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Assessing soil fertility index under different forest land cover

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ABSTRACT

Soil fertility is often evaluated under various forest land cover types to determine the capacity of each area to support plant productivity. Therefore, this study aimed to (1) assess the current soil fertility status of six land cover types in the Alas Bromo educational forest of Universitas Sebelas Maret using the Soil Fertility Index method and (2) identify the factors influencing the status. The six different land cover types investigated in this descriptive-exploratory study using a survey method included (1) pine, (2) pine-mahogany, (3) mahogany, (4) mixed trees, (5) annual crops, and (6) pine replanting, with four repetitions. Furthermore, the composite soil sample represented each repetitive area, and the assessment results showed that the soil fertility status was categorized as low to moderate. The categorization order was mahogany>mixed trees>pine replanting>annual crops>pine>pine-mahogany which had fertility indices of 0.57, 0.56, 0.53, 0.51, 0.49, and 0.45, respectively. Soil fertility determinants across the six land cover types comprised litterfall, breast height diameter, and tree density. Future investigations should evaluate the relationship between litter quality, soil biota, and decomposition rate with fertility to identify the appropriate strategy for fertility enhancement on each land cover.

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1. INTRODUCTION

Forest areas are environmental service providers with conformations to community-accepted economic, social, and ecological standards while maintaining environmental friendliness (Marchi et al., 2018). Moreover, forest has ecological components including carbon sequestration, water and air provisioning, biodiversity conservation, and food supply, which play crucial roles in ensuring human survival (Vergílio et al., 2016). In this context, soil serves as a growing medium that provides plants with water and nutrients, while fertility status is crucial in sustainable forest management because tree productivity directly hinges on soil fertility (Hansson et al., 2020). Forest ecosystems showing optimal fertility and adequate moisture levels are more resilient due to rapid vegetation recovery facilitated by robust soil resources (Ibáñez et al., 2019). Optimal tree growth performance enhances the ability of the forest ecosystems to provide essential environmental services.

Fertility is the capacity of the soil to provide available nutrients to plants in sufficient quantities (Munawar, 2018), with good fertility supporting biomass production and carbon sequestration in forest ecosystems (Nurfansyah et al., 2019). This is commonly influenced by inherent factors, including soil types which impact physical, chemical, and biological soil characteristics. Meanwhile, dynamic factors influencing fertility originate from human activities, such as land utilization and management practices (Chase & Singh, 2014; Zake et al., 2015). The characteristics of land cover such as high-vegetation-density forests play important roles (Shen et al., 2022) in supporting nutrient cycles and maintaining fertility through litter decomposition (Carnol & Bazgir, 2013). The litter productivity of a land cover estimates organic matter contribution influencing the return of nutrients. In this context, the surface litter prevents soil erosion that can actively lead to the leaching of nutrients (Sari et al., 2022).

Soil quality evaluation based on fertility (Xie et al., 2015) has been carried out for different land uses (Chase & Singh, 2014), including agricultural land (Dewi et al., 2022; Sasongko et al., 2022; Supriyadi et al., 2022) and forest (Jamaluddin et al., 2013; Perumal et al., 2017; Yang et al., 2021). Additionally, soil fertility assessment reflects the capacity of the ecosystems to support optimal tree growth (Singh et al., 2016) and it can be applied in sustainable management (Callesen et al., 2019). This has been performed recently according to the purpose of the assessment, such as

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conducting calculations through the Nutrient Index (Khadka et al., 2018), the combined Soil Fertility Index (SFI) & Soil Evaluation Factor (SEF) method (Lu et al., 2002; Moran et al., 2000), the SFI method (Mukashema, 2007), and the Fuzzy method (Dobermann & Oberthür, 1997). The advantages of the Nutrient Index as well as the combined SFI & SEF method include testing fewer soil indicators at low costs. The limitation of the SFI & SEF method is the failure to explain the relationship between SFI and SEF, while the ability of the Nutrient Index to capture all soil indications signifies inadequate precision. The Fuzzy method has the advantage of being able to model extremely complex nonlinear functions, but the disadvantages include a lack of standardized systematic knowledge required to solve control problems. This study applied the SFI method described by Mukashema (2007) due to being flexible in evaluating the fertility level. The three main steps in the evaluation of soil fertility are: 1) selection of indicators, 2) weighting and scoring, as well as 3) SFI calculation (Chen et al., 2020). In most cases, the indicators for soil fertility are physico-chemical parameters which have been previously used to evaluate fertility status in *Shorea robusta* forest (Thapa et al., 2019).

The Alas Bromo educational forest, previously managed by Perum Perhutani as a restricted production forest, was transferred to Universitas Sebelas Maret Surakarta in April 2018 (Wicaksono et al., 2020). Additionally, the area was designated for study and education without altering the primary production function (Nugroho et al., 2017). The forest is located in Karanganyar Regency, Central Java, Indonesia, and occupies approximately 126.29 ha with an undulating to hilly terrain (Darmawan et al., 2022), spanning an elevation range of 200 to 337.5 m above sea level. Furthermore, it falls under climate type C (slightly wet) according to the Schmidt and Ferguson classification, with an average monthly rainfall of 180 mm, 29.5°C air temperature, 27.40°C soil temperature, and 77.20% air humidity (Dewi et al., 2023). The forest comprises six land cover types, including pine, pine-mahogany, mahogany, mixed trees, annual crops, and pine replanting. Variations in land cover impact nutrient cycling through litter decomposition, while the use of different land cover by the local community for farming activities may potentially reduce soil fertility (Zake et al., 2015).

Previous investigations focused on soil temperature (Ariyanto et al., 2021), plant diversity (Nufus et al., 2020), the density and diversity of mycorrhizal spores (Dewi et al., 2021), as well as animal diversity (Pertiwi et al., 2020; Sugiyarto et al., 2020). More information is needed regarding the evaluation of soil fertility status in the Alas Bromo educational forest. Therefore, this study aimed to (1) assess soil fertility status in six different land cover types in the Alas Bromo educational forest using the SFI method and (2) identify the influencing factors.

2. MATERIAL AND METHOD

2.1. Study Area

This descriptive-exploratory study was conducted at the Alas Bromo educational forest of Universitas Sebelas Maret located in Karanganyar Regency between latitude 7°34’21.93”-7°35’38.90” S and longitude 110°59’40.39”-111°0’49.36” E, Central Java. Furthermore, a survey method was used to perform investigations on six land cover types, including (1) pine, (2) pine-mahogany, (3) mahogany, (4) mixed trees, (5) annual crops, and (6) pine replanting (Figure 1). The six land cover types have different characteristics and are subjected to various land management practices (Table 1), while the forest area features Alfisol soil, 28°C to 31°C air temperature, and an average monthly rainfall of 180 mm.

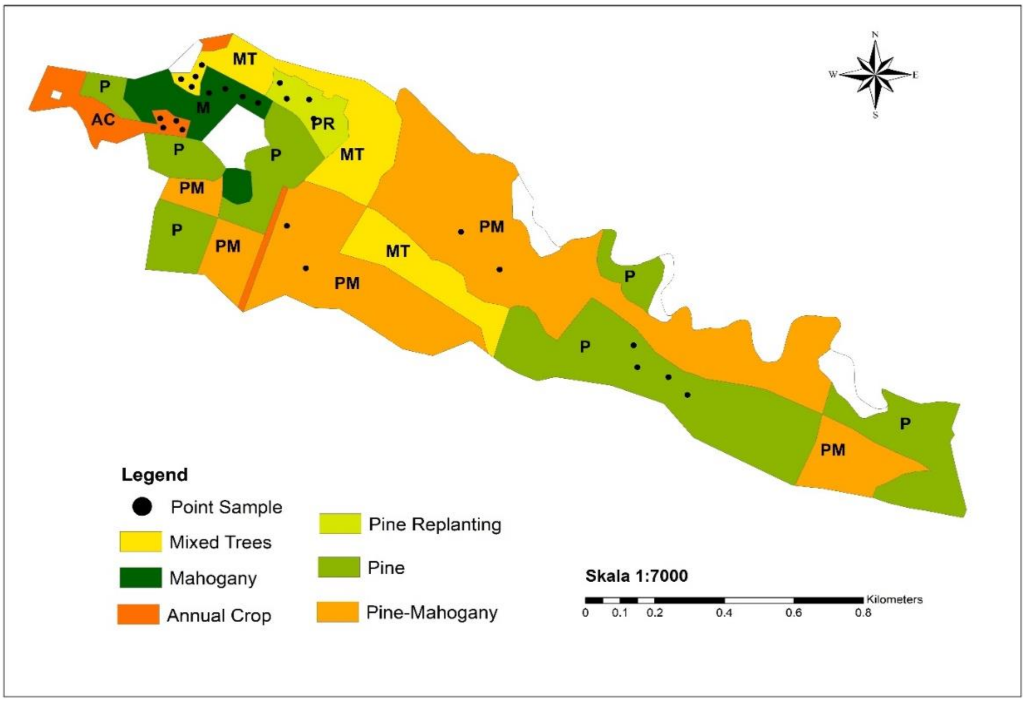

Figure 1. Sampling point distribution at the study area
Remarks: P = pine, PM = pine-mahogany, M = mahogany, MT = mixed trees, AC = annual crop, PR = pine replanting.

Table 1. Land Cover Characteristics and Management

Land Cover	Vegetation	Land Management
Pine (±38.96 ha)	Pine	No fertilization and soil management. The sap continues to be actively tapped. 4m x 4m tree spacing.
Pine-Mahogany (±55.30 ha)	Pine Mahogany	No fertilization and soil management. The sap continues to be actively tapped. 4m x 4m pine tree spacing. 8m x 8m mahogany tree spacing.
Mahogany (±5.51 ha)	Mahogany	No fertilization application. Terraces to conserve soil. 8m x 8m Mahogany tree spacing.
Mixed Trees (±13.70 ha)	Mahogany, *Schleichera oleosa*, *Ceiba petandra*, *Leucaena leucocephala*	No fertilization application. Terraces to conserve soil. Tree with irregular spacing.
Annual Crop (±4.84 ha)	Cassava	Addition of manure. Terraces to conserve soil. Crop rotation including maize and peanuts.
Pine Replanting (±2.98 ha)	Pine	Addition of manure. Terraces to conserve soil. Crop rotation including maize and peanuts. 4m x 4m tree spacing.

2.2. Soil Sampling and Analysis

Soil samples were collected from a 200 m² transect area at five predetermined points for each replication using purposive random sampling. These represented the conditions of the area and were combined into a single unit, while the sampling method included using a soil monolith of 25 cm × 25 cm × 30 cm as well as collecting the macrofauna. The composite samples were air-dried, then filtered using 0.5 mm as well as 2.00mm diameter sieves for the analysis of characteristics including soil texture (pipette method), water pH (Electrometry), organic carbon (C) (Walkley and Black), and total nitrogen (N) (Kjeldahl). Other characteristics examined were available Phosphor (Bray I method), cation exchange capacity (CEC) (NH_4OAc extraction), exchangeable cation (K^+, Ca^{2+}, Mg^+, Na^{2+}) (NH_4OAc extraction), base saturation (NH_4OAc extraction), aluminum saturation (KCl extraction), and Fe-available (Extraction of ammonium acetate). These entire indicators were analyzed during the investigation process according to the guidelines provided by Sulaeman et al. (2021).

2.3. Land Cover Characteristics

Litter production and standing or soil surface litter were used to determine a certain aspect of plant characteristics for each land cover. During the experimental process, produced litterfall was collected with a modified trap as applied in a previous investigation conducted by Apriyanto et al. (2021). This trap measured 2.0 m^2 in size and was positioned 1 m above the ground to estimate litter production based on the total amount accumulated weekly for four months. Additionally, the surface litter amount present in the 50 cm^2 frame was estimated to determine the standing litter quantity. These samples of surface litter were separated before measuring the wet and dry weight based on the stems, twigs, leaves, and fruit fractions. Measurements of diameter breast height (DBH) and tree height were respectively performed using a tape at breast level (1.3 m) and Hagameter (Bahru & Ding, 2020).

2.4. Determination of SFI

Determination of SFI in this study was performed using the Pearson correlation followed by the Principal Component Analysis (PCA) method, which identified the Minimum Soil Fertility Indicator (MSFI). The indicators selected as MSFI had a significant correlation and an eigenvalue greater than 1, while the weight and score of each MSFI (c_j) was determined with equation (1). In the PCA analysis, w_i represents an index weight derived from proportion divided by cumulative, and s_i represents the indicator score (equation 1). Using equations (2) and (3), the total weight of all MSFI was computed during the analysis process (3). According to the model, p_c is the probability of each soil fertility indicator class in the MSFI, and n_c signifies the number of SFI classes which are five, and Sc_i is the weight of MSFI. The determination of SFI value was achieved through the division of MSFI total weight by the total indicator number, as shown in Equation 4 (Mukashema, 2007). The scoring was based on the procedure described by Sulaeman et al. (2021) (Table 2), and the classification of soil fertility status was consistent with Bagherzadeh et al. (2018) (Table 3). Equations 1 – 4 were used for assessing the soil fertility index (Mukashema, 2007).

$$c_j = w_i \times s_i \quad [1]$$

$$p_c = \frac{1}{nc} \quad [2]$$

$$Sc_i = c_j \times p_c \quad [3]$$

$$\text{SFI} = \left(\frac{\sum_{i=1}^{n} Sci}{N}\right) \text{X } 10 \quad [4]$$

where SFI= soil fertility index, c_j= total score weight, w_i= weight index; s_i= score index; p_c= the probability of SFI class for each MSFI; n_c= the number of SFI classes; Sc_i= MSFI weights; and N= the total number indicators of MSFI.

Table 2. Scoring of Soil Fertility Indicators

Indicators	1 (VL)	2 (L)	3 (M)	4 (H)	5 (VH)
pH	<5 >8.2	5-5.4 7.8-8.2	5.4-5.8 7.4-7.8	5.8-6 7-7.4	6.7
Total N (%)	<0.1	0.1-0.2	0.21-0.5	0.51-0.75	>7.5
Organic C (%)	<1	1-2	2-3	3-5	>5
Available P (Bray) (ppm)	<4	5-7	8-10	11-15	>15
CEC (cmol(+) kg^{-1})	<5	5-16	17-24	25-40	>40
Base Saturation (%)	<20	20-40	41-60	61-80	>80
Ex-K (cmol(+) kg^{-1})	<0.1	0.1-0.3	0.4-0.5	0.6-1.0	>1
Ex-Ca (cmol(+) kg^{-1})	<2	2-5	6-10	11-15	>20
Ex-Mg (cmol(+) kg^{-1})	<0.3	0.4-1	1.1-2.0	2.1-8.0	>8
Ex-Na (cmol(+) kg^{-1})	<0.1	0.1-0.3	0.4-0.5	0.8-1.0	>1
Ex-Al (me 100g^{-1})	1	3	8	21	40
Ex-Fe (cmol(+) kg^{-1})	1	3	5	19	53
Soil Texture	S, Si	LS	SL, L, SiL	SiC, CL, SCL	SiCL, SC, C

Remarks: CEC= cation exchange capacity, VL= very low, L= low, M= moderate, H= high, VH= very high, S= sand, Si= silt, LS= loamy sand, SL= silty loam, L= loam, SiL= silty loam, SiC= silty clay, CL= clay loam, SCL= silty clay loam, SiCL= silty clay loam, SC= sandy loam, and C= clay.

Table 3. The Classification of SFI

SFI Classification	Value
Very High	0.90-1.00
High	0.75-0.90
Medium	0.50-0.75
Low	0.25-0.50
Very Low	0.00-0.25

Source: Bagherzadeh et al. (2018)

2.5. Statistical Analysis

One-way analysis of Variance (ANOVA) and Tukey honestly significant differences (HSD) test were used to assess statistically significant differences (p<0.05) between land cover types. Additionally, the Pearson correlation test was used to evaluate the relationship between indicators, and all statistical analysis was conducted with Minitab 18 software.

3. RESULT

3.1. Land Cover Characteristics

Land cover was found to significantly (p<0.05) affect the production of litterfall, standing litter, average tree height, DBH, and tree density, as presented in Tables 4 and 5. The highest litterfall was detected in mahogany land cover at 14.23 tons ha^{-1} year^{-1}, followed by mixed trees at 11.78 tons ha^{-1} year^{-1}. These were significantly different (p<0.05) from the 9.33, 6.32, and 3.00 tons ha^{-1} year^{-1} observed among pine, pine-mahogany, and annual crops, respectively, while pine replanting had the lowest value at 0.56 tons ha^{-1} year^{-1}. The highest standing litter was found in mahogany land cover (11.84 tons ha^{-1}) and the lowest in pine replanting (0.78 tons ha^{-1}). Therefore, the obtained results showed that standing litter significantly correlated with litterfall production (r= 0.64, p<0.05).

According to Table 4, the proportion of litter fraction composition, including twigs, leaves, fruits, and flowers, in the six land cover types was different and mainly consisted of leaves. DBH and average tree height strongly correlated with litterfall (r = 0.774 and r = 0.822, respectively), while the highest tree density was found in pine-mahogany (688 individuals ha^{-1}) (Table 5). This density value was not significantly different (p<0.5) from 600 individuals ha^{-1} found in pine land cover, while the lowest was 238 individuals ha^{-1} detected among the mahogany which comprised the biggest tree DBH.

Table 4. Litter characteristics

Litter Production	Pine	Pine-Mahogany	Mahogany	Mixed Trees	Annual Crop	Pine Replanting
Litterfall (tons ha^{-1} year^{-1})						
Total	9.33 ± 2.97bc	6.32 ± 1.47cd	14.23 ± 2.52a	11.78 ± 2.50ab	3.00 ± 1.61de	0.56 ± 0.36e
- Twigs	0.87 ± 0.76ab	0.76 ± 0.34ab	1.61 ± 0.49a	1.42 ± 0.48a	0.16 ± 0.10b	0.01 ± 0.01b
- Leaf	6.27 ± 1.21bc	4.40 ± 0.52cd	10.63 ± 1.75a	8.59 ± 1.61ab	2.56 ± 1.70de	0.50 ± 0.32e
- Fruit	2.19 ± 1.83a	1.03 ± 0.61a	1.49 ± 0.75a	1.17 ± 0.76a	0.25 ± 0.32a	0.05 ± 0.01a
- Flowers	0	0.13 ± 0.11a	0.45 ± 0.56a	0.61 ± 0.61a	0.03 ± 0.3a	0
Standing litter (tons ha^{-1})						
Total	5.71 ± 0.99abc	7.41 ± 6.00ab	11.84 ± 3.10 a	4.30 ± 0.81bc	3.17 ± 1.01bc	0.78 ± 0.37c
- Twigs	0.89 ± 0.67b	0.35 ± 0.22b	3.60 ± 2.65a	0.99 ± 0.62a	0.59 ± 0.78b	0.44 ± 0.53b
- Leaf	4.20 ± 1.15ab	6.20 + 4.04a	6.40 ± 0.6a	3.16 ± 0.6ab	2.58 ± 1.02ab	0.19 ± 0.16b
- Fruit	0.61 ± 0.59a	0.86 ± 0.70a	1.68 ± 1.50a	0.15 ± 0.12a	0	0.02 ± 0.01a
- Flowers	0	0	0	0	0	0

Remarks: Numbers followed by different letters in the same row show a significant difference based on the Tukey HSD test at 5%

Table 5. Land Cover Characteristics

No	Land Cover	Tree height (m)	DBH (cm)	Tree Density (individual ha^{-1})
1	Pine	16.31 ± 0.79a	28.44 ± 2.35bc	600 ± 108ab
2	Pine-Mahogany	16.67 ± 1.67a	27.55 ± 1.97bc	688 ± 179a
3	Mahogany	17.13 ± 1.52a	56.24 ± 8.93a	238 ± 86c
4	Mixed Trees	14.29 ± 3.46a	31.33 ± 12.26b	288 ± 75bc
5	Annual Crop	1.53 ± 0.1c	16.01 ± 6.09cd	313 ± 225bc
6	Pine Replanting	4.5 ± 0.78b	8.40 ± 0.84d	450 ± 108abc

Remarks: DBH= Diameter breast height. Numbers followed by different letters in the same column show a significant difference based on the Tukey HSD test at 5%

Table 6. The Pearsons' Correlation Coefficient (r) between the Fraction of Litter with SFI and Soil Characteristics

	Twig L	Flower L	Fruit L	Leaf L	Twig SL	Flower SL	Fruit SL	Leaf SL	SFI
Flower L	0.656								
Fruit L	0.709	0.253							
Leaf L	0.819	0.54	0.353						
Twig SL	0.561	0.539	0.386	0.444					
Flower SL	0.341	0.43	0.041	0.238	0.013				
Fruit SL	0.407	0.018	0.242	0.418	0.363	-0.117			
Leaf SL	0.397	0.258	0.23	0.521	0.281	-0.006	0.334		
SFI	**0.42***	**0.604***	0.079	**0.422***	**0.435***	0.266	-0.004	0.039	
pH	0.108	0.391	-0.005	-0.009	0.225	0.088	-0.089	0.081	0.668
TN	0.294	0.361	-0.037	0.371	0.267	0.179	0.051	-0.169	0.782
Av-P	-0.221	-0.162	-0.304	-0.1	0.01	-0.19	0.069	-0.155	-0.05
Ex-K	**0.518***	**0.464***	0.134	**0.588***	0.194	**0.46***	-0.022	0.035	0.633
Ex-Ca	**0.455***	**0.669***	0.187	0.393	**0.517***	0.348	0.286	0.13	0.696
Ex-Na	-0.374	-0.188	-0.321	-0.095	-0.321	0.153	-0.261	-0.014	0.015
Ex-Mg	0.073	0.249	-0.274	0.265	0.139	-0.086	0.185	-0.103	0.627
CEC	0.093	0.242	-0.056	0.407	-0.152	-0.092	0.015	0.328	0.09
BS	0.248	0.329	0.15	-0.018	0.527	0.326	0.149	-0.164	0.52
Org-C	**0.592**	**0.608**	0.186	**0.593**	**0.458**	0.357	0.255	0.204	0.738
Ex-Al	0.068	-0.093	0.302	0.2	0.128	-0.173	-0.033	0.238	-0.319
Ex-Fe	-0.103	0.142	-0.194	-0.2	-0.342	0.103	-0.32	-0.438	0.163
Texture	-0.419	-0.299	-0.31	-0.392	-0.254	-0.153	-0.312	-0.281	-0.094

Remarks: L= Litterfall, SL= Standing Litter, SFI = soil fertility index, TN= Total Nitrogen, Av-P= Available Phosphor, Ex-K= exchangeable Kalium, Ex-Ca= exchangeable Ca, Ex-Na = exchangeable Na, Ex-Mg= exchangeable Mg, CEC= cation exchange capacity, BS= base saturation, Org-C= Organic Carbon, Ex-Al= exchangeable Al, Ex-Fe= exchangeable Fe, and the number bold* = 5% significance level (p<0.05).

3.2. Soil Characteristics of Different Land Cover Types

The result of the soil characteristics in Table 7 showed a significant effect ($p<0.05$) of forest land cover on the total N, organic-C, Ex-K, Ex-Mg, and Ex-Al content. Different land cover types of the Alas Bromo educational forest have low to moderate amounts of total N and organic-C. Mixed tree and mahogany have the highest percentages of organic-C (2.07% and 2.05%, respectively), which are significantly different ($p<0.05$) from the values observed among pine replanting (1.49%), pine-mahogany (1.43%), pine (1.36%), and annual crops (1.31%). Additionally, the average soil pH measured across all land cover types was 5.6, signifying slightly acidic.

Ex-Mg was highest in mahogany (0.64 cmol(+) kg^{-1}) and not significantly different ($p>0.05$) from the values obtained among other land cover, except for pine-mahogany (0.32 cmol(+) kg^{-1}) (Table 7). The highest Ex-K was found in mixed tree land cover (0.80 cmol(+) kg^{-1}) and not significantly different from the value detected in mahogany (0.66 cmol(+) kg^{-1}), but significantly different when compared with pine (0.58 cmol(+) kg^{-1}), annual crops (0.54 cmol(+) kg^{-1}), pine replanting (0.53 cmol(+) kg^{-1}), and pine-mahogany (0.46 cmol(+) kg^{-1}). The highest total-N was found in mahogany at 0.48%, which was not significantly different ($p>0.05$) from the 0.45% in pine replanting and 0.44% in mixed trees. This value was significantly different when compared with pine (0.24%), annual crops (0.19%), and pine-mahogany (0.15%). The pine land cover had the highest Ex-Al concentration (1.40 me 100 g^{-1}), which was not significantly different ($p>0.05$) from the 0.63 me 100 g^{-1} measured in mixed trees, but significantly different from the four other land cover types.

Table 7. Soil Characteristics on Various Land Cover Types

No	Indicators	P	PM	M	MT	AC	PR	Average
1	pH	5.43 ± 0.17a	5.46 ± 0.28a	5.71 ± 0.14a	5.56 ± 0.23a	5.58 ± 0.24a	5.76 ± 0.06a	5.58
2	Total N (%)	0.24 ± 0.11b	0.15 ± 0.03b	0.48 ± 0.03a	0.44 ± 0.06a	0.19 ± 0.05b	0.45 ± 0.07a	0.32
3	Organic C (%)	1.36 ± 0.21b	1.43 ± 0.12b	2.05 ± 0.48a	2.07 ± 0.21a	1.31 ± 0.22b	1.49 ± 0.17b	1.62
4	Available P (ppm)	3.42 ± 0.98a	2.52 ± 0.85a	3.11 ± 1.26a	2.17 ± 0.34a	3.58 ± 1.06a	3.37 ± 1.16a	2.88
5	CEC (cmol(+) kg^{-1})	26.74 ± 5.24a	23.46 ± 2.95a	24.51 ± 5.44a	26.75 ± 7.47a	22.06 ± 2.17a	21.64 ± 3.04a	24.19
6	Base Saturation (%)	30.24 ± 5.01a	30.97 ± 6.16a	40.89 ± 12.01a	35.12 ± 8.08a	37.40 ± 4.61a	37.72 ± 5.06a	35.39
7	Exchangeable K (cmol(+) kg^{-1})	0.58 ± 0.04bc	0.46 ± 0.07c	0.66 ± 0.08ab	0.80 ± 0.06a	0.54 ± 0.07bc	0.53 ± 0.06bc	0.60
8	Exchangeable Ca (cmol(+) kg^{-1})	6.56 ± 0.71a	6.15 ± 0.99a	7.41 ± 1.71a	8.05± 1.04a	6.67 ± 0.28a	6.74 ± 0.73a	6.93
9	Exchangeable Mg (cmol(+) kg^{-1})	0.41 ± 0.04ab	0.32 ± 0.05b	0.64 ± 0.14a	0.56 ± 0.20ab	0.59 ± 0.20ab	0.53 ± 0.06ab	0.51
10	Exchangeable Na (cmol(+) kg^{-1})	0.35 ± 0.13a	0.24 ± 0.06a	0.22 ± 0.06a	0.35 ± 0.05a	0.38 ± 0.06a	0.28 ± 0.11a	0.30
11	Exchangeable Al (me 100g^{-1})	1.40 ± 0.60a	0.63 ± 0.27a	0.54 ± 0.37b	0.55 ± 0.47b	0.32 ± 0.10b	0.31 ± 0.05b	0.62
12	Exchangeable Fe (cmol(+) kg^{-1})	0.18 ± 0.01a	0.27 ± 0.05a	0.17 ± 0.02a	0.37 ± 0.1a	0.32 ± 0.03a	0.39 ± 0.2a	0.26
13	Texture	Clay	Clay	Clay	Clay	Silty Clay Loam	Clay	Clay

Remarks: P= Pine. PM= Pine-Mahogany. M= Mahogany. MT= Mixed Trees. AC= Annual Crop. PR= Pine Replanting. Numbers followed by different lowercase letters in the same row show a significant difference based on the Tukey HSD test at 5%

Other soil characteristics had extremely low to moderate levels, such as CEC and Ex-Ca measured with moderate average values of 24.19 cmol(+) kg^{-1} and 6.39 cmol(+) kg^{-1}, respectively. The average base saturation (BS) of 35.39% and Ex-Na of 0.30 cmol(+) kg^{-1} were both at low levels on different land cover types. All average values of available-P and -Fe were low at 2.88 ppm and 0.28 cmol(+) kg^{-1}, respectively.

3.3. Soil Fertility Index

The initial stage of determining SFI included correlation analysis between 13 indicators (Table 8). In this context, pH was found to significantly correlate with total-N (r=0.51), Ex-Ca (r=0.48), BS (r=0.44), and Ex-Al (r=-0.44). Organic-C significantly correlated with Total-N (r=0.63), Ex-P (r=0.68), Ex-Ca (r=0.52), and BS (r=0.43). Total-N correlated with Ex-P (r=0.58), Ex-Ca (r=0.48), and Ex-Mg (r=0.47), while Ex-Ca significantly correlated with Ex-Mg (r=0.44) and BS (r=0.56). Nine selected indicators known as MSFI obtained from the total 13 had a high level of sensitivity (Table 9).

The next step was the PCA analysis of MSFI and the results showed that the cumulative index was 0.75. PC1 with an eigenvalue of 3.68 and a proportion of 41% consisted of five indicators, namely pH, total-N, Ex-Ca, Ex-Mg, and organic-C. PC2 with an eigenvalue of 1.79 and a proportion of 19% consisted of three selected indicators, including Ex-P, CEC, and BS. PC3 with an eigenvalue of 1.26 and a proportion of 14% had only Ex-Al, while the PCA results were used for weight calculation.

SFI was calculated by multiplying weight with the index score of each selected indicator, then the obtained values were substituted into the formula described by Mukashema (2007). The calculated SFI had average values ranging from 0.45-0.57 with a low to medium classification, and ANOVA results showed that land cover significantly ($p<0.05$) influenced SFI. Mahogany land cover was not significantly different ($p>0.05$) from the mixed trees, pine replanting, and annual crops, but significantly ($p<0.05$) different from pine and pine-mahogany. The average SFI values for the six land cover types were in the order of mahogany (0.57)>mixed trees (0.56)>pine replanting (0.53)>annual crops (0.51)>pine (0.49)>pine-mahogany (0.45), with Figure 2 presenting the contribution of each MSFI to SFI.

3.4. Correlation between SFI and Land Cover Characteristics

SFI values in the various land cover types of the Alas Bromo educational forest were significantly impacted by litter production (litterfall) and standing litter (Table 6). Litterfall had a significant positive correlation with Ca (r = 0.45), organic-C (r = 0.59), and SFI (r = 0.42), while Ca, organic-C, and SFI positively correlated with DBH (r = 0.46, 0.66, and 0.44, respectively). However, tree density had a significant negative correlation with Ca (r = -0.52) and SFI (r = -0.67).

Table 8. The Correlation Coefficient (r) between Soil Fertility Indicators

	pH	TN	Ex-P	Ex-Ca	Ex-Mg	CEC	BS	OC	Ex-Al	Ex-Na	AP	Ex-Fe
TN	**0.51***											
Ex-P	0.03	**0.576***										
Ex-Ca	**0.484***	**0.437***	0.293									
Ex-Mg	0.312	**0.469***	0.249	**0.442***								
CEC	-0.075	0.097	0.169	0.223	0.15							
BS	**0.438***	0.296	0.155	**0.561***	0.287	**-0.662***						
OC	0.331	**0.631***	**0.675***	**0.517***	0.399	0.022	**0.434***					
Ex-Al	**-0.444***	-0.216	0.072	-0.352	**-0.43***	0.154	-0.329	-0.102				
Ex-Na	-0.227	-0.127	0.187	0.031	0.099	0.227	-0.089	-0.187	0.24			
AP	0.119	-0.101	-0.172	-0.152	0.14	0.008	-0.136	-0.29	-0.086	-0.059		
Ex-Fe	0.235	0.392	0.155	-0.122	0.214	-0.126	0.057	0.161	-0.231	-0.144	-0.295	
Texture	-0.056	-0.323	-0.187	-0.168	0.183	-0.295	0.14	-0.401	-0.353	0.331	0.28	-0.057

Remarks: TN= Total Nitrogen, Ex-P= Exchangeable Potassium, Ex-Ca= Exchangeable Ca, Ex-Mg= Exchangeable Mg, CEC= Cation Exchange Capacity, BS= Base Saturation, OC= Organic Carbon, Ex-Al= Exchangeable Al, AP= Available Phosphor, and Ex-Fe= Exchangeable Fe. 5% significance level = p<0.05. The correlation coefficient in bold* indicates a statistically significant (p<0.05) relationship between indicators and those selected as MSFI.

Table 9. PCA Analysis Results

Eigenvalue	3.6587	1.7891	1.264
Proportion	0.407	0.199	0.14
Cumulative	0.407	0.605	0.746
Variable	PC1	PC2	PC3
pH	**0.346**	0.216	0.254
TN	**0.410**	-0.208	-0.063
Ex-P	0.285	**-0.428**	-0.399
Ex-Ca	**0.403**	-0.021	0.184
Ex-Mg	**0.345**	-0.063	0.318
CEC	-0.02	**-0.603**	0.486
BS	0.344	**0.448**	-0.315
OC	**0.409**	-0.215	-0.312
Ex-Al	-0.252	-0.336	**-0.452**

Remarks: TN= total nitrogen, Ex-P= exchangeable potassium, Ex-Ca= exchangeable Ca, Ex-Mg= exchangeable Mg, CEC= cation exchange capacity, BS= base saturation, OC= organic carbon, and Ex-Al= exchangeable Al.

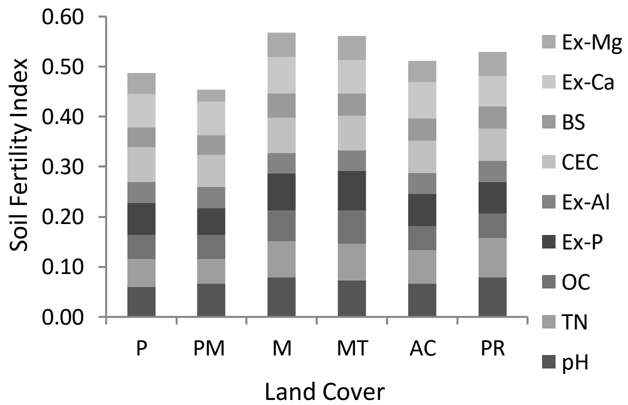

Figure 2. Soil Fertility Index and contribution of each indicator of MSFI in the six land cover of the Alas Bromo educational forest

Remarks: P= pine, PM= pine-mahogany, M= mahogany, MT= mixed trees, AC= annual crop, PR= pine replanting. TN= total nitrogen, OC= organic carbon, Ex-P= exchangeable potassium (K), Ex-Al= exchangeable Al, CEC= cation exchange capacity, BS= base saturation, Ex-Ca= exchangeable Ca, and Ex-Mg= exchangeable Mg.

4. DISCUSSION

The soil type constituting the Alas Bromo educational forest is Alfisol, specifically distinguished by the acidic conditions (Dutta et al., 2015). High rainfall can initiate alkaline cation leaching, while acidic ions such as Al and Fe are retained, leading to acidic soil. Across all land cover types, the soil pH was generally slightly acidic, with the lowest pH level observed in pine areas (5.43). Higher concentrations of Ex-Al in the soil show correlations to lower pH values (Dewi et al., 2018). This is further evidenced by a significant negative correlation (r = -0.44) between pH and Ex-Al in the study area. The acidic soil conditions associated with low pH enhance the solubility of Al, Fe, and manganese (Mn), which can potentially initiate soil toxicity (Tongka et al., 2019). Additionally, increased levels of Al and Fe can cause the precipitation of phosphate ions into insoluble Al-P and Fe-P compounds (Sachan & Krishna, 2022). The availability of phosphorus (P) across different land cover types in the Alas Bromo educational forest remains consistently low, correlating with the reports stated by Dewi et al. (2021).

Both pH and the characteristics of each land cover can influence plant nutrient availability (Neina, 2019). The Alas Bromo educational forest land cover significantly affected soil components such as organic-C, total-N, Ex-K, Ex-Al, and Ex-Mg (p<0.05). Furthermore, the mixed trees had the highest organic-C content at 2.07% due to high litter production (Table 4). This relationship is supported by the significant positive correlation (r=0.59) between litterfall and organic-C. The content of organic-C is influenced by litter input and decomposition rates (Adekiya et al., 2021; Darmawan et al., 2022). In addition to the correlation with litter production, organic-C is significantly correlated with total-N (r=0.63). This total-N exists predominantly in an organic form, comprising both litter and decomposed plant material (Wang et al., 2011). The substantial lignin content in the mahogany and pine land cover contributes to the limited N release from litter (Pei et al., 2019), and total-N positively correlates with soil pH (r = 0.50). Considering the suboptimal microbial activity responsible for organic matter degradation and N fixation in acidic soils, the total-N content in the Alas Bromo educational forest ranges from low to moderate.

In tropical soils, CEC particularly shows a positive correlation with base saturation (Supriyadi et al., 2022). However, a negative correlation between CEC and base saturation was observed in the Alas Bromo educational forest (r = -0.662). This discrepancy occurred because the calculated value represented potential CEC compared to effective CEC. Gillman and Uehara (1980) reported that tropical soil CEC accounted for variable charges and did not fully describe all base cations adsorbed on the soil surface. CEC generally showed moderate values all through the six land cover types investigated in this study, which were influenced by several factors, including soil pH, dominant minerals, and organic-C (Mulat et al., 2021).

The low value of base saturation is closely associated with soil acidic pH, similar to the report by Zhang et al. (2016) that base cations are less available in low-pH compared to high-pH soils. H+ ions dominate in acidic conditions, rendering base cations (K+, Ca2+, Na+, and Mg2+) less accessible (Nguemezi et al., 2020). Furthermore, the availability of base cations is influenced by soil organic-C content (Adekiya et al., 2021) due to the strong association between these two parameters, as shown in Table 8. The dominant soil texture in the study area is clay, which often presents challenges related to nutrient deficiencies, including low levels of N, P, K, and organic matter (Awopegba et al., 2017).

The fertility level in the study area was determined based on chemical and physical soil characteristics. In this context, PCA is particularly responsible for selecting the SFI calculation parameters. According to the PCA analysis, there are nine indicators, including soil pH, total-N, available P, Ex-Ca, Ex-Mg, CEC, base saturation, organic-C, and Ex-Al (Table 9). Each indicator is assigned a weight and score, which are calculated using the procedure described by Mukashema (2007). The SFI assessment results for the six land cover types in the Alas Bromo educational forest ranged between 0.45 to 0.57 in the order of mahogany (0.57), mixed trees (0.56), pine replanting (0.53), annual crops (0.51), pine (0.49), and pine-mahogany (0.45). Figure 2 shows the percentage contributions of the selected SFI indicators from various land cover types. The highest SFI was found in mahogany-dominated land cover, which was not significantly different from the value obtained for the mixed trees due to comprising similar nutrient content. According to Table 7, the SFI class of pine and pine-mahogany is low because of the low nutrient content. These two land cover contain lower levels of soil pH, total-N, organic-C, EX-Mg, and Ex-Al compared to other types. However, high Ex-Al content may lead to the insolubility of phosphate ions (Sachan & Krishna, 2022).

The variation in SFI values across different land cover types in the Alas Bromo educational forest can be attributed to agency and community management practices. Despite intensive management efforts, both pine replanting and annual crops show higher SFI values compared to pine and pine-mahogany. Community practices include cultivating ground cover such as peanuts, corn, cassava, and chilies in pine replanting and annual crop areas, as observed from land cover assessments. The presence of leguminous crops in under-crop rotations contributes to increased soil N content (Mugi-Ngenga et al., 2022). Furthermore, the application of manure enhances pH levels, nutrient availability, and soil aggregate stability in pine replanting and annual cropland. This is opposite to the impact of minimal management practices in pine and pine-mahogany areas, where sap production continues (Gautam et al., 2022). Mixed tree, pine replanting, and annual crops land cover feature bench terraces for soil conservation by reducing erosion rates to minimize nutrient loss (Ahuchaogu et al., 2022; Arora et al., 2023). However, the absence of terraces among pine and pine-mahogany allows erosion to persist, leading to lower SFI values.

This study identified that differences in land cover had a significant impact on soil fertility ($p<0.05$). There was a correlation between SFI and characteristics (litter production, DBH, tree height, and tree density per ha) of the six land covers in the Alas Brono education forest. The litterfall, DBH, and tree density significantly affected SFI ($p<0.05$), while the plant litter was composed of fallen leaves, twigs, flowers, and fruits. The amount of litterfall varied significantly (p 0.05) across land cover types, with the highest average production at 14.23 tons ha^{-1} year^{-1} being found in the mahogany area. The composition and structure of trees have the potential to influence the levels of litter biomass and soil nutrients (Drupadi et al., 2021). A significantly positive correlation between litterfall and SFI (r=0.42) shows that litterfall can affect soil fertility, while the role of litter in the nutrient cycle is crucial. Carnol and Bazgir (2013) reported that differences in nutrient return through litterfall on various land cover types affect nutrient availability in the soil. The return of nutrients such as C, N, P, and K is directly proportional to litter production (Zhu et al., 2019). This result is supported by the close relationship between the litter fraction and several nutrients in the six different land covers. Twigs and flower fractions in litterfall as well as standing litter were correlated with Ex-P, Ex-Ca, organic-C, and SFI (Table 6). Litter plays a crucial role as a source of nutrients in the form of soil organic matter (Adekiya et al., 2021) which the presence at high levels contributes to K and Ca availability. This fact was confirmed by the high K and Ca concentrations in the soil of mahogany and mixed-tree land.

According to a significant correlation (r=0.44), DBH contributes to soil fertility and is often used to make space management decisions. The presence of high DBH levels in trees signifies that a sufficient amount of nutrients are being received. The mahogany land cover had the highest DBH and SFI values, as shown in Table 5 and Figure 2, respectively. Large DBH trees grow well due to receiving sufficient sunlight, water, and soil nutrients (Appiah-Badu et al., 2022) which can be interpreted as evidence of relatively high nutrient availability. Variations in tree density per ha tend to provide adequate clarification to differences in soil fertility across the six land cover types which present a negative correlation between tree density and SFI. Tree density will increase nutrient availability and soil fertility (Shen et al., 2022), but this observation contradicts the obtained results. Tree density is a limiting factor for soil fertility because it causes intense competition for nutrients among vegetation (Lukina et al., 2019) and consequently reduces soil fertility.

The low SFI observed in this study could be attributed to inadequate nutrients originating from soil management practices and specific land cover characteristics. Effective soil management strategies and informed decision-making policies are crucial for enhancing soil fertility across the six land cover types in the Alas Bromo educational forest. In the case of pine and pine-mahogany land with low SFI values, targeted fertilization is essential. These land cover types show less diverse and lower-quality litter which is challenging to decompose, thereby contributing limited nutrient supply for trees. The direct association between litter quality, decomposition rates, soil biota, and nutrient availability was not assessed. Therefore, further investigation needs to identify the most effective strategies for enhancing soil fertility in the Alas Bromo educational forest.

The described land use types have distinct characteristics and are subject to management methods that directly impact soil properties (Olivares-Campos & López-Beltrán, 2019). Understanding the agri-environmental factors associated with these land cover types is essential for optimizing soil fertility and ensuring sustainable agricultural practices (Olivares-Campos et al., 2019). The results contribute to a broader comprehension of sustainable land management practices. Through evaluation of the influence of agri-environmental factors on soil fertility, this study provides valuable guidance for land managers and policymakers. The guidance will support decision-making processes aimed at promoting soil conservation, enhancing agricultural productivity, and mitigating the environmental consequences of land use practices.

5. CONCLUSION

In conclusion, the results showed that the soil fertility status of the six land cover types in the Alas Bromo educational forest of Universitas Sebelas Maret ranged from low (0.45) to moderate (0.57). Mahogany had the highest SFI, while external factors influencing SFI values included land cover characteristics such as litter production, DBH, and tree density. Moreover, this study identified the necessity for soil sustainability maintenance and the determination of appropriate land cover management strategies. Soil fertility should be improved and preserved in the diverse land cover types constituting the Alas Bromo educational forest. To determine the optimal method for sustainable land management in this forest area, the relationships between litter production, litter quality, soil biota, and decomposition rate must be examined.

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Declaration of Competing Interest

The authors declare that no competing financial or personal interests may appear and influence the work reported in this paper.

References

Adekiya, A. O., Aremu, C., Agbede, T. M., Olayanju, A., Ejue, W. S., Adegbite, K. A., . . . Oni, A. T. (2021). Soil productivity improvement under different fallow types on Alfisol of a derived savanna ecology of Nigeria. *Heliyon*, *7*(4), e06759. https://doi.org/10.1016/j.heliyon.2021.e06759

Ahuchaogu, I., Udoumoh, U., & Ehiomogue, P. (2022). Soil and Water Conservation Practices in Nigeria: A Review. *International Journal of Agriculture and Earth Science*, *8*(1), 25-39. https://www.iiardjournals.org/get/IJAES/VOL.%208%20NO.%201%202022/SOIL%20AND%20WATER%20CONSERVATION.pdf

Appiah-Badu, K., Anning, A. K., Eshun, B., & Mensah, G. (2022). Land use effects on tree species diversity and soil properties of the Awudua Forest, Ghana. *Global Ecology and Conservation*, *34*, e02051. https://doi.org/10.1016/j.gecco.2022.e02051

Apriyanto, E., Hidayat, F., Nugroho, P. B., & Tarigan, I. (2021). Litterfall Production and Decomposition in Three Types of Land Use in Bengkulu Protection Forest. *2021*, *9*(1), 7. https://doi.org/10.18196/pt.v9i1.4019

Ariyanto, D. P., Qudsi, Z. A., Sumani, Dewi, W. S., Rahayu, & Komariah. (2021). The dynamic effect of air temperature and air humidity toward soil temperature in various lands cover at KHDTK Gunung Bromo, Karanganyar - Indonesia. *IOP Conference Series: Earth and Environmental Science*, *724*(1), 012003. https://doi.org/10.1088/1755-1315/724/1/012003

Arora, S., Bhatt, R., Sharma, V., & Hadda, M. S. (2023). Indigenous Practices of Soil and Water Conservation for Sustainable Hill Agriculture and Improving Livelihood Security. *Environmental Management*, *72*(2), 321-332. https://doi.org/10.1007/s00267-022-01602-1

Awopegba, M., Oladele, S., & Awodun, M. (2017). Effect of mulch types on nutrient composition, maize (Zea mays L.) yield and soil properties of a tropical Alfisol in Southwestern Nigeria [Effect of mulch types on nutrient composition, maize (Zea mays L.) yield and soil properties of a tropical Alfisol in Southwestern Nigeria]. *Eurasian Journal of Soil Science*, *6*(2), 121-133. https://doi.org/10.18393/ejss.286546

Bagherzadeh, A., Gholizadeh, A., & Keshavarzi, A. (2018). Assessment of soil fertility index for potato production using integrated Fuzzy and AHP approaches, Northeast of Iran. *Eurasian Journal of Soil Science*, *7*(3), 203-212. https://doi.org/10.18393/ejss.399775

Bahru, T., & Ding, Y. (2020). Effect of stand density, canopy leaf area index and growth variables on Dendrocalamus brandisii (Munro) Kurz litter production at Simao District of Yunnan Province, southwestern China. *Global Ecology and Conservation*, *23*, e01051. https://doi.org/10.1016/j.gecco.2020.e01051

Callesen, I., Clarke, N., Lazdinš, A., Varnagiryte-Kabasinskiene, I., & Raulund-Rasmussen, K. (2019). Nutrient release capability in Nordic and Baltic forest soils determined by dilute nitric acid extraction – Relationships with indicators for soil quality, pH and sustainable forest management. *Ecological Indicators*, *96*, 540-547. https://doi.org/10.1016/j.ecolind.2018.09.027

Carnol, M., & Bazgir, M. (2013). Nutrient return to the forest floor through litter and throughfall under 7 forest species after conversion from Norway spruce. *Forest Ecology and Management*, *309*, 66-75. https://doi.org/10.1016/j.foreco.2013.04.008

Chase, P., & Singh, O. (2014). Soil nutrients and fertility in three traditional land use systems of Khonoma, Nagaland, India. *Resources and Environment*, *4*(4), 181-189. http://article.sapub.org/10.5923.j.re.20140404.01.html

Chen, S., Lin, B., Li, Y., & Zhou, S. (2020). Spatial and temporal changes of soil properties and soil fertility evaluation in a large grain-production area of subtropical plain, China. *Geoderma*, *357*, 113937. https://doi.org/10.1016/j.geoderma.2019.113937

Darmawan, A. A., Ariyanto, D. P., Basuki, T. M., Syamsiyah, J., & Dewi, W. S. (2022). Biomass accumulation and carbon sequestration potential in varying tree species, ages and densities in Gunung Bromo Education Forest, Central Java, Indonesia. *Biodiversitas Journal of Biological Diversity*, *23*(10). https://doi.org/10.13057/biodiv/d231016

Dewi, W. S., Nugroho, M. A., Maulana, M. A. D., Purwanto, Ariyanto, D. P., & Indrayatie, E. R. (2023). The Assessment of Soil Quality and Earthworms as Bioindicators in the Alas Bromo Education Forest, Central Java, Indonesia. *International Journal on Advanced Science, Engineering and Information Technology*, *13*(2), 452-461. https://doi.org/10.18517/ijaseit.13.2.18398

Dewi, W. S., Prasidina, S. D. C., Amalina, D. D., & Wongsoatmojo, S. (2021). The density and diversity of Arbuscular mycorrhizal spores on land covers with different tree canopy densities at the UNS educational forests. *IOP Conference Series: Earth and Environmental Science*, *824*(1), 012021. https://doi.org/10.1088/1755-1315/824/1/012021

Dewi, W. S., Puspaningrum, A., Tinuntun, R. S., Suntoro, S., & Mujiyo, M. (2022). A modified soil fertility assessment method using earthworm density and microbial biomass C at various land uses in Wonogiri, Indonesia. *International Journal of Design & Nature and Ecodynamics*, *17*(6), 929-936. https://doi.org/10.18280/ijdne.170614

Dewi, W. S., Widijanto, H., & Nofiantoro, S. (2018). The potential of pineapple rotations to improve chemical properties of Ultisols. *Bulgarian Journal of Agricultural Science*, *24*(1). https://journal.agrojournal.org/page/en/details.php?article_id=980

Dobermann, A., & Oberthür, T. (1997). Fuzzy mapping of soil fertility — a case study on irrigated riceland in the Philippines. *Geoderma*, *77*(2), 317-339. https://doi.org/10.1016/S0016-7061(97)00028-1

Drupadi, T. A., Ariyanto, D. P., & Sudadi. (2021). Pendugaan Kadar Biomassa dan Karbon Tersimpan pada Berbagai Kemiringan dan Tutupan Lahan di KHDTK Gunung Bromo UNS. *Jurnal Agrikultura*, *32*(2), 112-119. https://doi.org/10.24198/agrikultura.v32i2.32344

Dutta, J., Sharma, S. P., Sharma, S. K., Sharma, G. D., & Sankhyan, N. K. (2015). Indexing Soil Quality under Long-Term Maize-Wheat Cropping System in an Acidic Alfisol. *Communications in Soil Science and Plant Analysis*, *46*(15), 1841-1862. https://doi.org/10.1080/00103624.2015.1047845

Gautam, A., Guzman, J., Kovacs, P., & Kumar, S. (2022). Manure and inorganic fertilization impacts on soil nutrients, aggregate stability, and organic carbon and nitrogen in different aggregate fractions. *Archives of Agronomy and Soil Science*, *68*(9), 1261-1273. https://doi.org/10.1080/03650340.2021.1887480

Gillman, G. P., & Uehara, G. (1980). Charge Characteristics of Soils with Variable and Permanent Charge Minerals: II. Experimental. *Soil Science Society of America Journal*, *44*(2), 252-255. https://doi.org/10.2136/sssaj1980.03615995004400020009x

Hansson, K., Laclau, J.-P., Saint-André, L., Mareschal, L., van der Heijden, G., Nys, C., . . . Legout, A. (2020). Chemical fertility of forest ecosystems. Part 1: Common soil chemical analyses were poor predictors of stand productivity across a wide range of acidic forest soils. *Forest Ecology and Management*, *461*, 117843. https://doi.org/10.1016/j.foreco.2019.117843

Ibáñez, I., Acharya, K., Juno, E., Karounos, C., Lee, B. R., McCollum, C., . . . Tourville, J. (2019). Forest resilience under global environmental change: Do we have the information we need? A systematic review. *PLOS ONE*, *14*(9), e0222207. https://doi.org/10.1371/journal.pone.0222207

Jamaluddin, A. S., Abdu, A., Abdul-Hamid, H., Akbar, M. H., Banga, T. S., Jusop, S., & Majid, N. M. (2013). Assessing Soil Fertility Status of Rehabilitated Degraded Tropical Rainforest. *American Journal of Environmental Sciences*, *9*(3). https://doi.org/10.3844/ajessp.2013.280.291

Khadka, D., Lamichhane, S., Bhurer, K. P., Chaudhary, J. N., Ali, M. F., & Lakhe, L. (2018). Soil Fertility Assessment and Mapping of Regional Agricultural Research Station, Parwanipur, Bara, Nepal. *Journal of Nepal Agricultural Research Council*, *4*(1), 33-47. https://doi.org/10.3126/jnarc.v4i1.19688

Lu, D., Moran, E., & Mausel, P. (2002). Linking Amazonian secondary succession forest growth to soil properties. *Land Degradation & Development*, *13*(4), 331-343. https://doi.org/10.1002/ldr.516

Lukina, N. V., Tikhonova, E. V., Danilova, M. A., Bakhmet, O. N., Kryshen, A. M., Tebenkova, D. N., . . . Zukert, N. V. (2019). Associations between forest vegetation and the fertility of soil organic horizons in northwestern Russia. *Forest Ecosystems*, *6*(1), 34. https://doi.org/10.1186/s40663-019-0190-2

Marchi, E., Chung, W., Visser, R., Abbas, D., Nordfjell, T., Mederski, P. S., . . . Laschi, A. (2018). Sustainable Forest Operations (SFO): A new paradigm in a changing world and climate. *Science of The Total Environment*, *634*, 1385-1397. https://doi.org/10.1016/j.scitotenv.2018.04.084

Moran, E. F., Brondizio, E. S., Tucker, J. M., da Silva-Forsberg, M. C., McCracken, S., & Falesi, I. (2000). Effects of soil fertility and land-use on forest succession in Amazônia. *Forest Ecology and Management*, *139*(1), 93-108. https://doi.org/10.1016/S0378-1127(99)00337-0

Mugi-Ngenga, E., Bastiaans, L., Zingore, S., Anten, N. P. R., & Giller, K. E. (2022). The role of nitrogen fixation and crop N dynamics on performance and legacy effects of maize-grain legumes intercrops on smallholder farms in Tanzania. *European Journal of Agronomy*, *141*, 126617. https://doi.org/10.1016/j.eja.2022.126617

Mukashema, A. (2007). *Mapping and Modelling Landscape-based Soil Fertility Change in Relation to Human Induction* [Master thesis, International Institute for Geo-information Science and Earth Observation]. https://webapps.itc.utwente.nl/librarywww/papers_2007/msc/nrm/mukashema.pdf

Mulat, Y., Kibret, K., Bedadi, B., & Mohammed, M. (2021). Soil quality evaluation under different land use types in Kersa sub-watershed, eastern Ethiopia. *Environmental Systems Research*, *10*(1), 19. https://doi.org/10.1186/s40068-021-00224-6

Munawar, A. (2018). *Kesuburan tanah dan nutrisi tanaman*. PT Penerbit IPB Press.

Neina, D. (2019). The Role of Soil pH in Plant Nutrition and Soil Remediation. *Applied and Environmental Soil Science*, *2019*(1), 5794869. https://doi.org/10.1155/2019/5794869

Nguemezi, C., Tematio, P., Yemefack, M., Tsozue, D., & Silatsa, T. B. F. (2020). Soil quality and soil fertility status in major soil groups at the Tombel area, South-West Cameroon. *Heliyon*, *6*(2), e03432. https://doi.org/10.1016/j.heliyon.2020.e03432

Nufus, M., Pertiwi, Y. A. B., & Sakya, A. T. (2020). Vegetation analysis and tree species diversity in KHDTK Gunung Bromo, Karanganyar, Central Java. *IOP Conference Series: Earth and Environmental Science*, *528*(1), 012010. https://doi.org/10.1088/1755-1315/528/1/012010

Nugroho, A. F., Ichwandi, I., & Kosmaryandi, N. (2017). Analisis pengelolaan kawasan hutan dengan tujuan khusus (Studi Kasus Hutan Pendidikan dan Latihan Gunung Walat). *Journal of Environmental Engineering and Waste Management*, *2*(2), 51-59. https://e-journal.president.ac.id/presunivojs/index.php/JENV/article/viewFile/219/116

Nurfansyah, E., Hendrayana, Y., & Adhya, I. (2019). Potensi karbon tersimpan pada tegakan pinus (Pinus merkusii) di Blok Pasir Batang Kawasan Taman Nasional Gunung Ciremai. *Wanaraksa*, *13*(1). https://doi.org/10.25134/wanaraksa.v13i01.4649

Olivares-Campos, B. O., & López-Beltrán, M. A. (2019). Normalized Difference Vegetation Index (NDVI) applied to the agricultural indigenous territory of Kashaama , Venezuela [Índice de Vegetación de Diferencia Normalizada aplicado al territorio indígena agrícola de Kashaama, Venezuela]. *Cuadernos de Investigación UNED*, *11*(2), 112-121. https://doi.org/10.22458/urj.v11i2.2299

Olivares-Campos, B. O., López-Beltrán, M. A., & Lobo-Luján, D. (2019). Changes in land use and vegetation in the agrarian community Kashaama, Anzoátegui, Venezuela: 2001-2013 [Cambios de usos de suelo y vegetación en la comunidad agraria Kashaama, Anzoátegui, Venezuela: 2001-2013]. *Revista Geográfica De América Central*, *63*(2), 224-246. https://doi.org/10.15359/rgac.63-2.10

Pei, G., Liu, J., Peng, B., Gao, D., Wang, C., Dai, W., . . . Bai, E. (2019). Nitrogen, lignin, C/N as important regulators of gross nitrogen release and immobilization during litter decomposition in a temperate forest ecosystem. *Forest Ecology and Management*, *440*, 61-69. https://doi.org/10.1016/j.foreco.2019.03.001

Pertiwi, R. A. P., Sugiyarto, S., Budiharjo, A., & Nayasilana, I. N. (2020). Diversity of Butterflies (Lepidoptera) in Mount Bromo Forest Area with Special Purpose (FASP), Karanganyar, Central Jawa. *Zoo Indonesia*, *29*(2), 166-176. https://biologyjournal.brin.go.id/index.php/zoo_indonesia/article/view/3993

Perumal, M., Wasli, M. E., Ying, H. S., Lat, J., & Sani, H. (2017). Association between Soil Fertility and Growth Performance of Planted Shorea macrophylla (de Vriese) after Enrichment Planting at Rehabilitation Sites of Sampadi Forest Reserve, Sarawak, Malaysia. *International Journal of Forestry Research*, *2017*(1), 6721354. https://doi.org/10.1155/2017/6721354

Sachan, H., & Krishna, D. (2022). Assessment of soil fertility status using nutrient index approach in cassava farms of rewa province, Fiji. *Indian Journal of Agricultural Research*, *56*(5), 594-598. https://doi.org/10.18805/IJARe.AF-680

Sari, R. R., Rozendaal, D. M. A., Saputra, D. D., Hairiah, K., Roshetko, J. M., & van Noordwijk, M. (2022). Balancing litterfall and decomposition in cacao agroforestry systems. *Plant and Soil*, *473*(1), 251-271. https://doi.org/10.1007/s11104-021-05279-z

Sasongko, P. E., Purwanto, P., Dewi, W. S., & Hidayat, R. (2022). Assessment of soil fertility using the soil fertility index method on several land uses in Tutur District, Pasuruan Regency of East Java. *Journal of Degraded and Mining Lands Management*, *10*(1), 3787-3794. https://doi.org/10.15243/jdmlm.2022.101.3787

Shen, Y., Li, J., Chen, F., Cheng, R., Xiao, W., Wu, L., & Zeng, L. (2022). Correlations between forest soil quality and aboveground vegetation characteristics in Hunan Province, China [Original Research]. *Frontiers in Plant Science*, *13*. https://doi.org/10.3389/fpls.2022.1009109

Singh, G., Sharma, M., Manan, J., & Singh, G. (2016). Assessment of soil fertility status under different cropping sequences in District Kapurthala. *Journal of Krishi Vigyan*, *5*(1), 1-9. https://doi.org/10.5958/2349-4433.2016.00023.4

Sugiyarto, Nayasilana, I. N., & Aditya. (2020). The suburban forest as a habitat of eagles (Accipitridae): a case study in Gunung Bromo University Forest, Karanganyar, Central Java, Indonesia. *IOP Conference Series: Earth and Environmental Science*, *590*(1), 012007. https://doi.org/10.1088/1755-1315/590/1/012007

Sulaeman, Suparto, & Eviati. (2021). *Petunjuk Teknis Analisis Kimia Tanah, Tanaman, Air, Dan Pupuk* (B. H. Prasetyo, D. Santoso, & L. R. Widowati, Eds.). Balai Penelitian Tanah, Badan Penelitian dan Pengembangan Pertanian, Departemen Pertanian.

Supriyadi, S., Ustiatik, R., Mukti, B., Minardi, S., Widijanto, H., & Sakti, M. B. G. (2022). Soil quality status under Hazton's paddy farming: A case study in Banyumas Regency, Indonesia. *SAINS TANAH - Journal of Soil Science and Agroclimatology*, *19*(2), 123-131. https://doi.org/10.20961/stjssa.v19i2.58375

Thapa, M. S., Bhattarai, T., Sharma, R. P., K. C, B., & Puri, L. (2019). Analytical Study on Fertility Status and Soil Quality Index of Shorearobusta Forest, Central Nepal. *Tribhuvan University Journal*, *33*(2), 1-14. https://doi.org/10.3126/tuj.v33i2.33560

Tongka, G. N. T. N., Wardah, W., & Yusran, Y. (2019). Kondisi kimia tanah di bawah tegakan pinus (Pinus merkusii jungh. Et de vriese) dan padang rumput Desa Watutau Kecamatan Lore Peore Kabupaten Poso Sulawesi Tengah. *ForestSains*, *16*(2), 69-76. https://interoperabilitas.perpusnas.go.id/record/detail/573109/kondisi-kimia-tanah-di-bawah-tegakan-pinus-pinus-merkusii-jungh-et-de-vriese-dan-padang-rumput-desa-watutau-kecamatan-lore-peore-kabupaten-poso-sulawesi-tengah

Vergílio, M., Fjøsne, K., Nistora, A., & Calado, H. (2016). Carbon stocks and biodiversity conservation on a small island: Pico (the Azores, Portugal). *Land Use Policy*, *58*, 196-207. https://doi.org/10.1016/j.landusepol.2016.07.020

Wang, Q., Wang, S., & Yu, X. (2011). Decline of soil fertility during forest conversion of secondary forest to Chinese fir plantations in subtropical China. *Land Degradation & Development*, *22*(4), 444-452. https://doi.org/10.1002/ldr.1030

Wicaksono, R. L., Rahmadwiati, R., & Apriyanto, D. (2020). INTERAKSI DAN KETERGANTUNGAN MASYARAKAT SEKITAR TERHADAP KAWASAN HUTAN DENGAN TUJUAN KHUSUS (KHDTK) GUNUNG BROMO. *Jurnal Belantara*, *3*(1), 1-11. https://doi.org/10.29303/jbl.v3i1.421

Xie, L. W., Zhong, J., Chen, F. F., Cao, F. X., Li, J. J., & Wu, L. C. (2015). Evaluation of soil fertility in the succession of karst rocky desertification using principal component analysis. *Solid Earth*, *6*(2), 515-524. https://doi.org/10.5194/se-6-515-2015

Yang, X., Wang, Y., Xu, Q., Liu, W., Liu, L., Wu, Y., . . . Lu, J. (2021). Soil fertility underlies the positive relationship between island area and litter decomposition in a fragmented subtropical forest landscape. *CATENA*, *204*, 105414. https://doi.org/10.1016/j.catena.2021.105414

Zake, J., Pietsch, S. A., Friedel, J. K., & Zechmeister-Boltenstern, S. (2015). Can agroforestry improve soil fertility and carbon storage in smallholder banana farming systems? *Journal of Plant Nutrition and Soil Science*, *178*(2), 237-249. https://doi.org/10.1002/jpln.201400281

Zhang, Y., He, X., Liang, H., Zhao, J., Zhang, Y., Xu, C., & Shi, X. (2016). Long-term tobacco plantation induces soil acidification and soil base cation loss. *Environmental Science and Pollution Research*, *23*(6), 5442-5450. https://doi.org/10.1007/s11356-015-5673-2

Zhu, X., Liu, W., Chen, H., Deng, Y., Chen, C., & Zeng, H. (2019). Effects of forest transition on litterfall, standing litter and related nutrient returns: Implications for forest management in tropical China. *Geoderma*, *333*, 123-134. https://doi.org/10.1016/j.geoderma.2018.07.023