



Evaluating the Accuracy of Soil Degradation Assessment Using OBIA and Sentinel-2A Imagery: A Case Study of the Tirtomoyo Sub-Watershed

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ABSTRACT

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accuracy assessment, Bengawan Solo watershed, Object-Based Image Analysis (OBIA), remote sensing, T-test, Sentinel-2A, soil degradation status

Soil degradation significantly affects land productivity and the sustainability of natural resources, particularly in watershed areas. This research aims to estimate and identify the level of soil degradation in the Tirtomoyo Sub-Watershed, assess its accuracy, and provide improvement recommendations based on key determining factors. The research was conducted in the districts of Wonogiri (Central Java) and Pacitan (East Java) using the Object-Based Image Analysis (OBIA) method with Sentinel-2A imagery, combined with a scoring system and exploratory descriptive analysis. Analysis of 45 samples was conducted using ANOVA to determine the effect of sources of diversity on factors determining soil degradation, DMRT to determine the average value of sources of diversity, correlation to determine the relationship between parameters and soil degradation, and the main method, the T-test, was used to evaluate the accuracy between soil degradation estimation (SDE) and soil degradation status (SDS). The results indicated that the estimated soil degradation in the sub-watershed area falls into three categories: DE I (Very Low Degradation Estimation) covering 2,959 hectares, DE II (Low Degradation Estimation) covering 5,091 hectares, and DE III (Moderate Degradation Estimation) covering 10,630 hectares, with porosity identified as the primary contributing factor. The actual status of soil degradation is categorized into DI (Light Degradation) covering 17,256 hectares and DII (Moderate Degradation) covering 1,424 hectares, with bulk density being the primary determining factor. Recommendations for mitigating soil degradation include the application of organic fertilizers, the cultivation of cover crops, and the implementation of conservation tillage. The T-test results showed no significant difference between the SDE and SDS, showing $T\text{-Value} < T\text{-Table}$ ($1.15 < 1.67$) with $P\text{-Value} > 0.05$, meaning that the two are not significantly different, so the OBIA method is accurate in mapping land use to estimate soil damage without having to take an actual approach.

1. INTRODUCTION

Soil is one of the most complex [1] and heterogeneous natural resources essential for human life [2]. Soil characteristics vary in mountainous regions, karst areas, and watershed zones. Soil conditions support biomass production; when these conditions fall below a certain threshold, the soil is degraded [3]. Soil degradation commonly occurs in areas with complex topography, such as watersheds. Soil degradation is mainly caused by soil management practices and land use [4]. Soil degradation can be observed through physical, chemical, and biological properties. For example, soil degradation due to erosion and continuous cultivation increases the likelihood that the soil cannot produce optimally, reducing agricultural sector output [5]. Degraded soil undergoes a decline in function and food production quality, which impacts human survival and various other organisms [6].

A watershed is a land area topographically bounded by mountain ridges and can collect rainwater [7]. The watershed

area also plays a role in draining water to be widely utilized [8]. One of the largest watersheds in Java is the Bengawan Solo watershed, which has many sub-watersheds. Tirtomoyo Sub-Watershed is a sub-watershed of the Upper Bengawan Solo 3 watershed, which empties into the Gajah Mungkur Reservoir in Wonogiri. Tirtomoyo Sub-Watershed has an undulating topography and a fairly steep slope. Factors that can trigger various types of land degradation are erosion and landslides. The Wonogiri District Government recorded landslides and floods at the end of 2007 in the Tirtomoyo Sub-district due to the rainy season at the end of the year, and 14 people died due to these natural disasters. These landslides indicate the region's vulnerability to such events [9]. Degradation in the sub-watershed area requires mitigation efforts to achieve ecosystem sustainability [10] and enhance the sustainable utilization of natural resources for human benefit, particularly in the agricultural sector [11]. Degradation mitigation can be done by mapping the affected areas through soil degradation estimation (SDE) and determining soil degradation status (SDS). SDE and SDS

serve to identify the level of soil degradation and the parameters that contribute to the degradation [12].

The soil degradation method used in this research is the OBIA-based analysis method with Sentinel-2A satellite imagery and weighting, and the Exploratory Descriptive Method through a field survey approach. OBIA not only considers the spectral aspects but also the spatial characteristics of the object [13]. The results of satellite image extraction using OBIA provide object-based classification to calculate the conversion of agricultural land to more precise built-up land. The OBIA approach reduces spurious changes caused by high spectral variability in high-resolution spatial imagery, such as Sentinel-2A imagery [14]. A three-year research on OBIA to determine soil damage was conducted in 2023, mapping soil damage using the OBIA method but using Sentinel-2B satellite imagery in the Lawu mountain slope area, producing damage estimation data that showed that slope and land use variables had a significant effect on the level of soil damage, but accuracy testing against field conditions had not yet been carried out [15]. A study in 2019 using OBIA on Landsat 8 imagery successfully mapped the earthquake-affected area in Palu City with a wide coverage area but limited spatial detail due to a 30-meter resolution, whereas Sentinel-2A has a 10-meter resolution, potentially producing more detailed damage maps capable of accurately identifying small-scale changes. Sentinel-2A also has more spectral bands in the visible, near-infrared (NIR), and shortwave infrared (SWIR) regions with narrower band widths, enabling it to distinguish land cover types or damage levels with better spectral contrast.

This research aims to map the estimation and actual status of soil degradation, as well as to test the accuracy of soil degradation estimation using Sentinel-2A satellite imagery compared to degradation status obtained through field surveys

and laboratory analysis, to determine the accuracy and effectiveness of the OBIA method relative to actual results. The results obtained from this study are intended to produce maps of the distribution of SDE and SDS in the Tirtomoyo Sub-Watershed area, based on the OBIA method using Sentinel-2A satellite imagery, which can serve as a guide for formulating recommendations to address and prevent soil Degradation in the Tirtomoyo Sub-Watershed area. This research can also be used as a reference for future studies related to the application of the OBIA method, the utilization of Sentinel-2A satellite imagery, and land resource management.

2. METHODOLOGY

2.1 Research location

This research was conducted in the Tirtomoyo Sub-Watershed, Wonogiri Regency, Central Java Province. The Tirtomoyo Sub-Watershed is astronomically located between 7°54'00" N–S to 7°59'30" N–S and 111°03'00" E to 111°12'30" E. The Tirtomoyo Sub-Watershed is situated in the southeastern part of Wonogiri Regency and is dominated by hilly to undulating topographic conditions. The elevation ranges from 200 to 700 meters above sea level [16]. These geographical conditions significantly influence the hydrological and land use characteristics of the sub-watershed area [17]. The Tirtomoyo Sub-Watershed covers an area of 21,669 hectares. It spans across 10 sub-watersheds, which are distributed within Wonogiri Regency, Central Java Province, Baturetno, Batuwarno, Jatiroto, Karangtengah, Kismantoro, Ngadirojo, Nguntoronadi, Sidoarjo, Tirtomoyo, and Nawangan in Pacitan Regency, East Java.

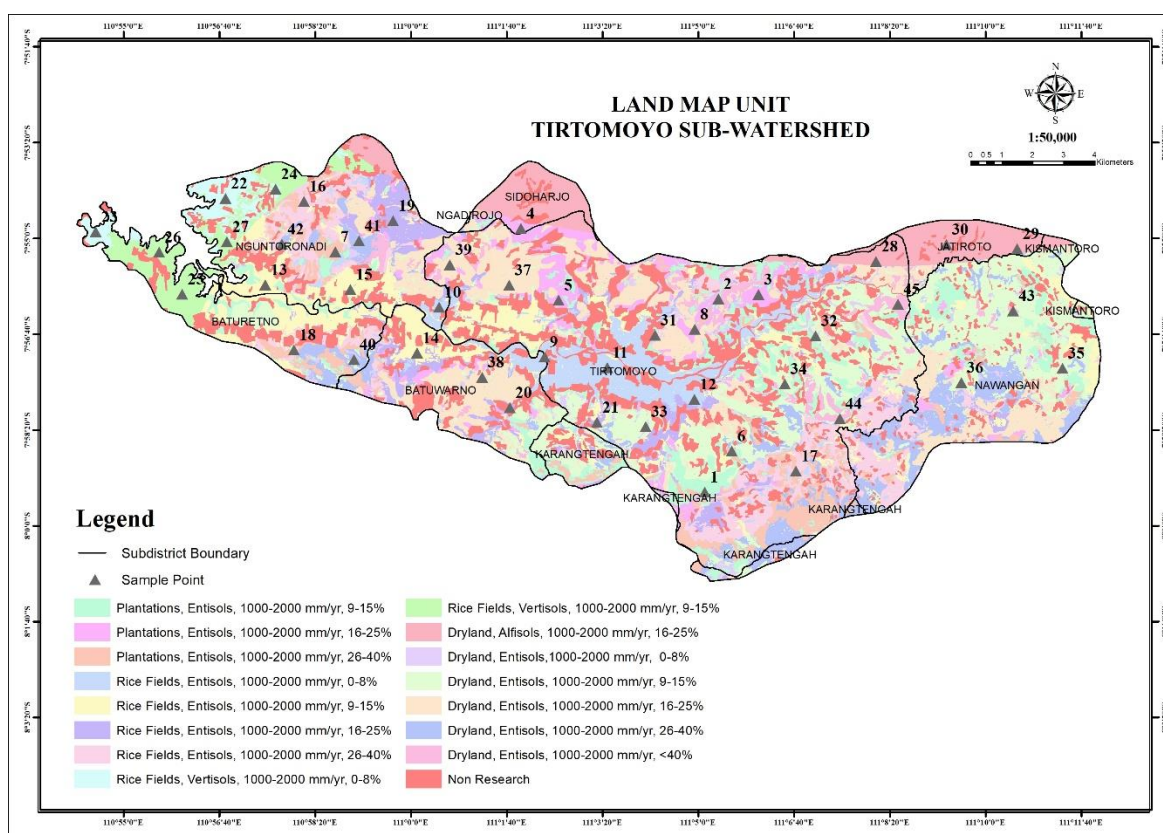


Figure 1. Land map unit of the Tirtomoyo Sub-Watershed area

2.2 Data collection and soil sampling

Materials used in research activities include land maps unit (LMU) processed from Sentinel-2A imagery, topographic maps processed from DEM data, rainfall, and soil types. Soil sample analysis in the laboratory, based on parameters in the standard criteria for soil damage in Government Regulation of the Republic of Indonesia Number 150 of 2000. Based on the Minister of Environment Regulation No. 7 of 2006, soil parameters measured to determine the status of soil degradation include soil physical properties consisting of texture (pipette method), bulk density (ring method), particle density (pycnometer), and porosity (ratio of bulk density and particle density).

2.3 Map of land unit

A land use map is created to determine SDE by retrieving image data in Google Earth Engine. Sentinel-2A satellite images were obtained through the Google Earth Engine platform on 24 November 2024 with maximum cloud cover <10% and then processed using ArcGIS through atmospheric correction, object segmentation, and image classification using the Support Vector Machine (SVM) method. This study utilized Sentinel-2A imagery with a spatial resolution of 10 m for visible and near-infrared bands, and 20 m for red-edge and shortwave infrared bands. Atmospheric correction aims to remove atmospheric disturbances such as water vapor, dust, and clouds using the Dark Object Subtraction (DOS) method [18]. Object segmentation was performed using a scale of 10–20, a region growing segmentation algorithm with a small spectral threshold, a shape of 0.10–0.20, a compactness of 0.4–0.6, and a minimum segment area of 1–2 pixels. Classification was carried out using Normalized Difference Vegetation Index (NDVI) analysis, which separates areas based on color to

indicate the presence of vegetation, bare land, settlements, rice fields, drylands, and water bodies [19]. Image classification employed the Support Vector Machine (SVM) algorithm to distinguish land cover classes in the image [20]. NDVI analysis combined Band 8 and Band 4 raster data to differentiate areas based on vegetation presence.

The land maps unit used to determine the status of soil degradation is the Indonesian landform map. The map is then overlaid with the soil type, rainfall, and slope maps, and produces a land unit map. Work map in 15 land map units for SDE and SDS with 3 replications, so that 45 sample points are obtained that represent the entire research area (Figure 1). The results of the OBIA method land use map analysis with the Indonesian landform map have similarities at 45 sample points, consisting of plantations, rice fields, and drylands, to use one LMU to determine SDE and SDS.

2.4 Data analysis

2.4.1 Determination of soil degradation estimation

SDE is carried out using a scoring approach based on several sources of variability that have been processed using the OBIA method with Sentinel-2A satellite imagery. The total area and proportion for each land map unit are shown in Table 1. Secondary data used to determine the level of soil degradation include land use (Table 2), slope (Table 3), rainfall (Table 4), and soil type (Table 5). Scoring and weighting are applied to determine the soil degradation class of an area (Table 6), based on the contributing factors [21]. The weighted score is obtained by multiplying each parameter's weight by its rating. This calculation aims to provide an overview of soil conditions and to support the design of appropriate management strategies according to the level of degradation observed [22].

Table 1. Proportion of land map unit (LMU) area

LMU	Area (ha)	Proportion (%)
1	1,107	6.5%
2	944	5.5%
3	1,078	6.3%
4	421	2.5%
5	1,874	10.9%
6	257	1.5%
7	1,100	6.4%
8	848	4.9%
9	1,329	7.8%
10	2,906	17.1%
11	274	1.6%
12	456	2.6%
13	2,634	15.5%
14	1,412	8.3%
15	441	2.6%

Table 2. Land use score for soil degradation estimation (SDE)

Land Use	Classification	Weight	Rating	Score
Natural forest, Rice fields, Reeds	Very low	2	1	2
Mixed plantations, Shrubs, Grasslands	Low	2	2	4
Production forests, Plantations	Moderate	2	3	6
Dryland (annual crops)	High	2	4	8
Bare Land	Very High	2	5	10

Source: Technical guidelines for the preparation of Soil Degradation Status Maps for biomass production (2009)

Table 3. Slope score for soil degradation estimation (SDE)

Slope (%)	Classification	Weight	Rating	Score
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

Source: Technical guidelines for the preparation of Soil Degradation Status Maps for biomass production (2009)

Table 4. Rainfall score for soil degradation estimation (SDE)

Rain Fall (mm/year)	Classification	Weight	Rating	Score
<1000	Very Dry	1	1	1
1000-1500	Dry	1	2	2
1501-2000	Moderate/Moist	1	3	3
2001-2500	Wet	1	4	4
>2500	Very Wet	1	5	5

Source: Technical guidelines for the preparation of Soil Degradation Status Maps for biomass production (2009)

Table 5. Soil type score for soil degradation estimation (SDE)

Soil Type	Classification	Weight	Rating	Score
Vertisols	Very low	2	1	2
Oxisols	Low	2	2	4
Alfisols, Mollisols, Ultisols	Moderate	2	3	6
Entisols, Histosols, Inceptisols	High	2	4	8
Andisols, Spodosols	Very High	2	5	10

Source: Technical guidelines for the preparation of Soil Degradation Status Maps for biomass production (2009)

Table 6. SDE classification

Symbol	Soil Degradation Potential	Weighting Score
DE 1	Very low	<15
DE 2	Low	15-24
DE 3	Moderate	25-34
DE 4	High	35-44
DE 5	Very High	>45

Source: Technical guidelines for the preparation of Soil Degradation Status Maps for biomass production (2009)

Table 7. Physical parameters of soil degradation status (SDS)

Soil Parameters	Critical Threshold
Solum Thickness	< 20 cm
Texture	< 18% colloidal; > 80% quartzitic sand
Bulk Density (BD)	> 1.4 g/cm ³
Porosity	< 30%; > 70%

Source: Government Regulation of the Republic of Indonesia Number 150 (2000)

Table 8. Soil degradation score based on relative frequency

Relative Frequency of Soil Degradation (%)	Score	SDS
0-10	0	Not Degraded
11-25	1	Slightly Degraded
26-50	2	Moderately Degraded
51-75	3	Severely Degraded
76-100	4	Extremely Degraded

Source: Technical guidelines for the preparation of Soil Degradation Status Maps for biomass production (2009)

Table 9. SDS based on accumulated soil relative frequency scores

Symbol	Accumulated Score Value	SDS
N	0	Not Degraded
D1	1-14	Slightly Degraded
D2	15-24	Moderately Degraded
D3	25-34	Severely Degraded
D4	35-40	Extremely Degraded

Source: Technical guidelines for the preparation of Soil Degradation Status Maps for biomass production (2009)

2.4.2 Determination of soil degradation status

Data were obtained from the analysis of soil samples in the laboratory. Identification and estimation of soil degradation factors were assessed and classified using quantitative analysis methods with matching and scoring approaches. Matching is performed by comparing the measured soil degradation data in the field with predetermined standard criteria. Scoring involves assigning a score to each soil parameter, which is then accumulated to determine SDS classification. Table 7 presents the critical thresholds for the physical parameters of soil degradation. The results of the sample analysis based on physical parameters were matched. Then the relative frequency score was calculated using the data in Table 8, followed by a weighting stage based on Table 9 to accumulate the relative frequency score.

2.4.3 Data analysis and accuracy level determination

An analysis of Variance (ANOVA) test was conducted to determine the effect of the source of diversity on the estimation and status of soil degradation, and the impact of soil parameters on the source of diversity on soil degradation parameters. A further test with Duncan was conducted to determine if the analysis results showed a significant effect. Correlation analysis determined the relationship between

parameters and soil degradation status. A T-test was used to compare the SDE and SDS.

3. RESULTS AND DISCUSSION

3.1 Soil degradation estimation

Figure 2 and Figure 3 present the classification of potential soil degradation into three distinct categories: DE I (Very Low Degradation Estimation), DE II (Low Degradation Estimation), and DE III (Moderate Degradation Estimation). This classification is based on a composite scoring system derived from multiple biophysical indicators, such as land use type, slope gradient, soil texture, rainfall intensity, and vegetative cover. Land units with a cumulative score of less than 15 are categorized as DE I, indicating minimal risk of degradation under current land management practices (Table 10). Units scoring between 15 to 24 fall under DE II, representing areas where degradation processes may initiate under persistent pressure, while those scoring between 25 and 34 are categorized as DE III, suggesting active degradation processes requiring urgent mitigation.

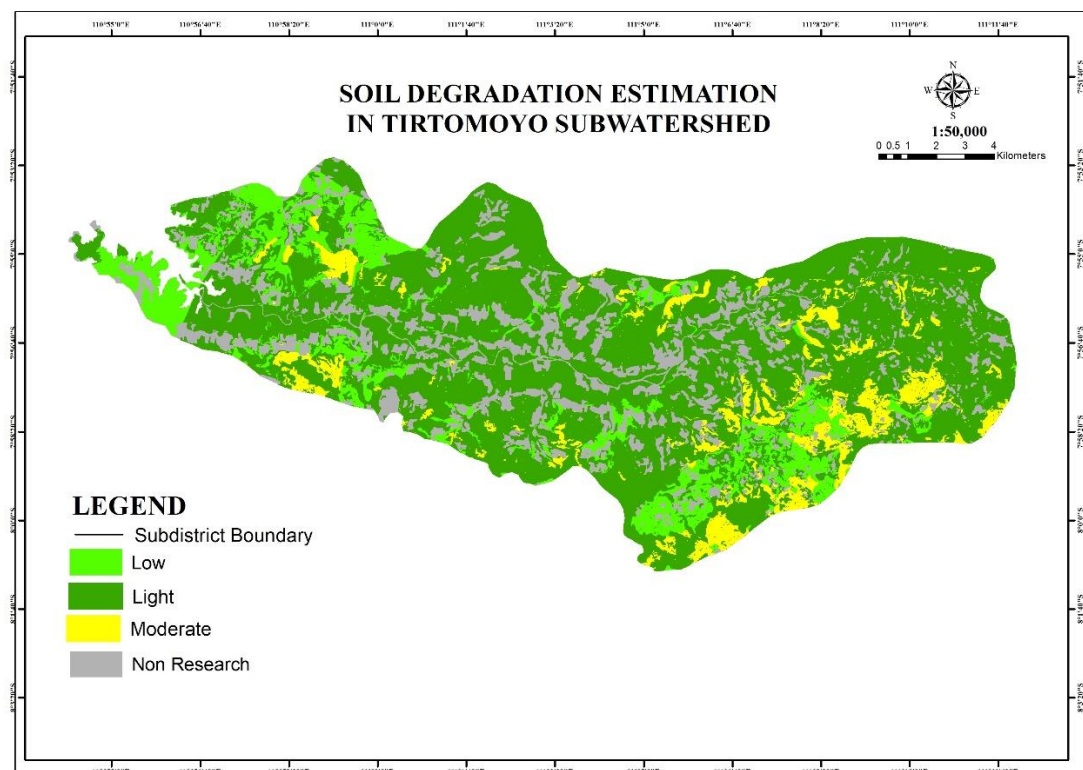


Figure 2. Soil degradation estimation in the Tirtomoyo Sub-Watershed

The scoring reflects how different land characteristics interact with environmental forces. For instance, steep slopes (>15%) significantly increase runoff velocity and erosion potential, particularly when vegetative cover is sparse or replaced by row crops or plantation systems with low canopy closure [23]. Similarly, regions with high annual rainfall (more than 2,000 mm) experience greater kinetic energy of raindrop impact, which accelerates soil detachment, especially on unprotected surfaces [24]. These conditions are exacerbated in dryland and plantation areas where the natural soil structure is often disrupted through tillage or heavy machinery use,

reducing organic matter content and water infiltration capacity. Consequently, these land use types contribute higher weights in the scoring system, reflecting their greater propensity to promote processes such as sheet erosion, rill formation, and nutrient leaching [25].

As depicted in the soil degradation estimation (SDE) map of the Tirtomoyo Sub-Watershed in Figure 4, the spatial distribution of degradation potential is evident across the landscape. Areas with very low degradation estimation (DE I), totaling approximately 2,959 hectares, are generally located on flatter terrain with stable land use practices, such as forested

zones or well-managed agricultural plots. In contrast, zones with low degradation estimation (DE II) cover around 5,091 hectares and are more widely dispersed across sub-district boundaries, indicating intermediate conditions where either topography or land management practices begin to compromise soil stability. Notably, moderate degradation estimation (DE III) dominates the study area, spanning approximately 10,630 hectares. These areas are characterized by a convergence of vulnerable factors—steep slopes, erosive rainfall, and intensive land use—making them priority zones for targeted soil conservation interventions such as contour farming, vegetative buffer strips, and agroforestry systems to restore ecological function and prevent further degradation [26].

The land use composition in the Tirtomoyo Sub-Watershed is dominated by dryland, covering an area of 8,411 ha or 45.1% of the total sub-watershed. This is followed by rice fields, which occupy 6,164 ha (32.9%), and plantations, with a coverage of 4,113 ha (22%). In terms of rainfall distribution, the majority of the area (14,371 ha or 63.6%) receives annual precipitation of less than 1,000 mm, while the remaining 8,217 ha (36.4%) falls within the 1,000–1,500 mm range. This variation in land use and rainfall patterns is an important factor influencing soil degradation processes in the study area. The slope distribution in the Tirtomoyo Sub-Watershed shows a predominance of moderately steep terrains, with slopes of 16–25% covering 6,178 ha (27.3%) and slopes of 26–40% occupying 6,066 ha (26.8%). Steeper slopes above 40% account for 4,435 ha (19.8%), while gentle slopes of 9–15% and 0–8% comprise 4,010 ha (17.7%) and 1,895 ha (8.4%),

respectively. In terms of soil types, Entisols dominate the area with 19,982 ha (88.4%), followed by Alfisols at 1,344 ha (6%) and Vertisols at 1,260 ha (5.6%). This combination of varied slope classes and diverse soil types provides a wide range of opportunities for implementing site-specific land management practices. The presence of different slope gradients and soil characteristics enables the application of tailored conservation strategies that can optimize land productivity while maintaining environmental sustainability.

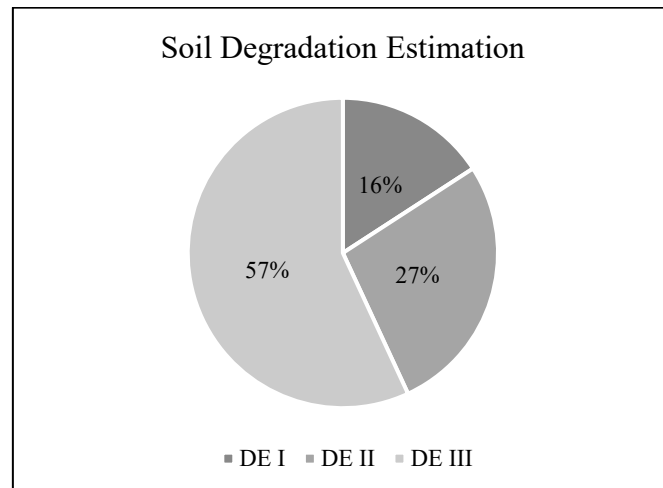


Figure 3. Soil degradation estimation in Tirtomoyo Sub-Watershed

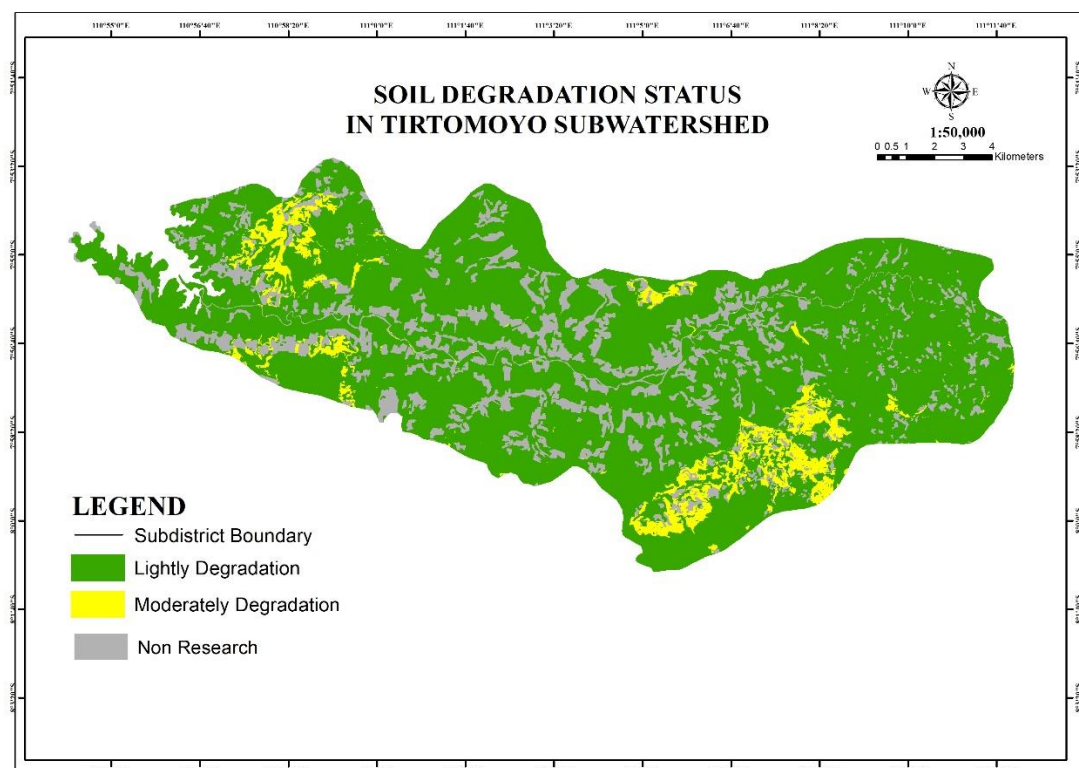


Figure 4. Soil degradation status in the Tirtomoyo Sub-Watershed

3.2 Soil degradation status

Degradation categories can be used for sustainable land management [27]. Based on the results of the scoring calculation of soil degradation in the Tirtomoyo Sub-

Watershed area, Table 11 shows that there are 2 categories of degradation: DI (light degradation), which dominates almost all LMUs except LMU 9, and DII (moderate degradation) [28]. The SDS map of the Tirtomoyo Sub-Watershed in Figure 4 and Figure 5 shows the distribution of areas based on the level

of soil degradation, which is divided into lightly degraded and moderately degraded categories. Lightly degraded areas dominate with 17,256 hectares, spread across most sub-watershed regions, especially in the western and central parts. Moderately degraded areas totaling 1,424 hectares are concentrated in the eastern and southeastern provinces. The SDS maps provide essential information on prioritized areas that require conservation treatment [29], to prevent more severe land degradation in the future [30]. Seasonal factors, including rainfall not significantly affect the actual level of soil degradation (SDS). During the observation period because low rainfall intensity in dry to very dry areas significantly limits water erosion. These drought conditions are still taken into account in the estimation weighting because they have the potential to indirectly reduce soil quality through reduced vegetation cover, increased vulnerability to wind erosion, and soil structure degradation due to reduced moisture. Although its influence is not directly significant, rainfall remains an important factor in predicting long-term soil degradation.

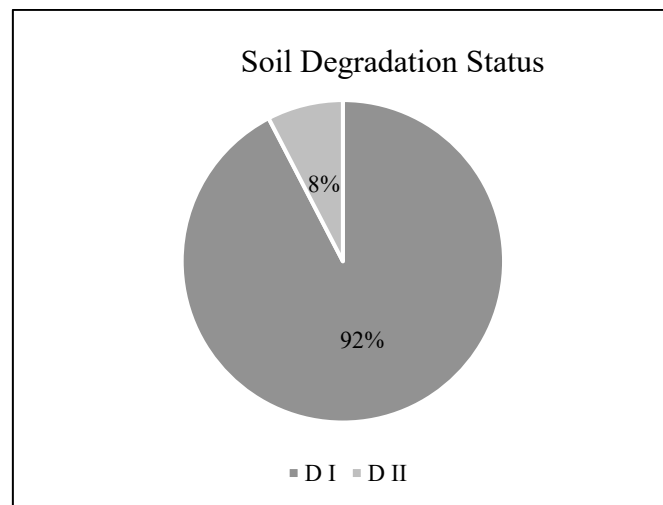


Figure 5. Soil degradation status in Tirtomoyo Sub-Watershed

Table 10. Scoring and weighting of soil degradation estimation in Tirtomoyo Sub-Watershed

LMU	Point	Soil Type	Weighting Score	Slope (%)	Rating × Weighting	Weighting Score	Rainfall (mm.yr ⁻¹)	Weighting Score	Land Use	Weighting Score	Total Weighting Score	Soil Degradation Estimation
1	1	Entisols	8	9-15	2 × 3	6	1,000-1,500	2	Plantation	6	22	DE II
	2	Entisols	8	9-15	2 × 3	6	1,000-1,500	2	Plantation	6	22	DE II
	3	Entisols	8	9-15	2 × 3	6	1,000-1,500	2	Plantation	6	22	DE II
2	1	Entisols	8	16-25	3 × 3	9	1,000-1,500	2	Plantation	6	25	DE III
	2	Entisols	8	16-25	3 × 3	9	1,000-1,500	2	Plantation	6	25	DE III
	3	Entisols	8	16-25	3 × 3	9	1,000-1,500	2	Plantation	6	25	DE III
3	1	Entisols	8	26-40	4 × 3	12	1,000-1,500	2	Plantation	6	28	DE III
	2	Entisols	8	26-40	4 × 3	12	1,000-1,500	2	Plantation	6	28	DE III
	3	Entisols	8	26-40	4 × 3	12	1,000-1,500	2	Plantation	6	28	DE III
4	1	Entisols	8	0-8	1 × 3	3	1,000-1,500	2	Rice fields	2	15	DE I
	2	Entisols	8	0-8	1 × 3	3	1,000-1,500	2	Rice fields	2	15	DE I
	3	Entisols	8	0-8	1 × 3	3	1,000-1,500	2	Rice fields	2	15	DE I
5	1	Entisols	8	9-15	2 × 3	6	1,000-1,500	2	Rice fields	2	18	DE II
	2	Entisols	8	9-15	2 × 3	6	1,000-1,500	2	Rice fields	2	18	DE II
	3	Entisols	8	9-15	2 × 3	6	1,000-1,500	2	Rice fields	2	18	DE II
6	1	Entisols	8	16-25	3 × 3	9	1,000-1,500	2	Rice fields	2	21	DE II
	2	Entisols	8	16-25	3 × 3	9	1,000-1,500	2	Rice fields	2	21	DE II
	3	Entisols	8	16-25	3 × 3	9	1,000-1,500	2	Rice fields	2	21	DE II
7	1	Entisols	8	26-40	4 × 3	12	1,000-1,500	2	Rice fields	2	24	DE II
	2	Entisols	8	26-40	4 × 3	12	1,000-1,500	2	Rice fields	2	24	DE II
	3	Entisols	8	26-40	4 × 3	12	1,000-1,500	2	Rice fields	2	24	DE II
8	1	Vertisols	2	0-8	1 × 3	3	1,000-1,500	2	Rice fields	2	9	DE I
	2	Vertisols	2	0-8	1 × 3	3	1,000-1,500	2	Rice fields	2	9	DE I
	3	Vertisols	2	0-8	1 × 3	3	1,000-1,500	2	Rice fields	2	9	DE I
9	1	Vertisols	2	9-15	2 × 3	6	<1000	3	Rice fields	2	13	DE I
	2	Vertisols	2	9-15	2 × 3	6	<1000	3	Rice fields	2	13	DE I
	3	Vertisols	2	9-15	2 × 3	6	<1000	3	Rice fields	2	13	DE I
10	1	Alfisols	6	16-25	3 × 3	9	1,000-1,500	2	Dryland	8	25	DE III
	2	Alfisols	6	16-25	3 × 3	9	1,000-1,500	2	Dryland	8	25	DE III
	3	Alfisols	6	16-25	3 × 3	9	1,000-1,500	2	Dryland	8	25	DE III
11	1	Entisols	8	0-8	1 × 3	3	1,000-1,500	2	Dryland	8	21	DE II
	2	Entisols	8	0-8	1 × 3	3	1,000-1,500	2	Dryland	8	21	DE II
	3	Entisols	8	0-8	1 × 3	3	1,000-1,500	2	Dryland	8	21	DE II
12	1	Entisols	8	9-15	2 × 3	6	<1,000	3	Dryland	8	25	DE III
	2	Entisols	8	9-15	2 × 3	6	<1,000	3	Dryland	8	25	DE III
	3	Entisols	8	9-15	2 × 3	6	<1,000	3	Dryland	8	25	DE III
13	1	Entisols	8	16-25	3 × 3	9	1,000-1,500	2	Dryland	8	27	DE III
	2	Entisols	8	16-25	3 × 3	9	1,000-1,500	2	Dryland	8	27	DE III
	3	Entisols	8	16-25	3 × 3	9	1,000-1,500	2	Dryland	8	27	DE III
14	1	Entisols	8	26-40	4 × 3	12	1,000-1,500	2	Dryland	8	30	DE III
	2	Entisols	8	26-40	4 × 3	12	1,000-1,500	2	Dryland	8	30	DE III
	3	Entisols	8	26-40	4 × 3	12	1,000-1,500	2	Dryland	8	30	DE III
15	1	Entisols	8	<40	5 × 3	15	<1,000	3	Dryland	8	34	DE III
	2	Entisols	8	<40	5 × 3	15	<1,000	3	Dryland	8	34	DE III
	3	Entisols	8	<40	5 × 3	15	<1,000	3	Dryland	8	34	DE III

Description: LMU = Land Map Unit; DE I = very low degradation estimation; DE II = low degradation estimation; DE III = moderate degradation estimation

3.3 Determinants of soil degradation

3.3.1 Soil degradation estimation

Table 12 presents the significant influence of several sources of variability on SDE. The factors of land use and soil type are at a very high level of significance ($p = 0.000^{**}$), meaning that these factors significantly influence the level of soil degradation. This indicates that the variety of sources of diversity is an essential factor that is proven to affect the level of soil degradation in the Tirtomoyo Sub-Watershed area [31].

The rainfall and slope factors do not affect SDE, with significance values of 0.433 and 0.233. Rainfall is generally considered one of the factors causing soil degradation [32], but the uniformity of rainfall and scores in the study area did not affect soil degradation. This could be due to the homogeneity of rainfall in the Tirtomoyo Sub-Watershed or the dominant influence of other factors such as land use and slope. Figures 6 and 7 present the results of the significant difference in SDE values concerning land use and soil type.

Table 11. Results of the scoring calculation of soil degradation status (SDS) in Tirtomoyo Sub-Watershed area

LMU	Texture		Bulk Density (g.cm ⁻³)	Particle Density (mg.m ⁻³)	Porosity (%)	Total Score	Symbol	Limiting Factors
	Colloidal	Sand						
1	2	0	0	2	4	8	D I	Texture, Particle Density, Porosity
2	0	0	0	0	4	4	D I	Porosity
3	4	0	2	0	4	10	D I	Texture, Bulk Density, Porosity
4	0	0	4	4	3	11	D I	Bulk Density, Particle Density, Porosity
5	0	0	4	4	3	11	D I	Bulk Density, Particle Density, Porosity
6	0	0	4	4	4	12	D I	Bulk Density, Particle Density, Porosity
7	0	0	4	2	4	10	D I	Bulk Density, Particle Density, Porosity
8	0	0	4	2	4	10	D I	Bulk Density, Particle Density, Porosity
9	4	0	4	3	4	15	D II	Texture, Bulk Density, Particle Density, Porosity
10	0	0	3	4	2	9	D I	Bulk Density, Particle Density, Porosity
11	0	0	0	4	2	6	D I	Bulk Density, Particle Density, Porosity
12	2	0	2	4	3	11	D I	Texture, Bulk Density, Particle Density, Porosity
13	0	0	4	4	0	8	D I	Bulk Density, Particle Density
14	0	0	4	4	2	10	D I	Bulk Density, Particle Density, Porosity
15	0	0	4	4	4	12	D I	Bulk Density, Particle Density, Porosity

Description: LMU = Land Map Unit

Table 12. Effect of the source of variance on SDE

Source of Diversity	Soil Degradation Estimation
Land Use	0.000**
Slope	0.233 ^{ns}
Soil Type	0.000**
Rainfall	0.433 ^{ns}

Remark: ^{ns}) = not significant, *) = significant, **) = very significant

Figure 6 shows significant differences in SDE based on land use type. The highest average value of SDE was found in dryland at 27.00c, followed by plantation land at 25.00b, and the lowest in paddy field at 16.66a. Paddy fields differ significantly from plantation and dryland fields, but plantation and dryland fields do not show significant differences. These results indicate that land use has an essential influence on soil degradation. Rice fields experience lower soil degradation compared to plantations and drylands. This difference can be caused by the characteristics of more regular management of paddy fields and the protection from water cover [33]. Plantation and dryland are more exposed to factors that cause soil erosion and degradation [34].

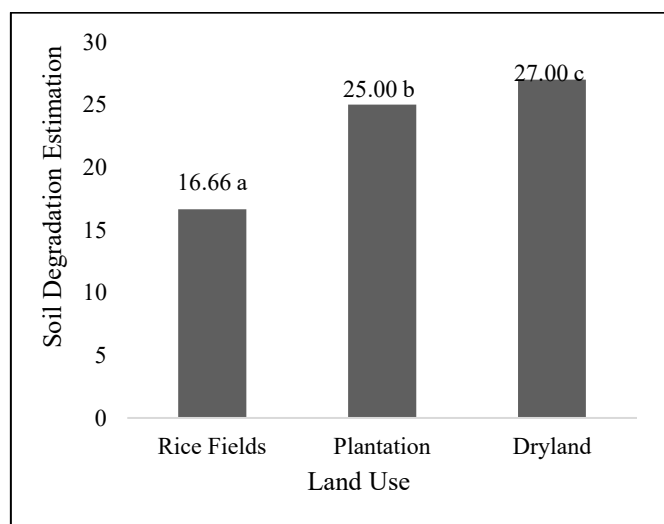
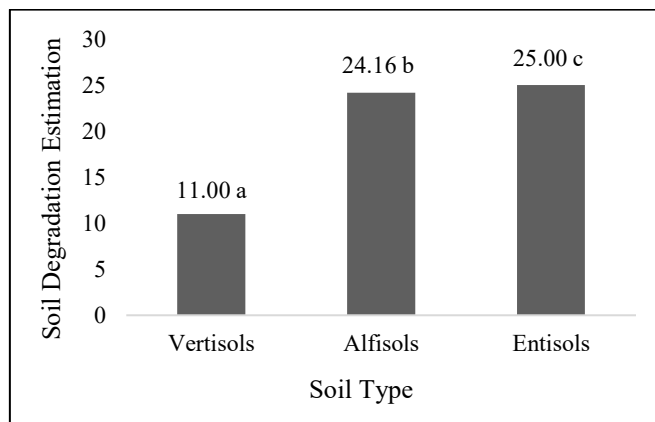
Remark: Different letters indicate significant differences at the 5% α level**Figure 6.** Distribution of SDE under various land useRemark: Different letters indicate significant differences at the 5% α level**Figure 7.** Distribution of SDE under various soil types

Figure 7 shows the significant differences in SDE across the different soil types. Entisols soils had the highest mean SDE of 25.00c, notably different from the other soil types. This shows that soil degradation in Entisols is statistically significantly different from other soil types. Alfisols had an average soil degradation value of 14.16b, and Vertisols showed the lowest SDE value of 11.00a. These results indicate that the characteristics of each soil type play an important role in determining the level of soil degradation [35]. Vertisols, which have a more stable soil structure and good water retention ability [36], experience lower soil degradation. In contrast, Entisols, which are young and have undeveloped soil horizons, tend to be more susceptible to degradation.

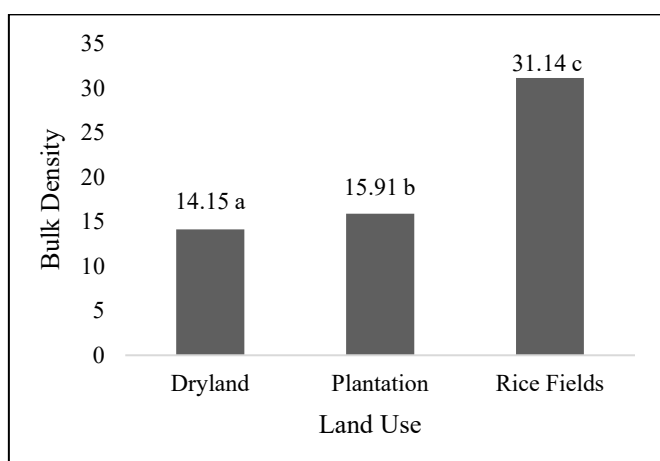
Table 13. Determinants of SDE

Soil Degradation Parameters	SDE
Porosity	-0.384*
Bulk Density	0.111
Particle Density	0.252
Texture	-0.127

Remark: *) = significant, **) = very significant

Soil porosity has a strong relationship with the level of soil degradation, with a correlation coefficient value ($r = -0.384$)

(Table 13). Soils with high porosity can reduce surface runoff and erosion because more water is absorbed into the soil [37]. Soils with low porosity accelerate runoff and increase the potential for soil degradation, especially in sloping areas. Particle Density has a positive correlation value of 0.252, indicating a tendency that the higher the particle density, the greater the estimated soil degradation, although this relationship is not significant. High particle density generally reflects a high content of heavy minerals or soil particle density, which can reduce pore space and decrease infiltration capacity. Bulk density showed a positive correlation of 0.111, meaning that the greater the bulk density, the greater the estimated degradation. This aligns with soil conservation theory, as high bulk density is associated with dense, poorly permeable soils prone to surface erosion. Soil texture showed a negative correlation (-0.127), which was also not significant. These parameters were analyzed integratively, as they influence each other in determining soil susceptibility to degradation.



Remark: Different letters indicate significant differences at the 5% α level

Figure 8. Distribution of porosity under various land use

Soil porosity is significantly affected by land use with a significance value ($p = 0.000^{**}$). This indicates that differences in land use, such as dry fields, rice fields, or plantations, have a significant effect on soil porosity values. These findings underscore the importance of considering soil physical properties, such as porosity, in determining land use patterns and management practices to align with the characteristics and capabilities of the soil. Figure 8 shows that soil porosity varies across land uses, with the highest value in rice fields (31.14%), followed by plantations (15.91%) and the lowest in dry fields (14.15%). These differences reflect the significant influence of land management on the physical properties of the soil, where rice cultivation activities and waterlogged conditions in rice fields tend to increase porosity, while soil compaction in dry fields and plantations decreases it.

3.3.2 Soil degradation status

Table 14 shows that all environmental factors tested significantly influence SDS. The significance values for the land use and rainfall variables are at a very high level of significance ($p = 0.000$), indicating that these two factors significantly affect soil degradation status. High rainfall can increase the risk of erosion and nutrient leaching [38]. Without conservation, settlement, or dryland land use types are more prone to soil degradation. Slope and soil type also significantly

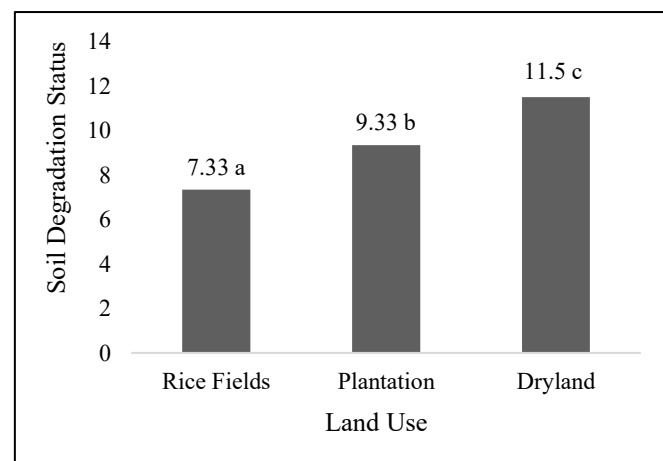
influenced soil degradation status, with significance values of 0.016 and 0.017, respectively. Steeper slopes increase the velocity of surface runoff, which can accelerate erosion [39]. Certain soil types degrade more easily depending on their aggregate structure and stability [40]. The analysis results reinforce the importance of a land management approach that considers a combination of environmental factors to minimize soil degradation effectively [41]. Decision-making in land management can be more targeted and data-driven by identifying the factors that significantly influence soil degradation status.

Table 14. Environmental factor effects on SDS

Environmental Factor	Soil Degradation Status
Land Use	0.000**
Slope	0.152 ^{ns}
Soil Type	0.142 ^{ns}
Rainfall	0.233 ^{ns}

Remark: ^{ns}) = not significant; **) = very significant

Figure 9 shows that land use significantly influences the status of soil degradation, as indicated by the significant differences between land use types. Rice fields have the lowest soil degradation status value of 7.33a, indicating that the management system in rice fields tends to maintain stable soil conditions and prevent severe degradation. Plantation land has an average degradation value of 9.33b, indicating a higher level of soil degradation than rice fields, but still lower than dryland. Dryland recorded the highest soil degradation status, at 11.5c significantly different from the other two land use types. This suggests that when managed openly without adequate conservation systems, dryland is more vulnerable to soil degradation [42].



Remark: Different letters indicate significant differences at the 5% α level

Figure 9. Distribution of SDS under various land use

Table 15. Determinant factors of SDS

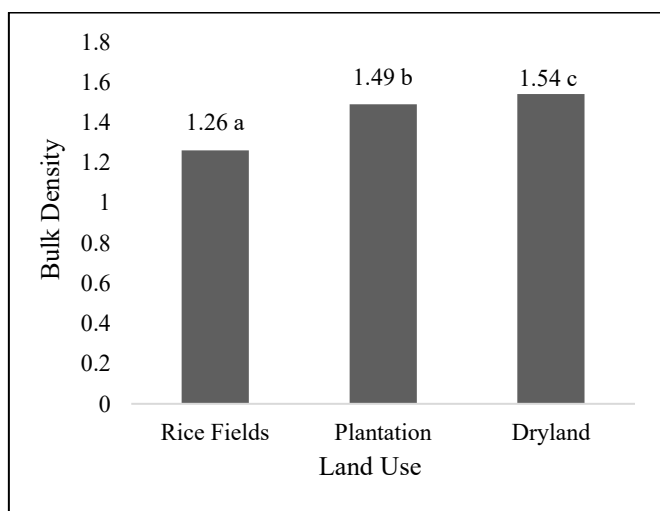
Soil Degradation Parameters	SDS
Porosity	-0.149
Bulk Density	0.488**
Particle Density	0.162
Texture	-0.213

Remark: *) = significant; **) = very significant

Based on Table 15, it can be seen that bulk density and soil degradation status in the Tirtomoyo Sub-Watershed area have a significant relationship. The bulk density parameter shows a

very significant positive correlation ($r = 0.488$) with SDS. High bulk density generally indicates soil compaction, inhibiting water infiltration, reducing aeration, and hindering plant root growth [43]. Compacted soil conditions are also more susceptible to erosion. ANOVA was conducted on the sources of variation in soil parameters to determine their effect on the sources of variability.

Soil bulk density is significantly influenced by land use factors. This indicates that variations in land use types such as fields, plantations, or rice paddies cause noticeable differences in soil bulk density (Figure 10). Land with intensive cultivation tends to have higher bulk density due to soil compaction, low organic matter content, and soil structure disturbance. The highest bulk density values were found in dry fields, followed by mixed plantations, and the lowest in rice fields. The high bulk density in dry fields is due to minimal soil cultivation activities and low organic matter content, and vegetation cover. Rice fields are often flooded and undergo intensive cultivation such as plowing, which can increase soil aggregation and reduce particle density. Mixed plantations do not have the same high intensity of soil cultivation as rice fields. High bulk density values indicate that the soil is in a more compacted state, hindering the movement of water and air within the soil. Dryland fields have the highest potential for soil degradation, followed by mixed plantations, while rice fields show the most stable conditions. Bulk density plays a role as a determining factor for SDS because it is influenced by land use and has a correlative relationship with SDS values.



Remark: Different letters indicate significant differences at the 5% α level

Figure 10. Distribution of bulk density under various land uses

Porosity and bulk density are closely related. Soils with high porosity generally have larger pore spaces, so bulk density tends to be lower because there are fewer solid particles filling each unit of volume [44]. Conversely, soils with low porosity have limited empty spaces, their particles are more compact, and their bulk density is higher. This relationship occurs because denser soil solids increase soil density and reduce total pore space [45]. When porosity decreases due to compaction, water infiltration decreases, soil aeration decreases, and oxygen availability for plant roots becomes limited. The accumulation of these conditions can worsen soil structure and accelerate degradation, including increasing susceptibility to erosion.

3.3.3 Accuracy level

The average value of SDE is 20.80 (Table 16), while the average value of SDS is much lower at 9.80. This shows that the results of SDE tend to be higher than the actual degradation values based on SDS. The standard deviation (StDev) for SDE is 5.25, higher than that of SDS, which is only 2.56, indicating that the data of SDE is more spread out or has greater diversity than that of SDS.

Table 16. Data description of accuracy between SDE and SDS

Sample	N	Mean	StDev
SDE	45	20.80	5.25
SDS	45	9.80	2.56

Remark: N = Total sample

Table 17. Accuracy between SDE and SDS

DF	P-Value	T-Value	T-Table
63	0.255	1.15	1.67

Remark: DF= Degree of Freedom

The results of the T-test analysis between the SDE and SDS in the Tirtomoyo Sub-Watershed showed a T-Value $<$ T-Table ($1.15 < 1.67$). The results prove that there is no significant difference between estimated (SDE) and actual (SDS) measurements of soil degradation (Table 17). The estimated results of soil degradation conform with actual conditions, so the potential for soil degradation mapped estimatively can be used as a reference in assessment without always having to conduct field surveys. The OBIA method can be used as an efficient soil degradation evaluation tool [46], especially for large or hard-to-reach areas. It can save time, costs, and energy in continuous environmental monitoring.

3.4 Land management recommendations

Based on the analysis, soil porosity and bulk density are the main determinants of soil degradation. These two parameters have a strong relationship in determining the physical quality of the soil, where low porosity is associated with high bulk density. This leads to reduced water infiltration, increased surface runoff, and ultimately accelerates the erosion process and the deterioration of soil structure. Soil management recommendations include Land management should include the application of organic materials to improve soil aggregation through organic fertilization adapted to sloping topography in the form of contour fertilization, so that the fertilizer is not easily washed away. This not only prevents fertilizer washout but also increases soil organic matter, which improves aggregation, thereby increasing porosity and decreasing bulk density [47]. Cover crops such as legumes or vetiver grass are also planted on sloping land to strengthen soil structure and reduce erosion. Cover crops help improve soil structure naturally through roots that penetrate compacted soil [48]. Cover crops increase soil pore space, thereby improving porosity, and help lower bulk density by promoting soil aggregation and reducing compaction. Conservation techniques such as minimum tillage and organic mulching help maintain stable soil structure and minimize mechanical disturbances that contribute to increased bulk density [49]. These steps can effectively reduce soil degradation by improving the fundamental physical properties of the soil [50]. Further research is needed to ensure that the analysis results

are accurate and representative. It is recommended that the research area cover at least one subdistrict with varied land use, using high-resolution satellite imagery such as Sentinel-2A, and utilizing more than one source of data diversity, such as land use, soil type, and topography, to improve the accuracy of classification and weighting.

4. CONCLUSION

Agricultural land in the sub-watershed area is vulnerable to degradation due to erosion and landslide events that reduce the soil's carrying capacity. The results showed that the estimation of soil degradation in the Tirtomoyo Sub-Watershed area based on OBIA analysis of Sentinel-2A satellite imagery and weighting was classified as very low degradation estimation (DE I), low degradation estimation (DE II), and moderate degradation estimation (DE III). The actual soil degradation status is classified as lightly degraded (DI) and moderately degraded (DII). The level of accuracy between the estimation and actual conditions is not significantly different, indicating that the OBIA method using Sentinel-2A satellite imagery is accurate for estimating soil degradation. The determining factor for the SDE is porosity. At the same time, for the SDS, it is bulk density; thus, appropriate land management recommendations to address and prevent soil degradation include the application of organic matter through organic fertilizers, additional planting of cover crops, and organic mulching, as well as conservation tillage techniques aligned with contour lines. This study refers to applicable regulations and is modified using the OBIA Sentinel-2A approach with a focus on physical soil parameters so that further research can expand the study by including chemical and biological soil parameters and comparing them with other OBIA applications at the watershed scale to produce more comprehensive damage estimates and improve accuracy.

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