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Effect of land management intensity on soil quality of Andisol in the Upper Brantas Watershed, Batu, Indonesia

Alfian Pujian Hadi[1], Didik Suprayogo*[2], Kurniatun Hairiah[2], Cahyo Prayogo[2]

[1] Brawijaya University, Faculty of Agriculture, Doctor of Agriculture Science Program, Jl Veteran No 1, 65145 Malang, Indonesia

[2] Brawijaya University, Faculty of Agriculture, Jl Veteran No 1, 65145 Malang, Indonesia

* Corresponding author

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Abstract: Soil quality plays an important role in maintaining agricultural productivity, land conservation, and ecosystem resilience, especially in volcanic landscapes such as the Upper Brantas Watershed. This study assesses the impact of land management intensity (*LMI*) on the soil quality index (*SQI*) across varying land-use types and slope gradients. Using a stratified random sampling approach, soil samples were analysed for physical and chemical properties, while *LMI* was evaluated based on input intensity and soil conservation practices. Statistical analyses, including ANOVA and correlation analysis, were performed to determine the relationships among *LMI*, vegetation biomass, and *SQI*. The results revealed a negative correlation between *LMI* and *SQI*. The highest soil quality was observed in protected forests (*SQI* = 0.64–0.76; biomass = 541.4–675.2 Mg·ha^{-1}) and pine–coffee agroforestry systems (*SQI* = 0.57–0.65; biomass = 387.1–475.7 Mg·ha^{-1}). In contrast, upland farming (*LMI* = 0.68–0.71; *SQI* = 0.37–0.52) and pine–horticulture agroforestry (*LMI* = 0.50–0.56; *SQI* = 0.40–0.51) exhibited the lowest soil quality. Steeper slopes are associated with greater soil degradation, particularly in regions of intensive activity. These findings demonstrate that intensive land management accelerates soil degradation, while agroforestry and conservation-oriented land uses enhance soil health through increased organic matter inputs and reduced soil disturbance. The study underscores the importance of adopting sustainable land management strategies such as mulching, minimum tillage, and terracing to mitigate soil degradation. These insights are crucial for policymakers and land managers in developing effective soil conservation programs for sustainable watershed management.

Keywords: agroforestry, Andisol, land management intensity, soil quality index, slope gradient, sustainable land management, vegetation biomass

INTRODUCTION

The sustainable development goals (SDGs), adopted by the United Nations, highlight the importance of sustainable land use and soil management in ensuring food security, climate resilience, and biodiversity conservation. Soil quality is fundamental to achieving the SDG targets, especially sustainable agriculture (SDG 2), climate action (SDG 13), and life on land (SDG 15) (Lal *et al.*, 2021). However, land degradation due to intensive agricultural practices and unsustainable management hinders the attainment of SDGs, especially in vulnerable areas such as the Andisol in mountainous volcanic watersheds (Liu *et al.*, 2023).

Soil quality is a critical factor for agricultural productivity (Wingeyer *et al.*, 2015; Paul Obade de, 2019) and ensuring ecosystem resilience (Zhu *et al.*, 2024). However, rapid land-use changes driven by deforestation and anthropogenic activities have significantly diminished soil quality on a global scale (Wei *et al.*, 2014; Nath *et al.*, 2018; Rutigliano *et al.*, 2023). The decline in soil quality poses challenges not only to agricultural output and economic sustainability but also to environmental health and biodiversity conservation (Girmay *et al.*, 2008; Zeraatpisheh *et al.*, 2020). Key contributors to soil degradation include inappropriate land use, soil erosion, deforestation, and high-intensity land management practices (Qasim *et al.*, 2017; Turan *et al.*, 2019). Vegetation biomass plays an important maintaining soil quality. Higher biomass levels contribute to increased organic matter inputs, improved soil structure, and enhanced moisture retention (Lavelle *et al.*, 2014). Studies have shown landscapes with dense tree cover and understorey vegetation support superior soil quality (Henry *et al.*, 2013). The importance of soil organic matter and microbial activity in maintaining soil health is particularly pronounced in volcanic soils on slopes (Schoonover and Crim, 2015).

In the Upper Brantas Watershed in Batu City, soil quality determines land productivity, ecological stability, and long-term sustainability. It is mostly made up of Andisol, which exhibit unique physicochemical properties that make them highly fertile but also highly vulnerable to degradation due to intensive agriculture (Arciniegas-Ortega, Molina and Garcia-Aranda, 2022). The continued expansion of agriculture and agroforestry on sloped terrain has significantly altered soil properties, often leading to increased erosion, organic matter depletion, and soil fertility decline (Suprayogo *et al.*, 2020).

Land management intensity plays an important role in determining soil quality. Intensive agricultural practices such as horticultural cropping are often associated with soil degradation to nutrient depletion (Bravo-Medina *et al.*, 2021). On the other hand, land with minimal soil disturbance contributes to improved soil quality by enhancing organic matter retention and reducing erosion (Fitria, Sudarto and Kurniawan, 2021). The concept of land management intensity by Giller *et al.* (1997) provides a framework for assessing the extent of human intervention on soil health. Empirical studies have shown that intensive land management, particularly on steep slopes, accelerates soil erosion and nutrient loss, thereby undermining soil quality and agricultural sustainability (Yin, Zhao and Pereira, 2022). Slope gradient is a factor influencing soil quality where steep slopes (>25%) are particularly susceptible to degradation due to reduced water infiltration capacity, increased runoff, and soil loss (Su *et al.*, 2023). However, monoculture-based farming systems with high land management intensity result in soil degradation and deterioration of its health (Visser *et al.*, 2019).

In contrast to previous studies in the Brantas Hulu watershed, which only identified soil degradation and water discharge (Yetti *et al.*, 2011; Lusiana and Rahadi, 2018; Lusiana *et al.*, 2020) or vegetation cover-erosion relationships (Wiwoho *et al.*, 2021; Wiwoho and Asuti, 2022; Pambudi *et al.*, 2023), this study quantifies the relationship between land management intensity (*LMI*) and soil quality index (*SQI*) in an integrated manner, provides empirical data that soil degradation (low *SQI*) is more severe on the slopes >30% when combined with high *LMI*. The quantitative interaction between slope + *LMI* is identified as a key factor driving soil degradation.

This study aims to evaluate the impact of land management intensity on soil quality in relation to land use and slope gradients. Land management intensity was assessed using the framework defined by Giller *et al.* (1997), while soil quality was evaluated through the principal component analysis following the approach of Andrews, Karlen and Mitchell (2002). Further analysis explored the relationship between vegetation biomass and soil quality, relationship between land management intensity and soil quality, identifying how intensification practices contribute significantly to soil degradation. Addressing these interlinked factors supports the achievement of SDGs by advocating strategies that balance agricultural productivity with long-term soil and water conservation to inform policymakers in developing sustainable land management programmes.

MATERIALS AND METHODS

STUDY AREA

The study was conducted in the Upper Brantas Watershed Batu City, East Java Province, Indonesia, a region characterised by mountainous volcanic landscapes dominated by Andisols. The study area lies at 7°51'59.5" S and 112°30'45.4" E, covering a total area of approximately 202.3 km^2 (Fig. 1). Elevations range from 1,045 to 1,557 m a.s.l., and the region experiences a humid tropical climate with annual rainfall between 1,700 and 1,900 mm. The research was conducted on Andisol type soils. This type of soil develops from volcanic tuff and volcanic ash parent material; the soil is still young so that the soil formation process is still weak. The depth of the horizon with the properties of the soil is 36–60 cm (Hardjowigeno, 2003).

During the period from 2012 to 2017, the average monthly rainfall reached its minimum in September (14 mm) and its maximum in December (374 mm), as shown in Figure 2. In the subsequent period (2018–2022), the average annual rainfall in Batu City was recorded at 1,705 mm per year, marking an 11% decrease compared to the previous period (BPS, 2024). Daily air temperatures in the region range from 21 to 24°C, and relative humidity levels vary between 75 and 98%.

Geomorphologically, the Upper Brantas Watershed in Batu City is characterised by varied topography ranging from gentle slopes to steep hillsides, flanked by Mount Arjuno and Mount Panderman. The terrain is classified into five slope categories: (a) K1 (0–8%): nearly flat to gently sloping is 14%, (2) K2 (8–15%): moderately sloping is 15%, (3) K3 (15–25%): strongly sloping is 12%, (4) K4 (25–40%): steep slopes is 30%, (5) K5 (>40%): very steep slopes is 29% of total area of Upper Brantas watershed.

Batu City is recognised as an agropolitan region with a strong focus on horticultural development, including crops such as potato, carrot, mustard greens, garlic, cabbage, cauliflower, and leek. It is also a centre for fruit cultivation, particularly apples (*Malus sylvestris*) and oranges (*Citrus reticulata*). This study concentrated on six dominant land-use types that reflect varying levels of land management intensity across the landscape.

The "protected forest" (PF) represents areas with minimal human intervention and dense natural vegetation, serving as a benchmark for low-impact land use. "Pine-coffee agroforestry" (PCA) consists of pine tree stands with a coffee understory, offering moderate disturbance while retaining significant vegetative cover. Similarly, "pine-grass agroforestry" (PGA) features pine trees accompanied by a natural grass ground cover, contributing to moderate ecological stability. In "pine-horticulture agroforestry" (PHA), pine trees are intercropped with a variety of horticultural crops, resulting in higher management input and disturbance compared to the previous systems.

"Fruit plantation" (FP) areas involve the intensive cultivation of fruit trees under managed conditions, while

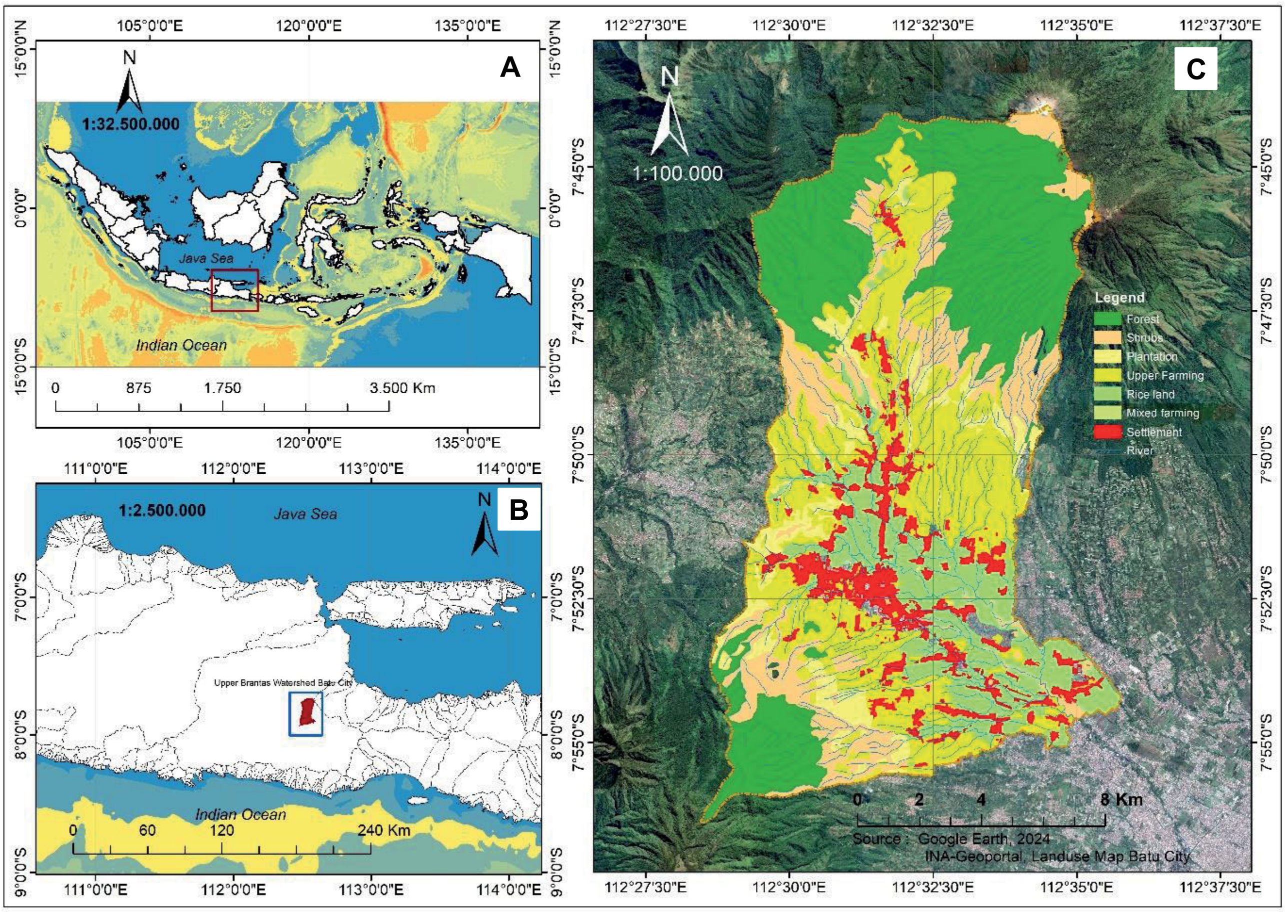

Fig. 1. Research locations in different scales: A) East Java Province, Indonesia, B) Brantas Watershed, C) Upper Brantas Watershed, Batu City, East Java Province; source: own elaboration based on https://tanahair.indonesia.go.id

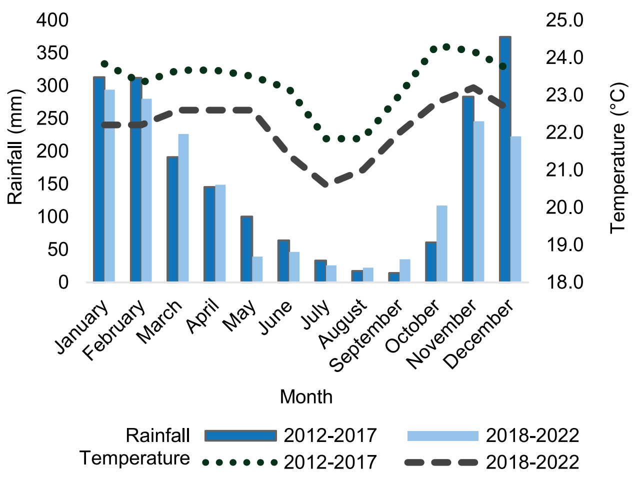

Fig. 2. Average annual rainfall and air temperature (2012–2017 and 2018–2022) Batu City; source: Central Statistics Agency, Batu City 2024

"upland farming" (UF) represents the highest land management intensity, characterised by open fields used for seasonal crops with frequent tillage and chemical input. These land-use types collectively form a gradient of land management intensity, ranging from the low-disturbance conditions of PF to the highly managed practices of upland farming. Their distribution and characteristics are detailed in Table 1 and visually represented in Photo 1.

DETERMINING LAND MANAGEMENT INTENSITY

Land management intensity (*LMI*) is a critical parameter used to quantify the extent of human intervention across different land-use systems. In this study, *LMI* was assessed using key indicators adapted from Giller *et al.* (1997), which include soil disturbance, chemical input levels, cropping intensity, vegetation cover, livestock grazing, and water conservation practices. These indicators collectively provide a comprehensive measure of how intensively a land area is managed and its potential impact on soil quality and ecosystem sustainability, which:

$$LMI = L \cdot N \cdot P \cdot E \cdot W \quad (1)$$

where: LMI = land management intensity, ranging from 0 (low) to 1 (high); L = land use intensity as defined by Ruthenberg (1980) with criteria if $L < 33\%$, the system is classified as shifting cultivation; if $33\% < L < 66\%$, it falls under the Bera farming system; and if $L > 66\%$, it is considered permanent farming, N = nutrient availability, with a value of 0 if the system relies entirely on internal nutrient recycling, and 1 if it depends 100% on external nutrient inputs; P = pest control, scored as 0 when there is no intervention and 1 when full mechanical or synthetic chemical control is applied; E = energy input per hectare, either in terms of labour or fuel usage; W = water management, where 0 signifies no intervention and 1 represents complete reliance on irrigation or drainage systems.

Table 1. Characteristics of the research site

Landscape	Location code	Height[1)] (m)	Land use
Protected forest (R-Suryo Forest Park, East Java Province)	protected forest (PF)	1,422–1,557	protected forest
State-Owned Forestry Enterprise of Indonesia (Perhutani)	pine-coffe agroforestry (PCA), pine-grass agroforestry (PGA), pine-horticulture agroforestry (PHA)	1,296–1,411	cultivation of coffee, grass and horticulture under pine stands; pine plants and horticultural crops (potatoes, carrots, broccoli, cabbage, leek)
Fruit garden (community property rights)	fruit plantation (FP)	1,045–1,290	monoculture apple and orange orchards
Upland farming (community property rights)	UF	1,376–1,466	horticultural crops (potatoes, carrots, leek, cabbage, broccoli)

[1)] Altitude is measured using Google Earth.
Source: own study.

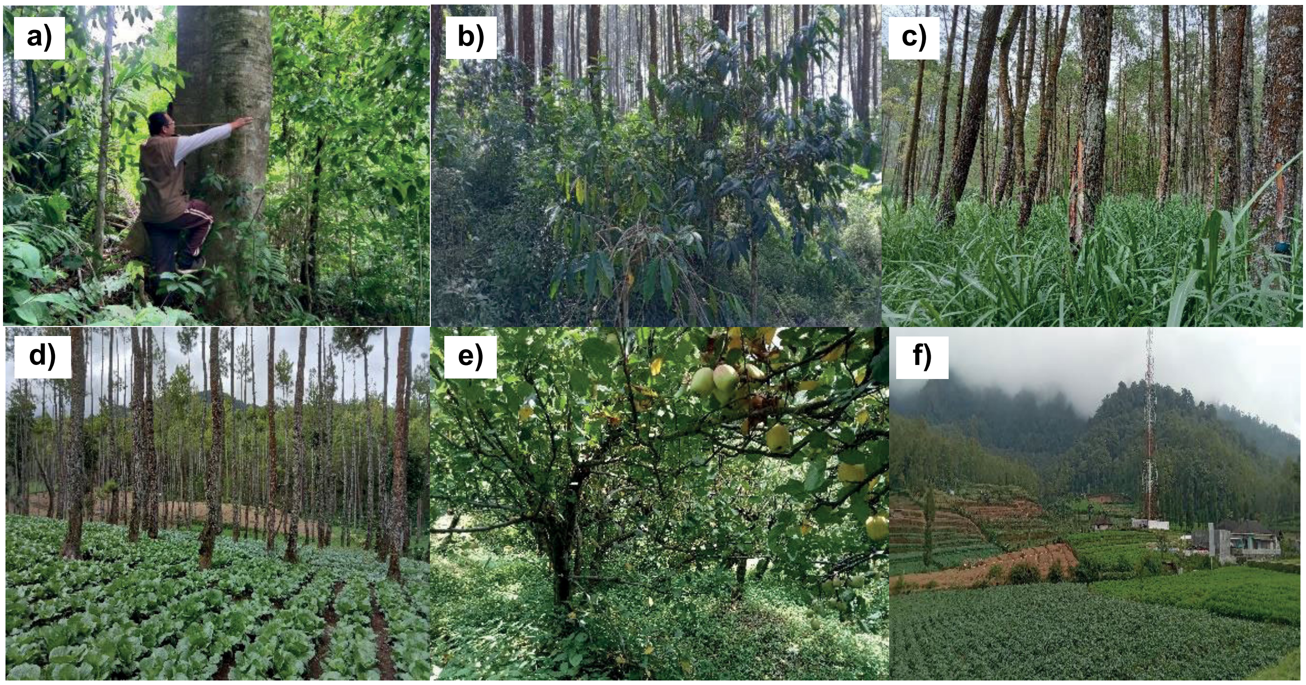

Photo 1. Land management patterns: a) protected forest (PF), b) pine-coffe agroforestry (PCA), c) pine-grass agroforestry (PGA), d) pine-horticulture agroforestry (PHA), e) fruit plantation (FP), f) upland farming (UF) (photo: *Hadi*)

Values of *LMI* were derived through interviews with 75 respondents, selected using a stratified random sampling method to ensure representative coverage across different land-use types.

EXPERIMENTAL DESIGN AND SAMPLING STRATEGY

A purposive random sampling approach was employed to capture the variability in soil quality and land management intensity across different land-use types and slope gradients. Sampling plots measuring 20 m × 20 m were established within each land-use category and slope class. Within each plot, three subplots of 1 m × 1 m were randomly selected for detailed soil sampling and vegetation biomass estimation. Soil samples were collected from a depth of 0–30 cm to assess topsoil characteristics. In total, 90 composite soil samples were collected for laboratory analysis, based on the sampling design of 3 subplots per plot across 6 land-use types and 5 slope categories.

DETERMINING OF VEGETATION DENSITY AND BASAL AREA

Vegetation density was determined by calculating the number of individual trees per unit area (ha). Data from each sample plot, measuring 20 m × 20 m for each land-use type, were converted to vegetation density per hectare. The basal area, also known as the ground area occupied by tree stems, represents the cross-sectional area of all trees at breast height per unit area of land and is a key parameter in estimating forest structure and biomass (Hairiah *et al.*, 2010). Basal area measurements were conducted as part of non-destructive tree biomass assessments. Within each sampling plot, all trees with a diameter at breast height (*DBH*) measured at 1.3 m above ground level were recorded. Only trees with a *DBH* between 5 cm and 30 cm were included in the analysis. Trees with a *DBH* less than 5 cm were categorised as part of the understory vegetation and excluded from basal area calculations. Vegetation density and basal area of the stand were computed using the appropriate standard equations, allowing for the quantification of aboveground biomass and its contribution to overall ecosystem structure and was calculated using the equation:

$$D = \frac{N}{A} \tag{2}$$

where: D = density of vegetation (tree·ha^{-1}), N = number of individuals, A = area of plot measurement.

$$BA = \frac{1}{4}\pi D^2 \tag{3}$$

where: BA = basal area (m^2·ha^{-1}), π = 3.14, D = diameter of the tree 1.3 m from the ground level (m).

DETERMINING PLANT BIOMASS WITH ABOVEGROUND BIOMASS (AGB)

Measurements were initially conducted within a standard plot size of 20 m × 20 m (400 m^2). However, if a tree with a diameter greater than 30 cm was present within the plot, the observation area was expanded to 20 m × 100 m (2,000 m^2) to minimise sampling error, following the methodology of Hairiah *et al.* (2011).

To estimate plant biomass across various land-use types, a combination of destructive and non-destructive methods was applied, depending on the type and structure of the vegetation. The focus was on estimating aboveground biomass (*AGB*) across different systems, including protected forests, agroforestry systems, fruit plantations, and upland farming areas. The allometric equations used for calculating tree biomass are provided in Table 2.

UNDERSTORY AND LITTER

Understory biomass sampling was conducted using a destructive method, in which plant material was harvested for analysis. Both understory vegetation and litter were measured following a rapid carbon stock assessment protocol, using sample quadrats measuring 50 cm × 50 cm. Fresh (wet) mass was recorded in the field, and sub-samples were collected for oven-drying to determine dry mass, in accordance with the method outlined by Hairiah *et al.* (2011). Collected samples were weighed to determine their wet mass and subsequently dried in an oven at 85°C for 48 h. After drying, the samples were reweighed to obtain their dry weight. Biomass of understory vegetation and litter was then calculated using standard equations described by Hairiah *et al.* (2011):

$$BK = \frac{BK_{\text{sub examples}}}{BB_{\text{sub examples}}}\ BB \tag{4}$$

where: BK = dry mass (g), BB = wet mass (g).

SOIL QUALITY INDICATOR ASSESSMENT

Soil quality was assessed using the *SQI* approach, incorporating principal component analysis and minimum data set scoring, as proposed by Andrews, Karlen and Mitchell (2002). This methodology integrates multiple physical, chemical, and biological indicators into a single composite index, providing a comprehensive evaluation of soil health.

The physical indicators used in this study included soil bulk density, particle density, porosity, soil texture, and aggregate stability. Bulk density (dry oven weight per unit volume) was determined from a block sample measuring 20 cm × 20 cm × 10 cm (4,000 cm^3), collected under field-moist conditions, following the method of Blake and Hartge (1986). Soil bulk density was also measured using the core method, which provides insight into compaction and soil porosity. Particle density (*PD*) was determined using the pycnometer method (Blake and Hartge, 1986).

Total soil porosity (ϕ), which is the percentage of total volume of soil that is not filled by solid particles (Nimmo, 2004) calculated using equations:

$$\phi = \left(1 - \frac{\rho_b}{\rho_p}\right)100\% \tag{5}$$

where: ϕ = porosity (%), ρ_b = bulk density (g·cm^{-3}), ρ_p = particle density (g·cm^{-3}).

Soil texture expressed as the percentage of sand, silt, and clay was analysed using the hydrometer method to classify soil types, following the procedure described by Aubert, Ollat and Pinta (1954). Aggregate stability, an indicator of a soil's resistance to erosion, was assessed using the wet sieving method, as outlined by Kemper and Rosenau (1986). Among the chemical indicators, soil organic carbon (SOC) was measured using the Walkley–Black

Table 2. Tree biomass calculation using allometric equations

Plant type	Allometric equation	Reference
Forest (humid)	$(AGB)_{\text{est}} = \rho\ x\ \exp(-1.499+2.148\ln(D)+0.207(\ln(D))^2-0.0281(\ln(D))^3)$	Chave *et al.* (2005)
Pine	$(AGB)_{\text{est}} = 0.0936D^{2.4323}$	Siregar (2007)
Mahogany	$(AGB)_{\text{est}} = 0.048\ D^{2.68}$	Adinugroho, Wahyu and Sidiyasa (2006)
Coffee tree trimmed	$(AGB)_{\text{est}} = 0.281D^{2.06}$	Arifin (2001)
Suren	$(AGB)_{\text{est}} = 0.00013D^{2.5017}$	Krisnawati, Wahyu and Rinaldi (2012)
Bamboo	$(AGB)_{\text{est}} = 0.131D^{2.28}$	Priyadarshini (2000)
Branched trees	$(AGB)_{\text{est}} = 0.11\rho\ D^{2.62}$	Ketterings *et al.* (2001)
Unbranched trees	$(AGB)_{\text{est}} = \pi\ \rho\ H\ D^2{:}40$	Hairiah *et al.* (2011)

Explanations: $(AGB)_{\text{est}}$ = estimated biomass of trees in the upper part of the soil (kg·tree^{-1}), $D = DBH$, diameter at breast height (cm), ρ = wood density (kg·m^{-3}).
Source: own elaboration based on literature.

method (Black, 1965), which provides an estimate of readily oxidisable organic matter in the soil. Soil total nitrogen (TN) was determined using the Kjeldahl digestion method, following the procedure outlined by Black (1965). Available phosphorus (P) was extracted using the Bray-1 method to evaluate nutrient availability, in accordance with Bray and Kurtz (1945). Soil pH (in H_2O) was measured using a calibrated pH meter, following standard procedures described by Clesceri, Greenberg and Eaton (1998).

DETERMINATION OF SOIL MICROBIAL BIOMASS

Microbial biomass was estimated using the chloroform fumigation extraction (CFE) method, as described by Vance, Brookes and Jenkinson (1987). Fresh, moist soil samples (10 g) were weighed and subjected to fumigation for 72 h using 40 cm^3 of alcohol-free chloroform ($CHCl_3$) placed in a desiccator stored in a dark environment. The fumigation process lyses microbial cells, releasing cytoplasmic contents into the soil matrix (Husen *et al.*, 2022). The extraction solution consisted of 0.5 M K_2SO_4, prepared by dissolving 87.135 g of potassium sulphate in 1,000 cm^3 of distilled water. After fumigation, the soil samples were extracted using 50 cm^3 of the 0.5 M K_2SO_4 solution. A parallel extraction was conducted on non-fumigated soil subsamples to serve as controls. All soil extracts were filtered through Whatman No. 42 filter paper prior to analysis.

The total C-microbial biomass in the soil subsample extract was calculated by the titration method. The C-microbial biomass (mg·kg^{-1} soil) estimate was calculated using the following Equation (Vance, Brookes and Jenkinson, 1987):

$$\mathrm{S, C} = \mathrm{Corganic(S, C)}\frac{V}{B} \tag{6}$$

$$\mathrm{Cmicrobial\ biomass} = \frac{S - C}{0,38} \tag{7}$$

where: S = value of C-organic extract sample with chloroform, C = value of C-organic extract control without chloroform, V = total sample volume extracted (cm^3), B = soil sample mass (g), 0.38 = kEC factor (conversion of C to C-microbial estimate)

CALCULATION OF SOIL QUALITY INDEX (*SQI*)

The *SQI* was determined using PCA with the aid of IBM SPSS 25. This was followed by the selection of a minimum data set derived from physical, chemical, and biological indicators of soil properties. The minimum data set variables were selected based on the highest loading values in the component matrix of each principal component (PC). Subsequently, the scoring of the minimum data set data was carried out using the method proposed by Andrews *et al.* (2002), as follow:

$$y = \frac{x - s}{1.1t - s}\ \text{for more is better} \tag{8a}$$

$$y = 1 - \frac{x - s}{1.1t - s}\ \text{for less is better} \tag{8b}$$

where: y = score from the ground, x = value of soil properties, s = the lowest possible value of the soil trait (s = 0), t = the highest value of the soil trait the combination of the indicator score is combined into a soil quality index.

Next, the weight is calculated using the equation:

$$W_i = \frac{\sum_{k=1}^{m} L_{i,k} \cdot V_k}{\sum_{j=1}^{p}\sum_{k=1}^{m} L_{i,k} \cdot V_k} \tag{9}$$

where: $L_{i,k}$ = loading of the i variable in the k principal component, V_k = percentage of variance explained by the k principal component, i = soil variable, j = sum of the all soil variable, k = principal component, p = total number of soil variables analysed, m = number of PCs retained (generally based on the criteria of eigenvalue > 1 or cumulative variance ≥ 70%).

The *SQI* was calculated using a scoring function in which each parameter was normalised on a scale from 0 to 1, with higher values indicating better soil quality. An *SQI* value closer to 1 reflects higher soil quality. The final *SQI* was computed as follows:

$$SQI = \sum_{I=1}^{n} W_i \cdot S_i \tag{10}$$

where: W_i = weight assigned to each parameter see Eq. (9), S_i = standardised score.

Classification criteria of the soil quality for the minimum data set using grade includes grade 1 (very high ≥0.60), grade 2 (high = 0.55–0.60), grade 3 (moderate = 0.45–0.54), grade 4 (low = 0.38–0.44), grade 5 (very low <0.38) (Li *et al.*, 2018).

DATA ANALYSIS

Data analysis was conducted to evaluate the effects of land management intensity, land use types, and slope gradients on soil quality indicators. Analysis of variance (ANOVA) was employed to compare soil physical and chemical properties across different land-use types and slope categories. Tukey's HSD post-hoc test was applied to identify statistically significant differences between groups at a significance level of $p < 0.05$. To assess relationships between land management intensity (*LMI*), vegetation biomass, and the *SQI*, Pearson's correlation analysis was performed. Multiple linear regression models were used to quantify the influence of *LMI* and slope gradients on soil degradation, which helped to identify key drivers of soil quality deterioration across various land uses. All statistical analyses were conducted using IBM SPSS Statistics (ver. 25). Prior to analysis, the data were tested for normality using the Shapiro–Wilk test, homogeneity of variances using Levene's test, and screened for outliers to ensure the reliability of the results.

RESULTS AND DISCUSSION

RESULTS

Land management intensity (*LMI*)

The amount of fertiliser, pesticide, labour and water use affected *LMI*. On UF land, the use of organic fertilisers reached 55.5 Mg·ha^{-1}·$year^{-1}$ and chemicals 3.64 Mg·ha^{-1}·$year^{-1}$. The highest pesticide use was 15 dm^3·ha^{-1}·$year^{-1}$ (liquid) and 45 kg·ha^{-1}·$year^{-1}$ (powder). In addition, the number of workers is 313 person-day·ha^{-1}·$year^{-1}$ and water consumption is 991.2 m^3·ha^{-1}·$year^{-1}$. The use of the smallest production factor is found on PGA land.

The average use of fertiliser of 0.3 Mg·ha^{-1}·year^{-1} (urea) to accelerate the growth of elephant grass. Labour consumption is very low at 15.1 person-day·ha^{-1}·year^{-1}. The average harvest period is 4–5 months and is harvested in stages according to the needs of farmers for animal feed. The production factors of several land uses are presented in Figure 3.

Results of farmer interviews indicate that UF demonstrates the highest land management intensity, ranging from 0.67 to 0.71, while PHA by 0.50–0.56 *LMI* and PGA shows the lowest intensity, ranging from 0.16 to 0.19. Based on the analysis, land management intensity follows a decreasing trend in the order: UF > PHA > FP > PCA > PGA (Tab. 3).

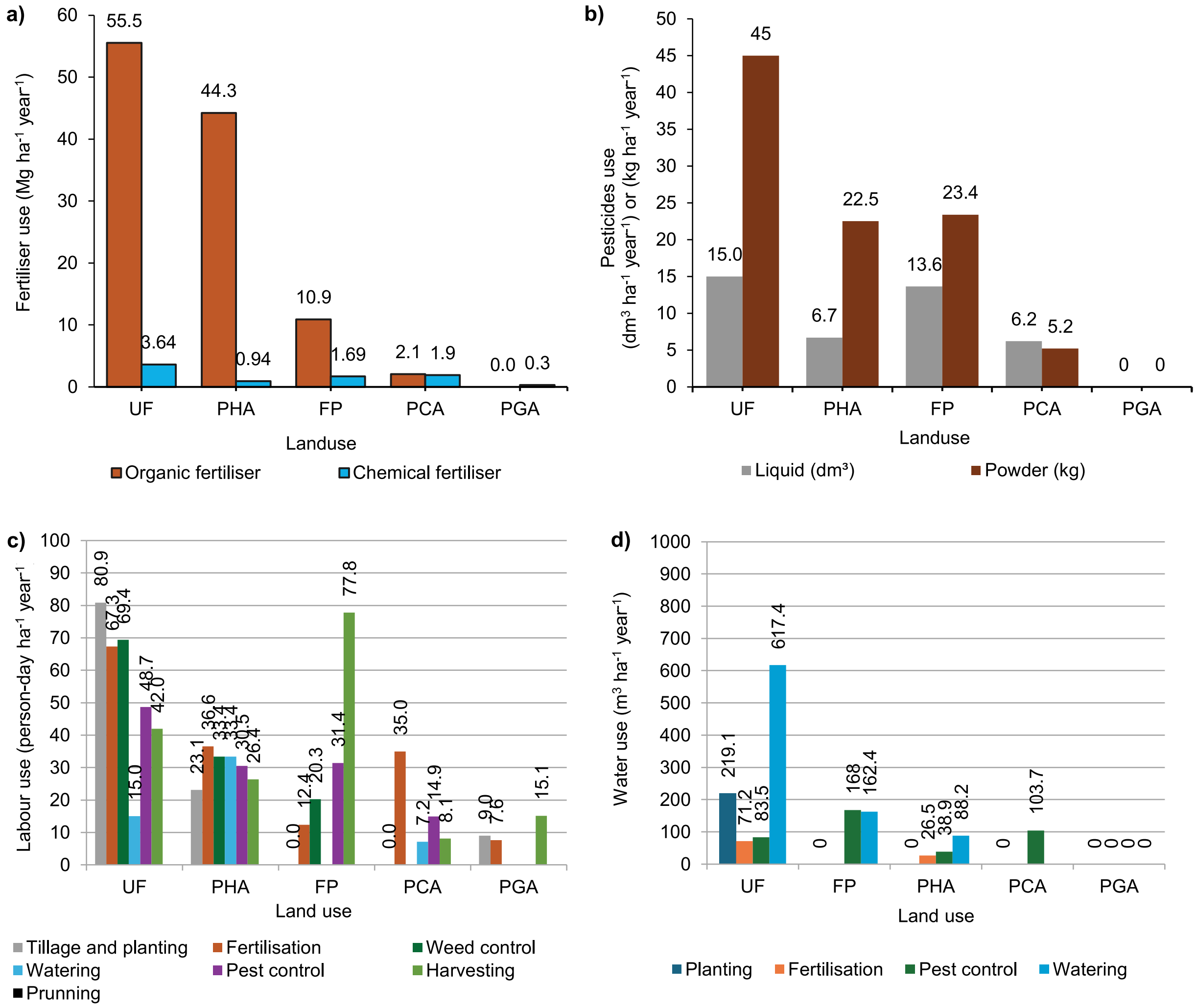

Fig. 3. The use of production factors in several types of land use: a) fertiliser use, b) pesticide use, c) labour use, d) water use; UF, PHA, FP, PCA, PGA = as in Photo 1; source: own study

Table 3. Intensity of land management in various land uses

Slope (%)	Land use management intensity (*LMI*)				
	UF	PHA	FP	PCA	PGA
K1	0.68 ±0.01b	0.50 ±0.01c	0.40 ±0.01b	0.19 ±0.01bc	0.16 ±0.01c
K2	0.70 ±0.00a	0.51 ±0.02bc	0.43 ±0.00ab	0.18 ±0.01c	0.16 ±0.01c
K3	0.69 ±0.01ab	0.51 ±0.05bc	0.43 ±0.01ab	0.20 ±0.00ab	0.18 ±0.01b
K4	0.71 ±0.01a	0.54 ±0.00ab	0.42 ±0.02ab	0.21 ±0.01a	0.19 ±0.00ab
K5	0.71 ±0.01a	0.56 ±0.04a	0.45 ±0.01a	0.22 ±0.01a	0.20 ±0.01a

Explanations: UF, PHA, FP, PCA, PGA = as in Photo 1, K1 = 0–8%: nearly flat to gently sloping, K2 = 8–15%: moderately sloping, K3 = 15–25%: strongly sloping, K4 = 25–40%: steep slopes, K5 = over 40%: very steep slopes; the same letter indicates no statistically significant differences between locations with Fisher's *LSD* test ($p < 0.05$).
Source: own study.

Plant biomass and soil quality index status

• Plant biomass

The biomass analysis across different land-use types reveals that PF possesses the highest vegetation biomass, ranging from 541.4 to 675.2 Mg·ha^{-1}, whereas UF areas record the lowest biomass, at only 3.5–5.5 Mg·ha^{-1}. In PF areas, the basal area ranges from 81.5 to 87.4 m^2·ha^{-1}, with tree densities between 1,163.3 and 1,325.0 trees per ha (Tab. 4). Biomass composition within PF is dominated by tree stands, which contribute 98.3–99.1% of the total biomass, while the understory and litter account for just 0.14–0.38% and 0.5–1.6%, respectively. In FP lands, total biomass ranges from 89.4 to 160.2 Mg·ha^{-1}, consisting of standing biomass (86.8–156.1 Mg·ha^{-1}), understory biomass (1.87–2.78 Mg·ha^{-1}), and litter biomass (0.68–1.29 Mg·ha^{-1}). Total biomass in different types of land and slopes is presented in Table 4.

• Soil quality index (*SQI*) status

The results of the analysis of soil indicators on Andisols in the upstream Brantas watershed Batu City showed that soil pH (4.24–6.95), N-total (0.15–1.24%), P-available (12.31–44.5 ppm), K-exchangeable (0.11–0.77 cmol·kg^{-1}), C-organic (1.45–11.7%), bulk density (0.54–0.94 g·cm^{-3}), soil specific gravity (1.66–2.29 g·cm^{-3}),

Table 4. The relationship between basal area, vegetation density, and biomass

Land type	Slope (%)	Basal area (m^2·ha^{-1})	Density (tree·ha^{-1})	Vegetation biomass (Mg·ha^{-1})			Total biomass (Mg·ha^{-1})
				tree	understory	litter	
PF	K1	87.4	1,325.0	663.5	0.95	10.79	675.2
	K2	83.8	1,225.0	632.3	1.35	8.59	642.2
	K3	81.2	1,201.7	594.9	1.75	7.41	604.1
	K4	81.5	1,228.3	560.4	1.79	6.15	568.3
	K5	83.5	1,163.3	536.6	2.06	2.72	541.4
PCA	K1	69.2	3,923.3	466.1	0.94	8.62	475.7
	K2	67.7	3,201.7	457.6	0.99	6.37	465.0
	K3	66.7	2,838.3	422.5	1.39	4.68	428.6
	K4	62.7	2,600.0	405.9	1.13	4.16	411.2
	K5	58.6	2,570.0	383.8	1.03	2.27	387.1
PGA	K1	30.1	170.0	281	4.86	1.89	287.7
	K2	28.3	156.7	276.7	4.17	1.18	282.1
	K3	26.3	158.3	243.5	3.81	0.98	248.3
	K4	25.1	145.0	236.5	3.84	0.93	241.3
	K5	23.4	160.0	221.7	3.76	0.68	226.1
PHA	K1	25.2	141.7	226.6	4.46	0.90	232.0
	K2	22.5	138.5	218.9	4.58	0.63	224.1
	K3	21.2	131.3	196.9	3.78	0.45	201.1
	K4	20.2	130.0	188.2	3.61	0.39	192.2
	K5	18.4	116.7	170.3	3.49	0.34	174.1
FP	K1	52.7	3,200	156.1	2.78	1.29	160.2
	K2	48.4	3,100	134.9	2.49	1.03	138.4
	K3	45.9	3,000	133.7	2.28	1.08	137.1
	K4	42.6	2,800	105.1	2.20	0.78	108.1
	K5	43.1	2,900	86.8	1.87	0.68	89.4
UF	K1	–	–	–	5.10	0.37	5.5
	K2	–	–	–	4.58	0.32	4.9
	K3	–	–	–	4.50	0.26	4.8
	K4	–	–	–	3.84	0.28	4.1
	K5	–	–	–	3.30	0.21	3.5

Explanations: K1, K2, K3, K4, K5 = as in Tab. 3, PF, UF, PHA, FP, PCA, PGA = as in Photo 1, the sign (–) indicates that there are no components on the land.
Source: own study.

porosity (53.6–69.1%), sand fraction (44–66%), dust (22–42%), and clay (10–16%). Based on soil indicator analysis, PF had the highest indicator values at N-total (0.6–1.2%), P-available (34.8–42.9 ppm), K-exchangeable (0.46–0.75 cmol·kg^{-1}), C-organic (8.7–11.2%) and microbial biomass carbon (MBC), 67.9–79.3 mg·kg^{-1}). The results of the analysis of soil variables are presented in Table S1.

Based on the results of principal component analysis of soil indicators, it shows that there are three main components with a cumulative variance percentage of 81.143. The minimum data set (MDS) selected is based on the highest value of the soil indicator on each PC. The results of the principal component analysis are presented in Table 5.

Table 5. Principal component analysis of soil properties

Parameter	PC1	PC2	PC3
Principal component analysis			
Eigenvalue	6.433	2.001	1.303
Percentage of variance	53.612	16.676	10.856
Cumulative variance percentage	53.612	70.288	81.143
Factor loadings (rotated component matrix)			
pH	0.646	−0.109	−0.301
N-total (%)	0.877	0.148	0.314
P-available (ppm)	0.938	0.161	0.230
K-exchangeable (cmol·kg^{-1})	0.856	0.001	0.104
C-organic (%)	0.902	0.214	0.243
Bulk density soil (g·cm^{-3})	−0.774	−0.102	0.594
Soil specific gravity (g·cm^{-3})	−0.645	0.186	0.558
Porosity (%)	0.613	0.405	−0.361
Sand (%)	−0.425	0.886	−0.057
Dust (%)	0.288	−0.905	−0.037
Clay (%)	0.571	−0.233	0.373
MBC (mg·kg^{-1})	0.918	0.171	0.228

Explanation: PC = principal component, MBC = microbial biomass carbon.
Source: own study.

Result principal component analysis shows value eigenvalues of PC1 (6.433), PC2 (2.001) and PC3 (1.303). The MDS is selected based on the highest score. In PC1 the main component that has the highest loadings value is phosphorus, there is a very high correlation between P-available and N-total, K-exchangeable, C-organic and MBC. Therefore, the minimum variable of the data set taken is phosphorus because it has the highest loadings factor value of 0.938. In PC2, the sand variable was selected and PC3 the weight of the soil bulk density was selected. The MDS formed from the PCA analysis is the phosphorus, sand fraction and bulk density weight. Cumulative percentage variance and MDS weighting are presented in Table 6.

Based on the correlation analysis of soil quality indicators, pH has a significant relationship with all soil indicators, N-total has a very strong relationship with P-available, K-exchangeable, C-organic and MBC whereas C-organic has a strong

Table 6. Matrix of minimum data set (MDS) of soil quality indicator

PC	% variance	% cumulative	Weight[1)]	MDS
1	53.612	53.612	0.6607	phosphorus available
2	16.676	70.288	0.2055	sand
3	10.856	81.143	0.1338	bulk density soil

[1)] The weight is calculated from the % of the variant divided by the total % cumulative.
Explanation: PC = principal component.
Source: own study.

relationship with MBC, P-available, K-exchangeable. The results of the correlation analysis between variables are presented in Table 7.

The ANOVA statistical analysis revealed significant differences in soil quality across land-use types, with an F-value of 70.13 (p-value <0.000), indicating that variations in land management practices significantly impact soil quality. The smallest significant difference test showed that the *SQI* values in PGA and PF were not significantly different. Soil parameter analysis at 0–8% slope indicated that organic carbon (C) content was highest in PCA at 7.9 ±0.8%, with organic matter content at 13.7 ±1.4%. The total nitrogen (N) content (0.6%) was similar across PCA, PGA, and FP, while the highest available phosphorus (P) values (31.3–34.4 ppm) were found in PGA, FP, and PHA.

The *SQI* for slopes ranging from 0–8% across six land-use types varied between 0.51 and 0.76. The highest *SQI* was recorded in PF at 0.76, followed by PCA at 0.65 and FP at 0.60. Good soil quality was observed in unmanaged forested land and land managed under conservation-based agricultural systems, such as plantations and grasslands (Francaviglia *et al.*, 2014). The ranking of *SQI* values from highest to lowest was PF > PCA > FP > PGA > UF > PHA (Fig. 4).

At 8–15% slope, the *SQI* values ranged from 0.46 to 0.74, with the highest value recorded in PF (0.74) and the lowest in UF (0.46). The ANOVA analysis confirmed significant *SQI* differences across land uses, with an F-value of 23.41 (p-value < 0.000). The smallest significant difference test indicated that *SQI* values in FP (0.56) and PGA (0.55) were not significantly different, while PHA and UF also showed no significant differences. Soil parameter analysis for this slope category revealed C-organic content of 5.9 ±1.0% and organic matter content of 10.3 ±1.7%. In PHA and UF, C-organic content ranged from 2.6 ±0.3% to 3.4 ±0.1%, while total N ranged between 0.2 ±0.6% and 0.2 ±0.2%. Across all slope categories, PF consistently exhibited the highest *SQI*, whereas UF and PHA had the lowest values. Additionally, findings indicate that as slope increases, soil quality tends to decline.

Relationship between vegetation biomass and soil quality index

Correlation analysis revealed a positive relationship between vegetation biomass and the *SQI* across all land-use types. The strongest correlation was observed in PF (R^2 = 0.83) and PCA (R^2 = 0.75), followed by PHA (R^2 = 0.76), PGA (R^2 = 0.51), FP (R^2 = 0.42), and UF (R^2 = 0.75) – Figure 5.

Table 7. Pearson correlation matrix between soil properties

Soil quality indicator	pH	N-total (%)	P-available (ppm)	K-exchangeable (cmol·kg^{-1})	C-organic (%)	Soil bulk density (g·cm^{-3})	Soil specific gravity (g·cm^{-3})	Porosity	Sand	Dust	Clay	MBC (mg·kg^{-1})
								%				
pH	1.000											
N-total (%)	0.401*	1.000										
P-available (ppm)	0.520*	0.901*	1.000									
K-exchangeable (cmol·kg^{-1})	0.522*	0.803*	0.820*	1.000								
C-organic (%)	0.438*	0.902*	0.926*	0.740*	1.000							
Soil bulk density (g·cm^{-3})	−0.557*	−0.503*	−0.605*	−0.568*	−0.579*	1.000						
Soil specific gravity (g cm^{-3})	−0.489*	−0.387*	−0.455*	−0.529*	−0.416*	0.841*	1.000					
Porosity (%)	0.408*	0.453*	0.545*	0.398*	0.545*	−0.758*	−0.286*	1.000				
Sand (%)	−0.309*	−0.261*	−0.265*	−0.333*	−0.218*	0.216*	0.347*	0.028^{ns}	1.000			
Dust (%)	0.217*	0.145^{ns}	0.111^{ns}	0.229*	0.094^{ns}	−0.152^{ns}	−0.291*	−0.076^{ns}	−0.961*	1.000		
Clay (%)	0.374*	0.450*	0.585*	0.428*	0.476*	−0.246*	−0.246*	0.147^{ns}	−0.446*	0.199*	1.000	
MBC (mg·kg^{-1})	0.461*	0.910*	0.936*	0.759*	0.959*	−0.592*	−0.431*	0.554*	−0.265*	0.143^{ns}	0.474*	1.000

Explanations: MBC = microbial biomass carbon, * correlation is significant at the 0.05 level, ns = non-significant.
Source: own study.

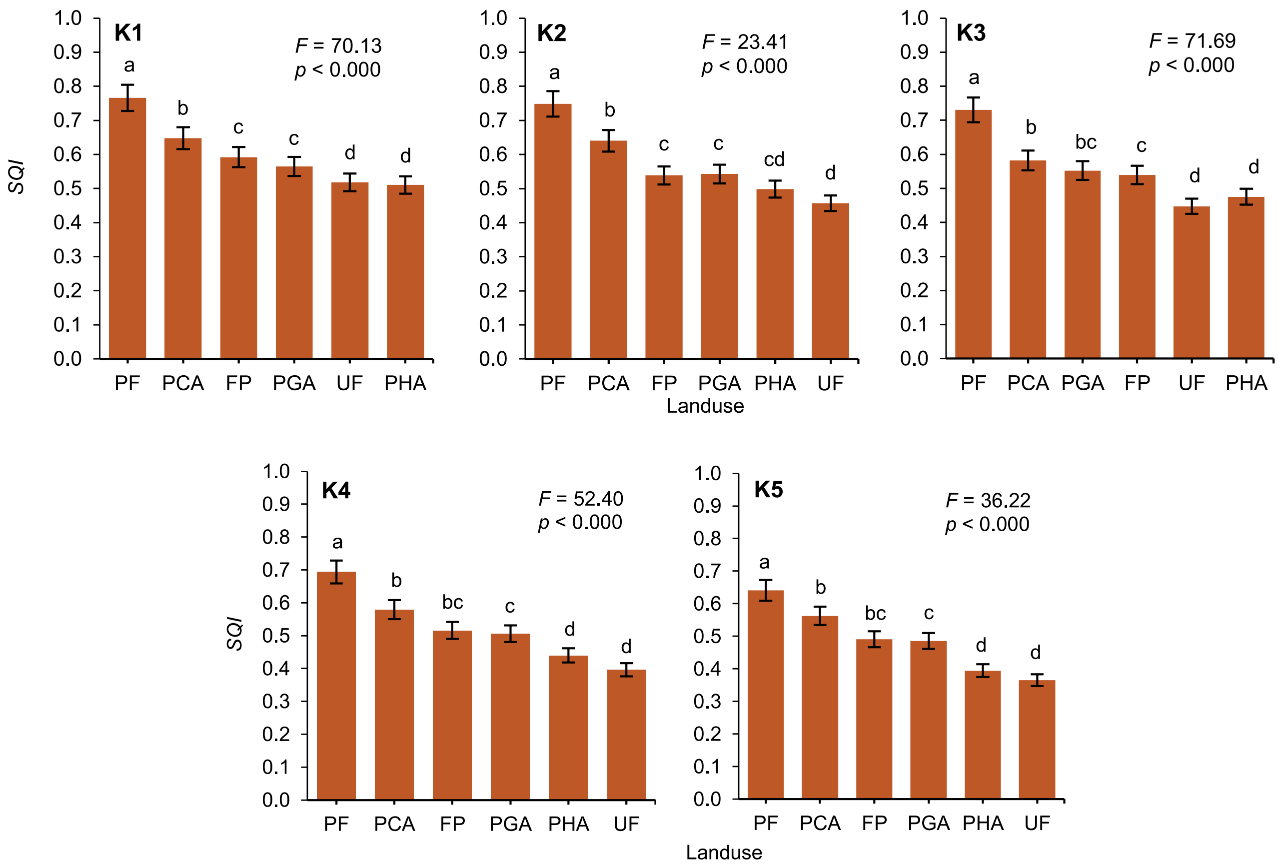

Fig. 4. Soil quality index (*SQI*) on various land uses based on slope class; K1, K2, K3, K4, K5 = as in Tab. 3, PF, PCA, FP, PGA, PHA, UF as in Photo 1; the same letter indicates no statistically significant differences between locations with Fisher's *LSD* test ($p < 0.05$); source: own study

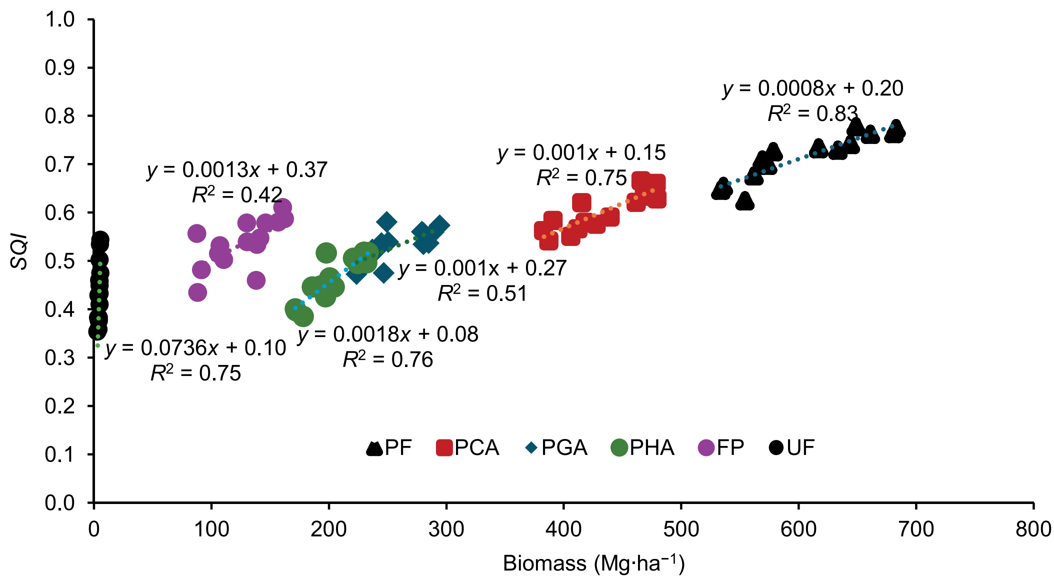

Fig. 5. Relationship between plant biomass and soil quality index (*SQI*) in Andisols; PF, PCA, PGA, PHA, FP, and UF as in Photo 1; source: own study

In PF land, vegetation biomass ranged from 541.4 to 675.2 Mg·ha^{-1}, with an *SQI* of 0.64–0.76. The biomass composition consisted of 98.3–99.1% tree biomass, 0.5–1.6% litter, and 0.14–0.38% understory vegetation. Similarly, PCA land had a vegetation biomass of 387.1–475.7 Mg·ha^{-1}, with an *SQI* of 0.57–0.65, composed of 98–99.2% tree biomass, 0.59–1.81% litter, and 0.2–0.32% understory vegetation. Litter contributes significantly to soil organic matter decomposition, facilitated by soil fauna and microbial activity (Prescott and Vesterdal, 2021). In both PF and PCA lands, litter biomass accounted for 3.7–4.2% of total biomass, enhancing soil fertility and *SQI* values.

In PGA land, vegetation biomass was 226.1–287.7 Mg·ha^{-1}, with an *SQI* of 0.49–0.57. The composition included 97.7–98.1% tree biomass, 1.48–1.69% understory, and 0.30–0.66% litter. In FP land, vegetation biomass was 89.4–160.2 Mg·ha^{-1}, with an *SQI* of 0.50–0.60, consisting of 97.7–97.9% tree biomass, 1.88–2.05% understory, and 0.2–0.39% litter.

Vegetation biomass in PHA land ranged from 174.1 to 232.0 Mg·ha^{-1}, with an *SQI* of 0.40–0.51. The biomass composition included 97.1–97.5% tree biomass, 1.6–2.03% understory, and 0.72–0.81% litter. The lowest biomass (3.5–5.5 Mg·ha^{-1}) was found in UF land, with a dominant contribution from understory plants (93.2–94.62%) and litter (5.38–6.78%). The *SQI* of UF land was 0.37–0.52. These results confirm that higher vegetation biomass contributes to better soil quality, particularly in forest and agroforestry systems, where tree biomass and litter input play a crucial role in maintaining soil health.

Relationship between land management intensity and soil quality index

Correlation analysis between *LMI* and *SQI* revealed a negative relationship across all land-use types, indicating that higher management intensity leads to lower soil quality. The strength of this negative correlation varied among land uses, with PCA (R^2 = 0.72), PGA (R^2 = 0.57), UF (R^2 = 0.80), PHA (R^2 = 0.65), and FP (R^2 = 0.66) – Figure 6.

existing root systems. Farmers employ a daily rotational harvest system, with fertilisation every 1–2 months using NPK fertilisers.

In FP land, *LMI* ranged from 0.40 to 0.45, with an *SQI* of 0.50–0.60. This moderate intensity is influenced by labour use (142 person-day·ha^{-1}·year^{-1}), fertilisation using compost (11 Mg·ha^{-1}·year^{-1}) and chemical fertilisers (1.69 Mg·ha^{-1}·year^{-1}), and pesticide applications of 13.6 dm^3·ha^{-1}·year^{-1} (liquid) and 23.4 kg·ha^{-1}·year^{-1} (powder). Additionally, farmers apply 1–2 kg of goat manure and 0.5–1 kg of inorganic fertiliser per tree per year.

The highest land management intensity was observed in PHA and UF lands, both exhibiting low *SQI* values. An *LMI* of PHA land was of 0.50–0.56 and an *SQI* of 0.40–0.51, while UF land had an *LMI* of 0.68–0.71 with an *SQI* of 0.37–0.52. The high *LMI* in UF was influenced by intensive labour input (313 person-day·ha^{-1}·year^{-1}) and extensive fertilisation, including compost (55.53 Mg·ha^{-1}·year^{-1}) and chemical fertilisers (3.64 Mg·ha^{-1}·year^{-1}). These findings confirm that higher land management intensity negatively affects soil quality, particularly in upland farming and horticultural agroforestry systems.

The findings of this study confirm that land management intensity significantly influences soil quality, with higher-intensity land use associated with lower soil quality indices. This is consistent with the hypothesis that intensive land management practices, particularly in UF and PHA, lead to soil degradation, while conservation-based systems such as PF and agroforestry maintain higher soil quality. The negative correlation between land management intensity and soil quality observed across all land-use types highlights the detrimental effects of excessive soil disturbance, chemical inputs, and continuous cropping on Andisol. This is in accordance with the results of intensive agricultural practice research that can significantly reduce soil organic C (SOC) (Don, Scumacher and Freibauer, 2011; Ali *et al.*, 2025) affect the abundance and activity of soil biota (Noordwijk van and Hairiah, 2006). Li *et al.* (2021) also stated that reducing the intensity of land management can improve soil quality.

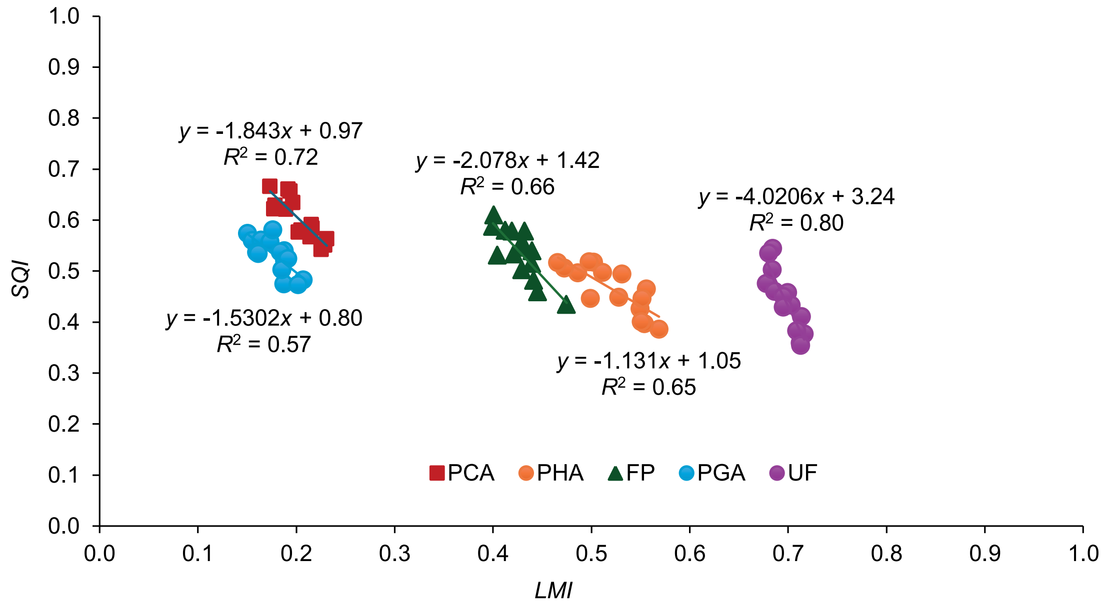

Fig. 6. The relationship between land management intensity (*LMI*) and soil quality index (*SQI*) in Andisols; PF, PCA, PGA, PHA, FP, and UF as in Photo 1; source: own study

DISCUSSION

In PCA land, *LMI* ranged from 0.19 to 0.22, with an *SQI* of 0.57–0.65. The low intensity of land management in PCA was attributed to minimal labour use (74 person-day·ha^{-1}·year^{-1}) and low fertiliser application, as high inorganic fertiliser costs (2.1 Mg·ha^{-1}·year^{-1}) limit usage. Higher *SQI* of PCA is largely due to organic matter accumulation from decomposing litter, which enhances soil fertility and supports coffee plant growth.

For PGA land, *LMI* was 0.16–0.20, with an *SQI* of 0.49–0.57. The moderate land management intensity in PGA results from minimal intervention, as farmers only harvest and fertilise grass. Grass planting occurs once, with new growth emerging from

Vegetation biomass plays a crucial role in maintaining soil fertility and organic matter levels, particularly in PF and PCA, where high aboveground biomass (541.4–675.2 Mg·ha^{-1} in PF and 387.1–475.7 Mg·ha^{-1} in PCA) supports high *SQI* values (0.64–0.76 and 0.57–0.65, respectively). On Lombok Island, the biomass of protected forests in the Jangkok watershed is 784.8 Mg·ha^{-1} (Markum *et al.*, 2013). The biomass value of the PGA in The Upper Brantas watershed was not too different from the results of the study in Kalikonto watershed, where the biomass reached 207.5 Mg·ha^{-1} in 24-year-old pine plants and elephant grass at four months of age (Hairiah *et al.*, 2010). These systems benefit from natural litter decomposition, which contributes to soil organic matter and nutrient cycling, enhancing soil structure, microbial activity, and moisture retention (Prescott and Vesterdal, 2021).

These findings align with León and Osorio (2014), who emphasised the role of litter and decomposition in improving soil properties. Litter fall is a key process in organic matter recycling, determining soil quality, nutrient cycling, and biological activity (Norgrove and Hauser, 2000; Wang *et al.*, 2008; Austin and Ballaré, 2010). Similarly, Zhang Y. *et al.* (2021) highlighted the role of vegetation in enhancing soil quality through litter decomposition and nutrient release, inducing ecological and physicochemical soil changes. The presence of trees in agroforestry systems can reduce the speed of surface runoff and thus reduce sediment transport capacity (Lal, 1989), while increased surface litter associated with perennials can help reduce damage and soil release (Fu, Luo and Chai, 1995). Results by Markum and Rahman (2024) of Jangkok watershed, Lombok Island, shows the average runoff of 3.61% for primary forest surfaces, disturbed forest – 5.67%, candlenut agroforestry – 6.60%, multistrata agroforestry – 10.20%, and simple agroforestry – 7.58%. In addition, land use changes in Batu City resulted in a reduction in forest cover (from 31 to 23%) and agroforestry (from 3 to 2%), which had an impact on increasing food hazards by 16% (Putra *et al.*, 2025).

The minimum data set analysis of the main components consists of phosphorus, and sand and soil content weight. The phosphorus content in the Brantas watershed upstream of Batu City is in the high category at PF (34.8–42.9 ppm), PCA (25.5–32.8 ppm) and UF (12.6–22.5 ppm). Phosphate levels are high due to fertilisation and volcanic ash (Anda and Sarwani, 2012). Phosphorus as a PC in line with research (Masto *et al.*, 2008; Li *et al.*, 2018; Yu *et al.*, 2018; Saurabh *et al.*, 2021; Zou *et al.*, 2021) while, sand as PC was identified in line with previous research (Zou *et al.*, 2021; Zahedifar, 2023) and the bulk density soil as PC was considered consistent with previous research (Masto *et al.*, 2008; Guo *et al.*, 2017; Li *et al.*, 2018; Shao *et al.*, 2020).

A notable finding in this study was that soil quality declined with increasing slope gradients, regardless of land-use type. At 0–8% slope, *SQI* values ranged from 0.51 to 0.76, with the highest in PF and the lowest in PHA. The conversion of forest to PHA reduced the *SQI* by 33.3%. However, at 8–15% slope, *SQI* values dropped (0.46–0.74), with UF exhibiting the lowest soil quality (0.46). The change of forest to UF land led to a decrease in *SQI* by 39.1% while the conversion of forest functions to intensively managed PHA resulted in a decrease in *SQI* by 33.4%. The intensity of PHA managed by forest farmer groups ranged from 0.50 to 0.56. If not accompanied by soil and water conservation, this community activity have an impact on declining land quality in the future. This is in line with Safaei *et al.*, (2019), who found that soil quality indicators decline significantly when dense forests turn into sparse forests or degraded land. This is in line with Bakhshandeh *et al.* (2019) that land use change lowers all soil quality parameters (physical, chemical, biological properties) associated with tillage, poor management and soil erosion.

This aligns with previous studies (León and Osorio, 2014; Zhang B. *et al.*, 2021), which emphasise the role of litterfall and organic matter decomposition in improving soil properties. The results of the research by Shao *et al.* (2020) showed that in pine forests in China with a canopy density of 60–70%, the *SQI* value ranged from 0.53 to 0.63. Similarly, in Nepal, the *SQI* value was 0.82 for forest land and 0.40 for degraded land (Ghimire *et al.*, 2018). Moreover, the *SQI* at a depth of 0–10 cm was 2.23 in land with tree vegetation and 2.57 in grassland, with a drastic decrease observed at a depth of 40–60 cm (Zhang Y. *et al.*, 2022). Soil quality in the Sisim Micro Watershed, Batu City, in production forests (0.57–0.63) and mixed gardens (0.49–0.53) (Nurhutami, Kusuma and Nita, 2020).

At the slope of >40%, the *SQI* value is 0.37–0.64. The highest *SQI* value is found in forests (0.64) and lowest in UF land (0.37). Soil quality degradation due to forest conversion to UF can reduce *SQI* by 43.1%. These results show that high slopes and higher *LMI* have an impact on low *SQI*. The low *SQI* value on UF land in the upper Brantas watershed, Batu City, is in line with Erkossa, Itanna and Stahr (2007), who reported value of 0.35–0.45 on bedding engineering agricultural land. Similarly, *SQI* values of 0.39 under high management intensity and 0.50 under low intensity were reported (Klimkowicz-Pawlas, Ukalska-Jaruga and Smreczak, 2019). Values of *SQI* on dry agricultural land (corn, soybeans and peanuts) in West Java Province, Indonesia, are characterised by rather low to rather good, with most being medium. The limiting factors of *SQI* are low organic C, phosphate and nitrogen (Rachman, 2021). In line with other studies showing that upland farming of corn, soybeans and beans in Aceh Regency shows an *SQI* value of 0.46 (Abdullah *et al.*, 2022) and *SQI* value of moorland is 0.32–0.35 (Nurhutami, Kusuma and Nita, 2020), while the *SQI* value of farmland in Canada is 0.25–0.50 (Chaudhry *et al.*, 2024). The *SQI* on the reclamation of coal mining land in Poland shows following values in different layers (0.63 at 0–10 cm, 0.60 at 10–20 cm, 0.43 at 20–40 cm, and 0.40 at 40–60 cm) (Grzywna and Ciosmak, 2021). The *SQI* on farmland is the lowest and has a much lower damage index value than other uses (Zahedifar, 2023). Soil quality is controlled by land use and soil erosion (Nosrati and Collins, 2019)

Conversely, land-use types with lower biomass, such as UF and PHA, exhibited lower *SQI* values. The lack of permanent vegetation cover and high soil disturbance from continuous cultivation result in organic matter depletion, increased erosion, and reduced microbial activity. The findings reinforce existing literature arguing that monoculture and intensive cropping systems degrade soil quality over time due to organic matter loss and soil structure deterioration (Norgrove and Hauser, 2000; Wang *et al.*, 2008).

The negative correlation between land management intensity and soil quality confirms that excessive human intervention reduces soil health. In UF, where land management intensity is highest (0.67–0.71), soil organic carbon (SOC) and total nitrogen levels were significantly lower, reflecting the negative impact of intensive land use. Similarly, PHA land (0.53–0.63 *LMI*) exhibited lower *SQI* values (0.40–0.51), highlighting how horticultural practices degrade soil due to excessive tillage, synthetic fertilisers, and pesticide applications. These findings align with previous studies that suggest high-input farming systems accelerate soil degradation by depleting essential nutrients and disrupting soil microbial communities (Francaviglia *et al.*, 2014; Zhang B. *et al.*, 2021).

In contrast, agroforestry systems such as PCA and PGA showed moderate land management intensity and intermediate *SQI* values – PCA had an *LMI* of 0.19–0.22 and an *SQI* of 0.57–0.65, benefiting from minimal soil disturbance, organic inputs from tree litter, and reduced dependence on chemical fertilisers. A slightly lower *SQI* (0.49–0.57) is exhibited in PGA, likely due to lower biomass and fewer organic matter inputs. These results support the notion that agroforestry systems can mitigate land degradation by integrating tree-based components that enhance soil organic matter and microbial activity.

These results highlight the increased susceptibility of sloped lands to erosion and nutrient loss, particularly in highly disturbed farming systems (Suprayogo *et al.*, 2020). This aligns with studies indicating that steep slopes are more prone to soil degradation due to runoff and reduced water infiltration (Francaviglia *et al.*, 2014; Zhang B. *et al.*, 2021). The presence of vegetation cover in protected forests and agroforestry systems helps mitigate these effects, further reinforcing the importance of sustainable land management practices on sloped landscapes.

The results of this study provide clear implications for sustainable land management. Protected forests and agroforestry systems demonstrated higher *SQI* values due to their ability to maintain soil organic matter, reduce erosion, and enhance microbial activity. Strategies such as cover cropping, minimum tillage, organic fertilisation, and agroforestry integration could help improve soil quality in more intensively managed lands like PHA and UF.

Additionally, the findings highlight the need for land-use policies that promote conservation-oriented agriculture, particularly in areas with high land management intensity and steep slopes. The adoption of soil and water conservation techniques, such as terracing, mulching, and vegetative barriers, could help reduce soil degradation and improve long-term land productivity. The study provides quantitative evidence that high *LMI* (e.g., intensive tillage of soils, low vegetation cover) correlates with a decrease in *SQI* especially in dryland agriculture and pine-horticultural agroforestry systems. These findings strengthen theoretical models of soil degradation while providing region-specific data for volcanic soils that are fertile but vulnerable to unsustainable management. Agroforestry as a sustainable solution showing that PCA maintains soil quality close to forest level (*SQI* = 0.57–0.65) even with moderate land use, confirming its role in balancing productivity and conservation. The interaction of land slope and degradation reveals that steep slopes exacerbate soil degradation below high *LMI*, a critical finding for watershed management in erosion-prone volcanic regions to support practical priorities such as contour/terrace farming on slopes >30% in conservation policies. This study has several limitations, including the physico-chemical and biological parameters of the soil in the calculation of limited *SQI*, the contribution of soil biodiversity to ecosystem resilience in the assessment of *SQI*, the analysis of *SQI* and *LMI* is only carried out on Andisols and it is necessary to include *SQI* and *LMI* analysis on Inseptisols located in the upper Brantas watershed of Batu City and seasonal variations in *SQI* and *LMI* to monitor soil dynamics throughout the year.

CONCLUSIONS

Vegetation biomass plays an important role in maintaining soil quality and organic matter levels, especially at protected forest (PF) and pine-coffee agroforestry (PCA), where high above-ground biomass (541.4–675.2 $Mg \cdot ha^{-1}$ in PF and 387.1–475.7 $Mg \cdot ha^{-1}$ in PCA) supports high soil quality index (*SQI*) values (0.64–0.76 and 0.57–0.65, respectively). The negative correlation between land management intensity (*LMI*) and *SQI* observed across all types of land use highlights the adverse effects of excessive soil disturbance, chemical inputs, and continuous planting on Andisols. This is consistent with the hypothesis that intensive land management practices especially in upland farming (UF) and pine-horticulture agroforestry (PHA) lead to soil degradation, while conservation-based systems such as PF and agroforestry maintain higher soil quality. The highest soil quality was observed in PF (*SQI* = 0.64–0.76; biomass = 541.4–675.2 $Mg \cdot ha^{-1}$) and PCA (*SQI* = 0.57–0.65; biomass = 387.1–475.7 $Mg \cdot ha^{-1}$; *LMI* = 0.18–0.22). This contrasts with UF and PHA lands, which showed the lowest soil quality – UF (*SQI* = 0.37–0.52, biomass = 3.5–5.5 $Mg \cdot ha^{-1}$, *LMI* = 0.68–0.71) and PHA (*SQI* = 0.40–0.51, biomass = 174.1–232.0 $Mg \cdot ha^{-1}$, *LMI* = 0.50–0.56). This study confirms that higher land management intensity negatively impacts soil quality, particularly in upland farming and horticultural agroforestry systems. In contrast, protected forests and agroforestry systems maintain better soil health due to increased organic matter input, reduced disturbance, and sustainable management practices. Indicators of phosphorus availability, sand fraction and bulk density soil can be used as the main components of the soil quality index. These findings highlight the need for integrated soil conservation approaches, particularly on sloped lands and intensively managed agricultural areas, to ensure long-term soil sustainability and agricultural productivity.

SUPPLEMENTARY MATERIAL

Supplementary material to this article can be found online at: https://www.jwld.pl/files/Supplementary_material_67_Hadi.pdf.

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CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

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