Soil Environ. 45(1): 127-140, 2026
DOI: doi.org/10.25252/SE/2026/253894
Online ISSN: 2075-1141
Print ISSN: 2074-9546

Distribution of soil quality across various land uses in the Mount Lawu highlands, Indonesia

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***[Received:** July 20, 2025 **Accepted:** March 26, 2026 **Published Online:** March 26, 2026]*

Abstract

Mountain highlands in tropical regions contribute to cultivation and buffer zones, however, these areas are vulnerable to soil degradation. For this reason, soil quality evaluation is necessary to assess the area's ability to maintain its function. This study aims to analyze the distribution of soil quality index (SQI), identify the determining factor, and formulate recommendations for land management. This research was conducted in Poncol Sub-district, which is part of the Mount Lawu highland of Indonesia. Overlaying sources of variation of land use, slope, rainfall, and soil type resulted in 12 Land Map Units (LMUs), each repeated 3 times, thus resulting in 36 sampling points. Soil quality was determined using the SQI method based on Principal Component Analysis (PCA) of soil properties. The effect of sources of variation on SQI and the identification of determining factors were analyzed statistically. The results showed that the SQI across all LMU was classified as low to moderate. Land use, slope, and rainfall significantly influenced the SQI, with the highest values found in forest land use. The relatively high SQI at slopes of 25–45% were closely related to the dominance of forest land use in that slope class. The SQI was highly correlated with bulk density, porosity, soil organic carbon, base saturation, available P, and total N, which were identified as the main determinants of SQI. These findings confirm that soil quality improvement is still needed in all land use systems, including forests, to support their function, particularly as sustainable environmental buffer zones. Soil quality in agricultural land uses (plantations, crop fields, paddy fields) can be improved through management that focuses on increasing C-organic.

Keywords: Buffer zone, forest, land use, slope gradient, soil quality index

Introduction

Tropical mountain highlands play a strategic role in maintaining the stability of terrestrial ecosystems, particularly as regulators of hydrological processes, surface runoff control, and environmental buffers for downstream areas. Mountain ecosystems contribute significantly to the provision of ecosystem services, including water regulation, soil conservation, and maintaining landscape balance (Pătru-Stupariu *et al.,* 2020). However, the biophysical characteristics of these areas, such as steep topography and high rainfall intensity, make tropical mountain highlands highly vulnerable to land degradation. This vulnerability increases when uncontrolled land-use changes occur, which can accelerate erosion, degrade soil quality, and disrupt overall ecosystem function (Moncayo *et al.,* 2022). Soil quality refers to the soil's ability to perform ecological and productive functions, including supporting plant productivity and maintaining water quality. It is a crucial foundation for achieving healthy soil in agricultural land and environmental buffer zones. Research in buffer zones shows that the interaction between soil quality and soil community structure significantly influences soil ecological recovery, particularly when environmentally friendly management practices are implemented (Kurniawan *et al.,* 2025). Furthermore, scientific literature confirms that soil management that maintains organic matter, good physical structure, and chemical balance is crucial for maintaining soil's function as a buffer zone and supporting sustainable agricultural production (Marinari *et al.,* 2022).

Healthy soils with good quality are essential as they serve as the primary medium for plant growth and are key determinants of land productivity. High-quality soils support sustainable land use to meet human needs (Rahayu

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Cite This Paper: Cahyono, O., A. Lidyawati, A. Herawati , M.F. Wiraatmaja and M. Mujiyo. 2026. Distribution of soil quality across various land uses in the Mount Lawu highlands, Indonesia. *Soil Environ*. 45(1): 127-140.

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et *al.,* 2024). Soil quality evaluation is essential in assessing the soil's capacity to support agricultural production optimally (Wu et *al.,* 2025). This assessment also plays a role in detecting and restoring soil quality degradation caused by improper management practices, depletion of organic matter, and disruption of soil microbial activity (Ma et *al.,* 2024). The loss of soil organic matter can reduce the soil's capacity to retain water and nutrients, thereby decreasing overall soil productivity (Sprunger, 2023).

Variation in soil quality across different regions are strongly influenced by environmental factors such as land use and slope gradient, which directly affect the physical, chemical, and biological properties of the soil (Alebachew and Dengiz, 2025). Differences in vegetation, tillage intensity, and cultivation systems result in varying soil characteristics across agricultural lands, forests, and shrublands. Land with dense vegetation cover and deep-rooted plants tends to preserve soil structure, enhance water retention, and reduce erosion, thereby maintaining better soil quality (Lozano *et al.,* 2021). Changes in land use and land cover are key drivers of soil degradation and environmental alteration. Soil quality deterioration leads to reduced agricultural productivity and poses a serious threat to food security (Yeneneh *et al.,* 2024). However, in highland areas, land use variation presents complex issues that often increase pressure on soil quality. The highlands of Mount Lawu have agricultural land which is of economic value to the local community, most of whom are farmers. Intensively managed agricultural land has the potential to reduce organic matter content and soil aggregate stability. Furthermore, the Mount Lawu region, characterized by relatively high rainfall and varying slope gradients, often makes the soil vulnerable to erosion and degradation if not managed properly. These conditions make soil quality evaluation in the highlands of Mount Lawu crucial as a basis for sustainable agricultural land management.

The Soil Quality Index (SQI) determination method integrates various soil variables into a single quantitative measure, facilitating holistic assessments and comparing differences in land use (Hafshejani and Saeidinia, 2026). Meanwhile, the PCA-based Minimum Data Set (MDS) approach simplifies data by combining various variables into the most influential principal components, making it effective in estimating vulnerability levels under various variability conditions (Gao *et al.,* 2025). The MDS approach is the most commonly used method for selecting the most representative soil quality indicators and reducing data redundancy more efficiently (Supriyadi *et al.,* 2021). The use of this approach is still limited and has not been widely studied spatially in the Mount Lawu highlands. Therefore, mapping SQI values based on Geographic Information Systems (GIS) using thematic map overlay techniques is essential for spatial analysis of soil quality (Mulia and Wiwandari, 2024). The use of GIS in mapping these soil properties highlights the changes and variations in the Soil Quality Index (SQI) from one location to another (Abdel *et al.,* 2021).

Various previous studies have highlighted the impact of land use on soil quality in hilly and highland areas. For instance, a study by (Nugraha *et al.,* 2025) slope is a key variable in the development of Land Mapping Units (LMUs) as it strongly influences soil characteristics and land management potential. Zhu *et al.* (2022), concluded that slope position and management systems influence soil properties. However, most of these studies have not comprehensively integrated slope conditions, land-use types, and the Soil Quality Index (SQI), particularly in highland areas such as the slopes of Mount Lawu (600-1,200 m asl). In this study, an MDS-based SQI evaluation was used to help identify the most influential soil properties and improve SQI interpretation. This approach provides a comprehensive overview of the influence of various land uses, slopes, rainfall, and soil types on soil quality, a practice rarely studied in Indonesia's mountain highlands. This study aims to analyze the distribution of soil quality index (SQI), identify the determining factor, and formulate recommendations for land management. The results of this study are expected to enrich scientific understanding of the dynamics of soil quality in tropical mountain highlands and support sustainable land management strategies in upstream areas.

Materials and Methods

Site description

The research area is Poncol Sub-district, Magetan Regency, at 7°42′00″–7°45′30″ S and 111°13′30″–111°18′00″ E, which is located in the western part of Magetan Regency, precisely on the southeastern slope of Mount Lawu. The topography varies from flat, wavy, undulating, hilly to mountainous, with an altitude of 500-2,200 m asl. Rainfall varies from 1,000 mm/year to 3,000 mm/year with temperatures ranging from 18-26 ^{0}C. The soil type is Andisols which developed from volcanic ash material. The area is 5,131 ha with a range of land use for forests 1,541 ha, plantations 500 ha, crop fields 1,716 ha, and paddy fields 647 ha. In this study, the terminology of land use for plantations is identical to smallholding plantations, and land use for crop fields is identical to dry fields.

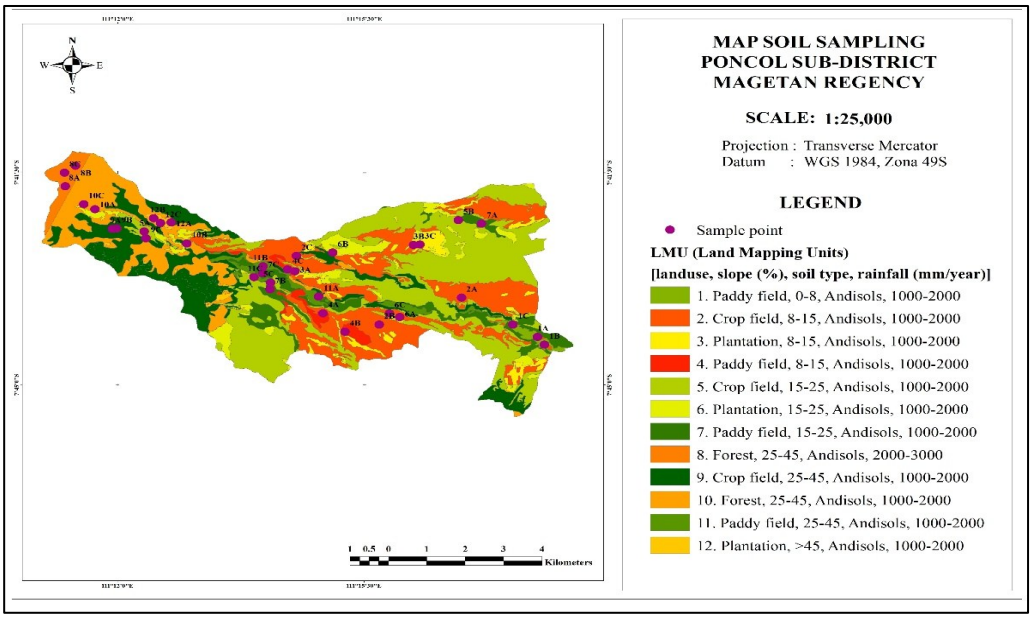


Figure 1. Land Mapping Units (LMUs) and soil sampling points

Table 1. Soil Quality Index (SQI) scoring

Indicators	Relative SQI score				
	1	2	3	4	5
Physical properties					
BD (g cm^{-3})	>1,6	1,5-1,6	1,4-1,5	1,3-1,4	<1,3
Texture	S, C	SiC, LS	CL, SL	SiL, Si, SCL	L
Porosity (%)	<10	10-15	15-18	18-20	>20
Chemical properties					
SOC (%)	5-10	3-5	1-3	0,5-1	<0,5
pH	<5	5-5,4	5,4-5,8	5,8-6	6-7
CEC (c mol(+) kg^{-1})	<5	5-16	17-24	25-40	>40
BS (%)	<20	20-30	30-50	51-70	>70
Total N (%)	<0,10	0,10-0,20	0,21-0,50	0,51-0,75	>0,75
Available P (mg kg^{-1})	<10	10-15	16-25	26-35	>35
Available K (c mol(+) kg^{-1})	<0,1	0,1-0,2	0,3-0,5	0,6-1,0	<1,0
Biological properties					
MBC (mg C kg^{-1})	<5	5-10	10-20	20-25	>25

BD = Bulk Density, S = Sand, C = Clay, SiC = Silty Clay, LS = Loamy Sand, CL = Clay Loam, SL = Sandy Loam, SiL = Silty Loam, Si = Silt, SCL = Sandy Clay Loam, L = Loam, SOC = Soil Organic Carbon, CEC = Cation Exchange Capacity, BS = Base Saturation, MBC = Microbial Biomass Carbon

Soil observation, sampling, and laboratory analysis

Land Mapping Units (LMUs) were derived from an overlay of thematic maps, including soil type, land use, slope gradient, and rainfall maps, at a semi-detailed scale of 1:50,000. A total of 12 LMUs were identified, with three replications each, resulting in 36 sampling points (Figure 1). Soil samples were collected at a depth of 0–30 cm. Laboratory analysis of physical soil properties included porosity, determined using the gravimetric method for soil moisture content; bulk density, measured using the clod

method to calculate bulk density (BD) and particle density (PD); and soil texture, analyzed using the pipette method (Kurnia *et al.,* 2022). Laboratory analysis of chemical soil properties included soil organic carbon (SOC) determined by the Walkley–Black wet oxidation method; soil pH measured potentiometrically in a soil and water suspension; cation exchange capacity (CEC) and base saturation (BS) determined by the extraction of exchangeable cations using 1 N ammonium acetate solution (pH 7); available phosphorus analyzed by the Olsen method; available potassium determined by the extraction of 1 N ammonium acetate (pH 7) and measured using a flame photometer; and total nitrogen analyzed using the Kjeldahl method (Black et al., 1965). Soil biological properties were analyzed by determining microbial biomass carbon (MBC) using the fumigation–extraction method to assess soil microbial activity (Vance *et al.,* 1987).

Calculation of soil quality index

The selected soil indicators in the Minimum Data Set (MDS) revealed that Principal Component Analysis (PCA) represented soil functions in calculating the Soil Quality Index (SQI). The indicators included bulk density (BD), texture, porosity, soil organic carbon (SOC), pH, cation exchange capacity (CEC), base saturation (BS), available phosphorus (available P), total nitrogen (total N), available potassium (available K), and microbial biomass carbon (MBC), which were used to determine vulnerability values across different variability conditions. Only principal components (PCs) with eigenvalues greater than 1 were selected. The weighting of each indicator score was based on a classification system of limiting factor values, which were divided into five classes, referring to criteria based on Lal (1994) with several modifications adjusted to local conditions and the objectives of this study (Table 1). This classification aims to provide a quantitative interpretation of the contribution of each indicator to the overall soil quality. The score of each indicator was multiplied by its weight (Wi) derived from PCA, and the values were then summed to obtain the Soil Quality Index (SQI) for each observed land unit.

After obtaining the selected soil quality indicators and their respective weights through Principal Component Analysis (PCA), the next step was calculating the Soil Quality Index (SQI) as a quantitative representation of soil quality conditions in each observed land unit. The SQI was calculated using the following equation (Mukhopadhyay *et al.*, 2014).

$$\text{SQI} = \sum_{i=1}^{n} (Wi \times Si)$$

Where *Wi* is the weight index, *Si* is the score of the selected indicator, and *n* is the total number of soil quality indicators. The calculated SQI values were then classified into five classes (Table 2), ranging from class 1 (very good) to class 5 (very low) (Cantú *et al.,* 2007).

Statistical analysis to determine the effect of sources of variation

The effect of land use and slope on SQI was analyzed using analysis of variance (ANOVA), and differences between means were further tested using Duncan's Multiple Range Test (DMRT), both tests used at a 95% confidence level. The effect of rainfall on SQI was determined by comparing two means using a t-test, as there were only two rainfall classes in the study area. Soil type was not statistically analyzed because only one soil type was present in all study locations.

Statistical analysis to identify the determining factor

The determining factor of soil quality were identified through correlation analysis between each soil indicator and the SQI. Indicators that showed a significant or very significant correlation with the SQI were then analyzed using ANOVA and DMRT to determine the effect of the source of variation on the indicator. An indicator is selected as a determining factor of soil quality if it met two criteria: (1) it had a significant or very significant correlation with the SQI, and (2) it was significantly or very significantly affected by the source of variation.

Formulation of land management recommendations

Land management recommendations are formulated to enhance or improve soil properties, which are the determining factors of soil quality. These recommendations are aimed at supporting the productive highlands of Mount Lawu as a sustainable area for cultivation and buffer zone.

Results

Distribution of SQI in various LMUs

Five principal components (PCs) with eigenvalues greater than 1 were identified (Table 3). Eight indicators were selected as the Minimum Data Set (MDS) out of 11 soil quality indicators. PC1 represents 49% of the total

Table 2. Classification of Soil Quality Index (SQI)

Soil Quality	SQI Value Scale	Class
Very good	0.80-1.00	1
Good	0.60-0.79	2
Moderate	0.40-0.59	3
Low	0.20-0.39	4
Very low	0.00-0.19	5

(Cantú *et al.*, 2007)

Table 3. Principal Component Analysis (PCA)

Eigenvalue	4.9006	1.4397	1.2516	0.9172
Proportion	0.490	0.144	0.125	0.092
Cumulative	0.490	0.634	0.759	0.851
Variable	**PC1**	**PC2**	**PC3**	**PC4**
BD	-0.378	0.043	-0.178	-0.209
Porosity	**0.390**	-0.270	0.183	0.069
SOC	**0.421**	0.141	-0.065	0.149
pH	0.082	**-0.620**	-0.400	0.091
CEC	0.194	0.382	**-0.600**	0.250
BS	0.399	-0.002	0.187	-0.151
Available P	**0.402**	-0.141	0.306	0.054
Available K	0.129	-0.440	**-0.447**	-0.309
Total N	0.331	**0.341**	-0.283	0.059
MBC	0.193	0.211	-0.043	**-0.857**

variance, with three highly influential indicators; porosity, SOC, and available P. PC2 represents 14.4% with two selected indicators; pH and total N. PC3 represents 12.5% with two selected indicators; CEC and available K. PC4 represents 9.2% with the selected indicator; MBC.

Scoring of soil quality indicators (Si) was conducted using the selected parameters (Table 4). The weighting was divided into five classes: Class 1 = extreme limitation; Class 2 = severe limitation; Class 3 = moderate limitation; Class 4 = slight limitation; and Class 5 = no limiting factor. The obtained scores were then used to calculate the weight indicator (Wi) to determine the weight of each indicator (Table 5). The Wi values were derived from the loading factors of the principal components, taken from the highest value in the selected PC columns based on the PCA results.

The results of the SQI analysis indicate that the soil quality index values for all LMUs in the study area are in the low to moderate category (Table 5 and Figure 2). No LMUs have a high SQI. Low SQI values were found in LMUs with paddy fields, crop fields, and plantations, while moderate SQI values were found in LMUs with forest land use. The distribution of SQI values shows clear spatial variation among LMUs, reflecting differences in land use conditions.

Distribution of SQI in various land uses, slopes, rainfall, and soil types

ANOVA results showed that land use had a very significant effect on the SQI ($F = 92.22$; $p < 0.01$; $n = 36$), and further DMRT tests showed that the SQI differed significantly between land use types. The order from lowest to highest was paddy fields, crop fields, plantations, and forests (Figure 3); forest land use had a significantly higher SQI compared to other land uses, while paddy fields land use showed the lowest.

Slope gradient also had a very significant effect on SQI ($F = 7.36$; $p < 0.01$; $n = 36$), further DMRT test showed that SQI was very significantly different between slope gradient classes. The lowest SQI was found at slope gradients of 0–8%, followed by 15–25% and >45% which were not significantly different from each other, then followed by 8–15%, and the highest at 25–45% (Figure 4).

The t-test result shows that the SQI in areas with rainfall of 2,000–3,000 mm/year is significantly higher than that of 1,000–2,000 mm/year ($t = 4.93$; $p < 0.05$; $n_1 = 3$, $n_2 = 33$), which can be interpreted that rainfall has a significant effect on SQI. However, the distribution of LMUs shows that the 2,000–3,000 mm/year rainfall class is only

Table 4. Scoring of soil quality indicators

Site Sampling	Indicator Scoring (Si)							
	Porosity	SOC	pH	CEC	Available P	Available K	Total N	MBC
1a	1	2	5	2	1	3	3	1
1b	1	1	5	4	1	3	2	1
1c	1	2	5	4	1	1	3	1
2a	3	3	5	5	2	4	3	1
2b	4	3	5	4	3	5	3	1
2c	3	3	5	5	2	2	3	1
3a	5	3	5	3	4	5	3	1
3b	5	4	5	2	4	3	4	1
3c	5	3	5	4	4	5	3	1
4a	1	2	5	4	1	4	3	1
4b	1	3	5	5	1	2	4	1
4c	1	2	5	3	1	3	4	1
5a	4	3	5	3	2	5	3	1
5b	3	3	5	3	2	4	4	1
5c	3	3	5	2	3	5	3	1
6a	5	4	5	4	4	3	3	1
6b	5	3	5	4	4	1	4	1
6c	5	4	5	4	5	2	3	1
7a	2	1	5	2	1	1	4	1
7b	2	2	5	3	1	4	4	1
7c	2	1	5	4	1	1	3	1
8a	5	4	5	5	4	5	5	1
8b	5	4	5	5	4	4	5	1
8c	5	4	5	5	4	5	5	1
9a	4	3	5	5	2	2	4	1
9b	4	3	5	5	2	5	4	1
9c	3	3	5	5	2	4	4	1
10a	5	4	5	5	4	5	5	1
10b	5	3	5	2	4	4	4	1
10c	5	4	5	5	4	5	5	1
11a	2	1	5	2	2	3	3	1
11b	2	2	5	2	1	3	3	1
11c	2	3	5	5	2	5	3	1
12a	5	3	5	3	2	4	3	1
12b	5	4	5	3	2	2	3	1
12c	4	2	5	3	2	4	3	1

represented by one LMU, while the 1,000–2,000 mm/year rainfall class is represented by eleven LMUs. The effect of soil type was not identified because in the research area there was only one type of soil, namely Andisols.

Determining factors of SQI

BD was highly significantly negatively correlated with SQI, while porosity, SOC, BS, available P, and total N were highly significantly positively correlated (Table 6), while other indicators showed no significant or weak correlation.

ANOVA results showed that land use had a significant effect on BD, porosity, SOC, BS, available P, and total N, while slope had a significant effect on porosity, and a significant effect on BD, SOC, BS, and available P, but no significant effect on total N (Table 7). In forest land use, BD was significantly lower, and conversely, porosity, SOC, BS, available P, and total N were significantly higher compared

Table 5. Soil Quality Index (SQI) values in each LMU

Indicator	Probability	Cumulative	Wi	Wi x Si											
				1	2	3	4	5	6	7	8	9	10	11	12
Porosity	0.490	0.851	0.14	0.14	0.47	0.70	0.14	0.39	0.56	0.28	0.70	0.51	0.70	0.28	0.65
SOC	0.490	0.851	0.14	0.23	0.42	0.47	0.33	0.39	0.46	0.19	0.70	0.42	0.56	0.42	0.42
pH	0.144	0.851	0.12	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60
CEC	0.125	0.851	0.05	0.17	0.23	0.15	0.20	0.14	0.19	0.15	0.25	0.25	0.25	0.25	0.15
Available P	0.490	0.851	0.14	0.14	0.33	0.56	0.14	0.28	0.49	0.14	0.56	0.28	0.56	0.28	0.28
Available K	0.125	0.851	0.05	0.12	0.18	0.22	0.15	0.21	0.11	0.10	0.23	0.18	0.25	0.25	0.17
Total N	0.144	0.851	0.06	0.16	0.18	0.20	0.22	0.21	0.21	0.22	0.30	0.24	0.30	0.18	0.18
MBC	0.092	0.851	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
IKT = $\sum_{i=1}^{n}(Wi \times Si)$				0.20	0.31	0.37	0.23	0.31	0.38	0.22	0.43	0.32	0.40	0.25	0.32
Class				L	L	L	L	L	L	L	M	L	M	L	L

Remark: L= low; M = medium

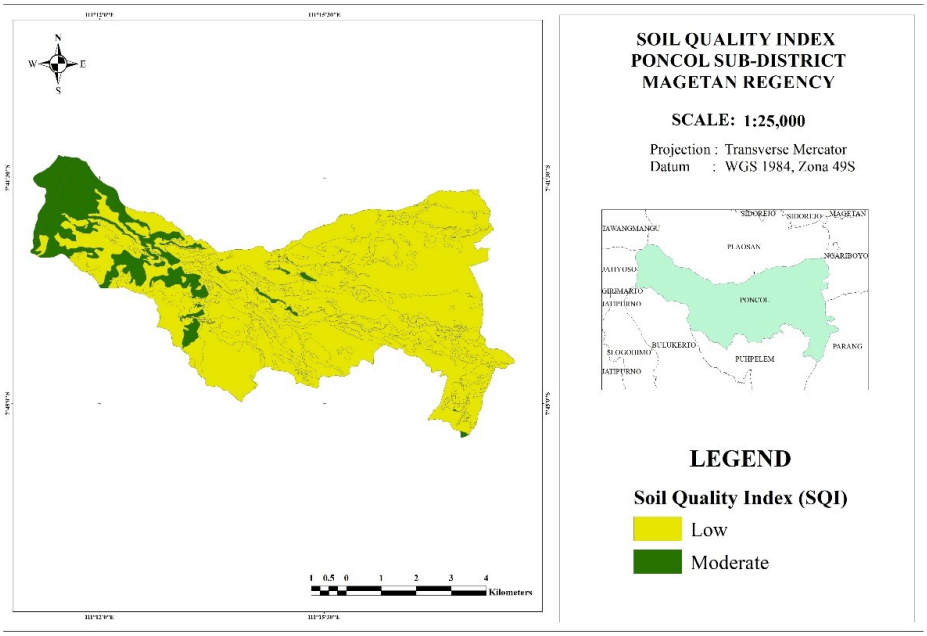


Figure 2. SQI in several land uses in Poncol Sub-district

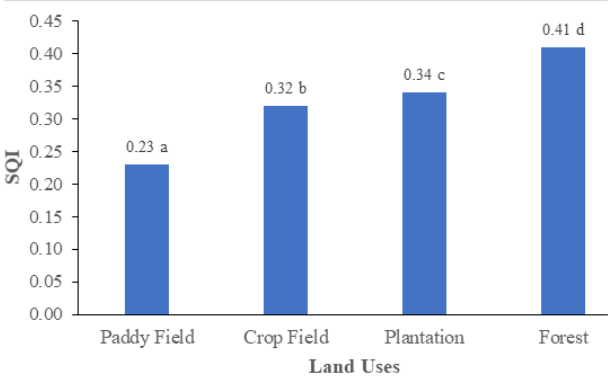


Figure 3. Average SQI across land uses

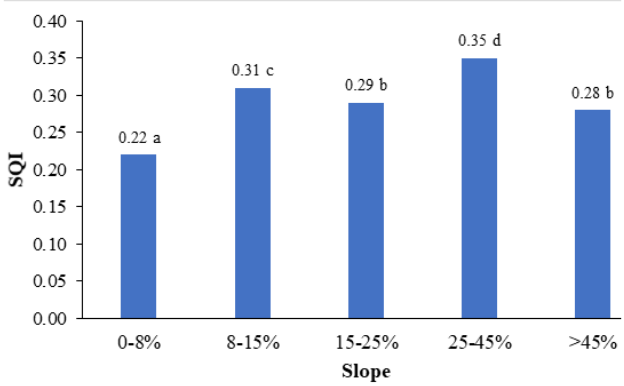


Figure 4. Average SQI at various slope gradients

Table 6. Correlation between SQI and soil indicators

Soil Quality Indicators	*Pearson Correlation*
BD	-0.833**
Porosity	0.809**
SOC	0.932**
BS	0.837**
Available P	0.886**
Total N	0.669**

Remark: ** = highly significant ($p < 0.01$)

Table 7. The effect of sources of variation on soil indicators

Sources of Variation	F-value					
	BD	**Porosity**	**SOC**	**BS**	**Available P**	**Total N**
Land uses	22.40**	50.03**	25.36**	83.76**	126.07**	14.33**
Slopes	2.91*	5.29**	3.82*	3.67*	19.25*	0.32^{ns}

Remark: ns = not significant ($p > 0.05$); * = significant ($p < 0.05$); ** = highly significant ($p < 0.01$)

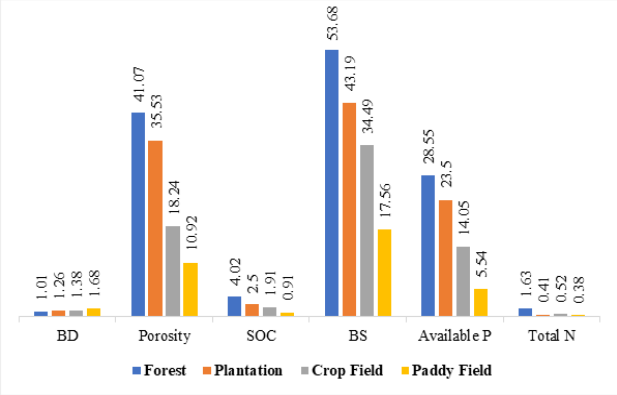


Figure 5. Soil indicators across land uses

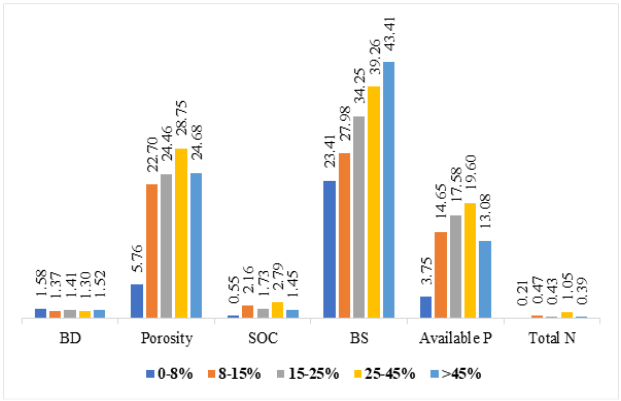


Figure 6. Soil indicators at various slope gradients

to plantations, crop fields, and paddy fields (Figure 5). Based on slope class, the lowest BD was found at slopes of 25–45%, while porosity, SOC, BS, available P, and total N showed the highest values in the same slope class (Figure 6). Differences in soil indicator values between land uses were more pronounced than between slopes, and for this reason, the total N indicator was still included as a determining factor even though it was not affected by slope.

Based on the results of the analysis and description above, the determining factors of SQI in the research area include BD, porosity, SOC, BS, available P and total N. These indicators meet the criteria as determining factors because they have a significant or very significant correlation with SQI, and are significantly or very significantly affected by land use and slope.

Discussion

Soil quality in Mount Lawu highlands

The study area is characterized by Andisol soils, which are known for their high natural fertility, making them highly suitable for agriculture in tropical and temperate regions (Avilés-Junco *et al.,* 2025). SQI at all LMUs in Mount Lawu highlands is in the low to moderate category. This condition reflects the general characteristics of soil in wet tropical regions which are vulnerable to degradation, especially in slope areas with high rainfall. High rainfall intensity, combined with sloping topography, increases the risk of erosion and loss of soil organic matter, ultimately reducing overall soil quality (Chang *et al.,* 2024). Although Andisols are known to have relatively high fertility potential, this study shows that this potential is not always reflected in high soil quality, particularly in non-forest land

uses. This indicates that land use pressures and inappropriate management can degrade soil quality, even in naturally productive volcanic soils (Aravena *et al.,* 2025).

The dominant role of land use on soil quality

Land use has been shown to be the most influential factor on soil quality compared to slope and rainfall. The highest SQI was found in forest land use, with the order from lowest to highest was paddy fields, crop fields, plantations, and forests. The forest area in the highlands of Mount Lawu is characterized by dense vegetation, predominantly planted with pine trees, whereas the plantation areas are cultivated with coffee, cacao, and other perennial crops. These deep-rooted plants enhance water infiltration and help prevent soil erosion (Ou *et al.*, 2023). This finding is in line with various studies reporting that natural vegetation cover plays an important role in maintaining soil structure stability, increasing organic matter content, and reducing mechanical disturbances in the soil by improving soil aggregation and organic matter accumulation (Duo *et al.,* 2020; Yang *et al.,* 2024). Forests provide continuous input of organic matter through litter and well-developed root systems, thereby improving the physical and chemical properties of the soil. In contrast, Topa *et al.* (2020) explain that intensive agricultural land generally experiences repeated tillage, compaction, and low crop residue return, which results in decreased soil quality.

Crop fields in the field study are commonly used for cultivating vegetables such as cabbage, carrots, and secondary crops, relying primarily on rainfall for irrigation. These crop fields characterized by low to moderate soil fertility, are prone to water deficiency when dependent solely on rainfall, and are relatively sensitive to land degradation. Meanwhile, the paddy fields are intensively used for rice cultivation. Intensive management without considering proper inputs, such as organic matter amendments, adequate water supply, and appropriate soil management practices, can degrade soil quality. Improper management of paddy fields will reduce crop production, imbalanced land-use intensification leads to a decline in ecosystem functioning (Nahib *et al.,* 2025). The inappropriate use of inorganic fertilizers without considering nutrient balance can lead to increased soil compaction, soil acidification, and deficiencies in essential nutrients. Limited organic matter input results in compacted soil structure, reduced water-holding capacity, and decreased soil microbial activity (Viandari *et al.,* 2022). The dominant influence of land use in this study confirms that land management strategies have a key role in maintaining soil quality in mountain highland areas.

The effect of slope and its interaction with land use

Slope gradient also significantly influences SQI, but its effect is indirect and heavily influenced by land use distribution. The highest SQI at slopes of 25–45% is closely related to the dominance of forest land use in that slope class. This suggests that vegetation cover can offset the potential for soil degradation resulting from relatively steep slopes. Land on slope gradient (25–45%) is predominantly occupied by forests, which are characterized by denser vegetation and perennial crops with stronger root systems. These root systems enhance water infiltration and improve soil structure. This is evidenced by the higher organic matter content (up to 4.66%) and high soil porosity observed in this slope class. These findings are supported by the study of Al Muamalah *et al.* (2024), which suggests that the slope gradient itself is not the primary factor determining soil quality, particularly on slopes prone to erosion. Instead, soil quality is largely influenced by soil properties such as porosity, organic matter content, and other key indicators.

However, the role of slope gradient in soil conditions cannot be ignored. Slope gradient determines drainage patterns and organic matter accumulation, which affect soil fertility and structural stability. This observed relationship makes slope an important factor in land evaluation and sustainable soil management (Rendana *et al.,* 2022). Therefore, in areas with steep slopes, the best land management is to add the same or similar composition of annual plants as in the forest. Belay *et al.* (2025) confirm this by stating that the impact of slope on soil quality cannot be separated from the land-use system implemented. Steep slopes managed conservatively can have better soil quality than gentle slopes managed intensively without soil conservation practices.

The effect of rainfall on soil quality

Rainfall showed a significant effect on SQI, with a higher value in the 2,000–3,000 mm/year rainfall class. However, these results should be interpreted with caution due to the limited number of LMUs in this rainfall class. The higher SQI in the higher rainfall class reflects the influence of forest land use rather than a direct effect of rainfall itself. In general, high rainfall can have both positive and negative impacts on soil quality, depending on the condition of land cover and its management. In areas with good vegetation cover, rainfall can support the accumulation of biomass and soil organic matter.

Conversely, in open areas, high rainfall actually accelerates soil degradation (Chang *et al.,* 2024).

Determing factors of soil quality

The determining factors of soil quality identified in this study include BD, porosity, SOC, BS, available P, and total N. The combination of these physical and chemical indicators indicates that soil quality in the Mount Lawu Highlands area is determined by soil structure and nutrient status. Low soil bulk density and high porosity reflect looser soil conditions that support water movement and plant roots. Regarding the chemical soil properties as determining factors, soil organic matter content was identified as the most significant indicator for assessing soil quality due to its high sensitivity to changes (Freitas *et al.,* 2024). Soil organic carbon (SOC) content is influenced by microbial activity in the soil. Higher microbial activity generally corresponds to higher organic matter content (Risma *et al.,* 2023).

Regarding the physical soil properties as determining factors, bulk density in forest and plantation land uses showed lower values. In contrast, paddy fields exhibited the highest bulk density due to higher soil compaction. High soil compaction is primarily caused by intensive land management practices and low organic matter availability (Triadiawarman *et al.,* 2022). Soil porosity was highest in plantation land use, followed by crop and paddy fields. Soil porosity is an important indicator of soil structure, as soils with higher organic matter generally exhibit greater porosity (Fatimah, 2023). In contrast, low soil porosity occurs when soil pores are filled with soil particles, reducing pore space and restricting water infiltration (Nuraida *et al.,* 2021). Compacted soil that clogs pore spaces can impede permeability, causing water to stagnate on the soil surface (Anissa and Herfandi, 2024).

Regarding the chemical soil properties as determining factors, soil organic carbon (SOC) was identified as the most significant indicator for assessing soil quality due to its high sensitivity to changes (Freitas *et al.,* 2024). SOC is influenced by microbial activity in the soil. Higher microbial activity generally corresponds to higher organic matter content (Risma *et al.,* 2023). In this study, the highest SOC content was observed in forest and plantation land uses, where dense vegetation provides a natural supply of organic litter, enriching soil organic matter. This organic matter contributes to nutrient reserves, improving overall soil conditions due to the abundance of available organic inputs. High organic matter content also positively influences other chemical soil properties, resulting in higher soil fertility.

It was observed that both land use and slope gradient did not exhibit low base saturation values. This may be attributed to the soil type in the study area, where Andisols dominate with neutral pH. Thus, base saturation is not solely influenced by soil pH but may also be affected by other factors such as soil organic matter, as the study area soils are not acidified. High base saturation indicates good nutrient availability in the soil, whereas low base saturation generally indicates soil acidification (Zhang *et al.,* 2023). The availability of phosphorus (available P) can increase through soil phosphate activity, which depends on multiple factors, including soil properties, interactions with soil microbes, and inhibitors and activators (Solangi *et al.,* 2023). In paddy fields, the low available phosphorus (available P) content may be influenced by fluctuating redox conditions caused by the irrigation system, particularly during periods of flooding and drying (Martinengo *et al.,* 2023).

Nitrogen (N) is a major limiting nutrient that determines crop yield and quality (Hei *et al.,* 2025). Insufficient nitrogen availability reduces soil productivity and agricultural yields (Zhao *et al.,* 2025). In this study, paddy fields showed low total nitrogen (total N), which may be attributed to low SOC levels and poor soil aeration caused by excessive flooding and high soil compaction that limits water infiltration. Soil nitrogen content is influenced by vegetation type and decomposed organic matter. The greater the amount of decomposed litter, the higher the nitrogen content available to the soil and plants (Pambayun *et al.,* 2023).

Land management recommendations

As an upstream area, the Poncol Sub-district, part of the Mount Lawu highlands, plays a strategic role in supporting productive areas for sustainable cultivation and buffer zones for downstream areas. Although forest land use has a relatively higher soil quality index compared to non-forest land use, the soil quality is still in the moderate category and has not yet reached optimal conditions as a buffer zone. This situation demonstrates that the presence of forest cover alone does not fully guarantee ideal soil quality. Natural environmental pressures, particularly in tropical areas, such as high rainfall and steep slopes, as well as the potential for anthropogenic disturbance, can limit soil quality improvement even within a relatively stable land-use system. Therefore, forest area management remains necessary to maintain and improve soil quality, particularly

through the protection of soil organic matter and the stability of soil structure, which support the sustainable functioning of forest ecosystems.

Nevertheless, forest land use in this study can still be considered the land-use system closest to ideal conditions compared to other land uses. Therefore, land management strategies for plantations, dry fields, and paddy paddies need to be directed toward mimicking the ecological functions of forests, thereby improving soil quality in non-forest land uses. Soil management recommendations based on indicators significantly influencing the soil quality include the application of organic amendments to enhance soil quality. These may involve the use of organic fertilizers such as compost, manure, green manure, and the addition of biochar, combined with land-use-specific soil management practices in the study area.

Compost application has been reported to improve soil quality by effectively reducing bulk density, alleviating soil acidification, and enhancing soil nutrient availability (Gao *et al.,* 2024). Using green manure combined with fertilization can improve soil quality, potentially addressing soil degradation and nutrient imbalance in agricultural systems (Jia *et al.,* 2025). Biochar is as effective as lime in improving soil quality and reducing soil acidification (He *et al.,* 2025). Application of biochar is effective in improving the fertility of Andisol soils by enhancing nutrient availability through increased soil pH, reduced phosphorus fixation, and providing a better adsorption surface for nutrient ions. Biochar also improves soil physical properties by increasing aeration, porosity, and cation exchange capacity (CEC), thereby supporting root development and enhancing nitrogen (N) and phosphorus (P) uptake (Karimah *et al.,* 2024).

Conclusion

Soil quality in the Poncol Sub-district, part of the Mount Lawu Highlands, is in the low to moderate category, including forest land use, which has relatively higher soil quality than non-forest land use. These results indicate that although forest is the land use system that best supports soil quality, it is not yet optimal as a buffer zone and therefore requires efforts to improve soil quality. Land use stands as the primary determinant affecting soil quality., followed by slope and rainfall. The determining factors of soil quality identified in this study include bulk density (BD), porosity, soil organic carbon (SOC), base saturation (BS), available P, and total N, reflecting the important role of soil structure and nutrient status in determining soil quality. Management of the Mount Lawu highlands as a cultivation area and buffer zone depends not only on the presence of forest cover but also on efforts to sustainably improve soil quality across all land use systems, including agricultural land uses, such as plantations, crop fields, and paddy fields. Soil quality in agricultural land uses can be improved through management that focuses on increasing the organic carbon content in the soil. This can be achieved through the application of organic fertilizers and amendments such as compost, farmyard manure, green manure, and biochar.

Acknowledgement

The authors would like to thank the General Directorate of Higher Education, Research and Technology – Ministry of Education, Culture, Research and Technology of the Republic of Indonesia for the research funding provided through the Regular Fundamental Research scheme with the number 1076.1/UN27.22/PT.01.03/2024. Appreciation was also given to Viviana Irmawati, Muhammad Rizky Romadhon, Tiara Hardian, and Nanda Mei Istiqomah who have provided much assistance in carrying out the research and writing the article.

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