally consistent data. Satellite imagery enables the monitoring of land surface changes, vegetation dynamics, and soil conditions, which are essential indicators of land degradation processes, particularly in tropical and semi-arid regions (Gibbs et al., 2021). One of the most widely applied remote sensing techniques in land degradation studies is the use of vegetation indices, such as the Normalized Difference Vegetation Index (NDVI), Enhanced Vegetation Index (EVI), and Soil Adjusted Vegetation Index (SAVI). These indices are effective proxies for vegetation health, biomass, and land productivity, allowing researchers to detect early signs of degradation caused by deforestation, overgrazing, and unsustainable agricultural practices (Fensholt et al., 2020; Zhu et al., 2022).

Remote sensing also supports the assessment of soil-related degradation indicators, including soil erosion, moisture stress, and surface roughness. High-resolution optical and radar data such as those from Sentinel-2 and Sentinel-1 enable the identification of erosion-prone areas, bare soil exposure, and changes in land surface characteristics. Synthetic Aperture Radar (SAR) is particularly valuable in tropical regions due to its ability to penetrate cloud cover and provide reliable information on soil moisture and surface conditions (Hosseini et al., 2021). Recent advancements in remote sensing-based land degradation assessment increasingly integrate time-series analysisand machine learning techniques.

Time-series datasets allow the detection of long-term degradation trends and differentiation between temporary disturbances and permanent land degradation. Machine learning algorithms, such as Random Forest and Gradient Boosting, enhance classification accuracy and improve the prediction of degradation severity by capturing complex interactions among environmental variables (Rodriguez-Galiano et al., 2021; Xie et al., 2023).

Overall, the application of remote sensing in land degradation assessment provides a cost-effective and scientifically robust approach for large-scale monitoring, early warning systems, and policy evaluation. When combined with GIS and field observations, remote sensing significantly enhances the reliability of land degradation assessments and supports sustainable land management and restoration planning (FAO & UNEP, 2021).

Research Gaps and Study Contribution

Despite the growing body of literature on GIS-based land degradation assessment, several gaps remain. Many existing studies focus on national or regional scales, limiting their applicability for local land management planning. Additionally, some studies rely heavily on quantitative models without adequately addressing the integration of multiple environmental indicators within a unified vulnerability framework (Chen et al., 2021). There is also a lack of localized vulnerability mapping in tropical agricultural areas, where degradation dynamics are highly site-specific. This study addresses these gaps by applying a GIS-based multi-criteria analysis to map land vulnerability to degradation at a detailed spatial scale. By integrating key environmental and land-use indicators, the research aims to provide comprehensive spatial insights that support sustainable land management and targeted restoration strategies.

3. Method

This study employed a quantitative–spatial research design integrating remote sensing, Geographic Information Systems (GIS), and multi-criteria analysis to assess land degradation vulnerability. The approach allows for the systematic evaluation of biophysical factors influencing land degradation and their spatial interactions across the study area. The study was conducted in a tropical agricultural region characterized by intensive land use, variable topography, and seasonal rainfall patterns. The area is particularly vulnerable to land degradation due to agricultural expansion, deforestation, and soil erosion processes. Administrative boundaries were used as spatial references for analysis and mapping.

Table 1. Study Utilized Multi-Source Spatial and Non-spatial Data

Data Type	Dataset	Spatial Resolution	Source
Satellite imagery	Sentinel-2 MSI	10–20 m	ESA (Copernicus)
Radar data	Sentinel-1 SAR	10 m	ESA (Copernicus)
Digital Elevation Model	SRTM DEM	30 m	USGS
Rainfall data	CHIRPS	5 km	Climate Hazards Group
Soil data	Soil texture & organic carbon	–	FAO SoilGrids
Land use/land cover	LULC map	10 m	Classified from Sentinel-2

Satellite imagery was preprocessed using atmospheric correction and cloud masking techniques. Vegetation and land condition indicators were derived, including:

a. Normalized Difference Vegetation Index (NDVI)
b. Soil Adjusted Vegetation Index (SAVI)
c. Bare Soil Index (BSI)

Radar-based soil moisture proxies were extracted from Sentinel-1 SAR data to support erosion and land degradation assessment. GIS spatial analysis was applied to generate thematic layers representing key land degradation factors:

a. Slope gradient (derived from DEM)
b. Rainfall erosivity
c. Land cover change
d. Soil erodibility
e. Vegetation condition

All spatial datasets were resampled to a common resolution and standardized using a normalization technique to ensure comparability. A Multi-Criteria Decision Analysis (MCDA) approach using the Analytical Hierarchy Process (AHP) was applied to assign weights to each degradation factor. Expert judgment and literature references were used to determine relative importance. The Land Degradation Vulnerability Index (LDVI) was calculated using a weighted overlay model:

$$LDVI=\sum(Wi\times Xi)$$

Where WiWi represents the weight of each factor and XiXi denotes the normalized factor value. The resulting LDVI map was classified into five vulnerability categories: very low, low, moderate, high, and very high, using the natural breaks (Jenks) classification method. Validation was conducted through comparison with field observations, secondary land degradation reports, and high-resolution imagery. Statistical accuracy was evaluated using correlation analysis and consistency checks between observed degradation indicators and modeled vulnerability levels. Data processing and spatial analysis were conducted using ArcGIS, QGIS, and Google Earth Engine (GEE), while statistical analysis was performed using SPSS and Python-based libraries.

4. Result

Spatial Distribution of Land Degradation Vulnerability

The GIS-based analysis produced a Land Degradation Vulnerability Index (LDVI) map that illustrates the spatial variation of land degradation risk across the study area. The results indicate that land degradation vulnerability is not uniformly distributed but exhibits clear spatial patterns influenced by topography, land use, vegetation cover, and rainfall intensity. The LDVI classification divided the study area into five vulnerability classes: very low, low, moderate, high, and very high. Areas categorized as high to very high vulnerability are predominantly concentrated in regions with steep slopes, sparse vegetation cover, and intensive agricultural activities. In contrast, low vulnerability zones are generally associated with flat terrain, dense vegetation cover, and relatively stable land use patterns.

Table 2. Parameters Determining Land Degradation Vulnerability

No	Parameter	Data Source	Class / Criteria	Score
1	Slope Gradient (%)	DEM (SRTM 30 m)	< 8% (Flat)	1
			8–15% (Gentle)	2
			15–25% (Moderately Steep)	3
			> 25% (Steep)	4
2	Land Use/Land Cover (LULC)	Sentinel-2 (2024)	Forest	1
			Plantation	2
			Open Agricultural Land	3
			Settlement / Bare Land	4
3	NDVI	Sentinel-2	> 0.6 (High Vegetation Density)	1

No	Parameter	Data Source	Class / Criteria	Score
			0.4–0.6	2
			0.2–0.4	3
			< 0.2 (Low Vegetation Density)	4
4	Annual Rainfall (mm/year)	CHIRPS	< 1,500	1
			1,500–2,000	2
			2,000–2,500	3
			> 2,500	4
5	Soil Type	National Soil Map	Clay	1
			Loam	2
			Sandy Loam	3
			Sand	4

The line chart illustrates the temporal trend of land degradation vulnerability from 2020 to 2024. The results indicate a consistent upward trend in vulnerability levels over the observed period. This increase reflects the growing pressure on land resources caused by intensive agricultural activities, land-use changes, and insufficient soil conservation practices. The gradual rise after 2022 suggests that environmental stressors such as soil erosion, declining vegetation cover, and reduced soil organic matter have intensified in recent years. These findings highlight the urgency of implementing sustainable land management strategies to mitigate further degradation, particularly in vulnerable tropical landscapes.

The pie chart presents the proportional distribution of land vulnerability classes, categorized as low, moderate, high, and very high vulnerability. The results show that moderate to high vulnerability areas dominate the study region, indicating that a significant portion of land is already under degradation risk. Areas classified as high and very high vulnerability are typically associated with steep slopes, sparse vegetation cover, and intensive land exploitation. In contrast, areas with low vulnerability are relatively limited and are generally characterized by better land cover management and lower erosion risk.

Contribution of Degradation Factors

The weighted overlay analysis revealed that slope gradient, land use/land cover change, and vegetation condition (NDVI) were the most influential factors contributing to land degradation vulnerability. Areas with slopes exceeding critical thresholds showed significantly higher vulnerability values, indicating increased susceptibility to soil erosion processes. Vegetation indices derived from Sentinel-2 imagery demonstrated that regions with consistently low NDVI values corresponded closely with areas classified as highly vulnerable. This finding suggests that reduced vegetation cover plays a crucial role in accelerating soil degradation in tropical agricultural landscapes.

Table 3. Weights of Land Degradation Vulnerability Parameters

Parameter	Weight
Slope Gradient	0.30
Land Use/Land Cover	0.25
NDVI	0.20
Rainfall	0.15
Soil Type	0.10
Total	1.00

Land use and land cover (LULC) analysis showed a noticeable expansion of agricultural land and built-up areas at the expense of natural vegetation. Regions experiencing rapid land cover change exhibited elevated vulnerability scores, particularly where agricultural practices were conducted without adequate soil conservation measures. Temporal analysis of vegetation indicators further revealed seasonal fluctuations, with vegetation stress intensifying during dry periods. These temporal variations contributed to increased vulnerability levels, especially in rainfed agricultural zones where soil protection is highly dependent on vegetation cover.

Rainfall and Soil Erodibility Effects

Rainfall erosivity data indicated that areas receiving high-intensity rainfall were strongly associated with increased land degradation vulnerability, particularly when combined with erodible soil types. Soil texture analysis showed that regions dominated by sandy loam and silty soils exhibited higher vulnerability compared to areas with more cohesive soil structures. The interaction between rainfall intensity and soil erodibility significantly amplified degradation risk, highlighting the importance of integrated land and water management strategies in vulnerable zones.

Table 4. Relationship Between NDVI and Land Degradation Vulnerability Index (LDVI)

NDVI Category	Average LDVI	Vulnerability Level
> 0.6	1.35	Very Low
0.4 – 0.6	1.88	Low
0.2 – 0.4	2.47	Moderate
< 0.2	3.12	High – Very High

Validation using field observations and secondary land degradation reports showed a strong agreement with the model vulnerability map. Areas identified as highly vulnerable corresponded with observed signs of erosion, land productivity decline, and surface runoff concentration. Correlation analysis between LDVI values and observed degradation indicators indicated a high level of consistency, confirming the reliability of the proposed GIS-based approach.

5. Conclusion

This study demonstrates that land degradation vulnerability in the study area varies spatially and is strongly influenced by topographic, vegetation, climatic, and soil characteristics. The GIS-based weighted overlay approach effectively integrated slope gradient, land use/land cover, NDVI, rainfall, and soil type to generate the Land Degradation Vulnerability Index (LDVI), providing a comprehensive and spatially explicit assessment. The results indicate that areas classified as moderate vulnerability dominate the region (29.7%), followed by low(22.9%) and high vulnerability classes (19.3%). Approximately 9.9% of the total area falls under very high vulnerability, primarily associated with steep slopes, sparse vegetation cover, intensive land use, and unfavorable soil conditions. In contrast, areas with dense vegetation cover (NDVI > 0.6) exhibit very low vulnerability, confirming the critical role of vegetation in reducing land degradation risk. A clear inverse relationship between NDVI and LDVI was observed, where decreasing vegetation density corresponded to increasing land degradation vulnerability. This finding highlights the importance of vegetation management, reforestation, and sustainable land use practices in mitigating soil degradation processes. Overall, the GIS-based land degradation vulnerability mapping provides valuable insights for spatial planning and environmental management. The generated vulnerability map can serve as a decision-support tool for local governments and stakeholders to prioritize conservation efforts, implement targeted land rehabilitation programs, and promote sustainable land management strategies, particularly in areas with high and very high vulnerability levels.

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