

# Agroforestry for soil health in a tropical national park of Gunung Halimun Salak, Indonesia

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**Abstract.** *Suharto FF, Wijayanto N, Wasis B. 2025. Agroforestry for soil health in a tropical national park of Gunung Halimun Salak, Indonesia. Asian J For 9: 346-360.* This study evaluated the Visual Evaluation of Soil Structure (VESS) method as a rapid assessment tool for soil health across six stand types in Gunung Halimun Salak National Park, Indonesia. The research employed a comparative design across natural forest, mixed stand, and four agroforestry systems (damar-cardamom, damar-coffee, damar-chili, damar-eggplant), with three replicate plots per stand. VESS assessment followed standardized protocols, evaluating aggregate size, porosity, root distribution, and structural strength in the 0-30 cm depth. Laboratory analyses quantified bulk density, porosity, moisture content, pH, organic carbon, and Cation Exchange Capacity (CEC). Statistical analyses included ANOVA, Duncan's test, Principal Component Analysis, and Spearman correlation. We linked VESS scores to vegetation composition and laboratory-measured soil properties. Vegetation analysis revealed distinct dominance patterns: natural forest by *Macropanax dispermus* (IVI=120.57%), agroforestry systems by *Agathis dammara* (IVI=158.05-300.00%), and mixed stand by *Altingia excelsa* (IVI=248.50%). VESS evaluation showed good soil structure (Sq=1.0-1.84) in natural forest and low-intensity agroforestry, with moderate degradation (Sq=2.5) in intensive systems. PCA confirmed VESS as an integrative indicator, with PC1 explaining 73.55% of variance along a soil structure gradient. Principal Component Analysis (PCA) and Spearman correlations revealed strong correlations emerged between VESS and bulk density ( $\rho=+0.85$ ), porosity ( $\rho=-0.85$ ), moisture content ( $\rho=-0.85$ ), organic carbon ( $\rho=-0.86$ ), and CEC ( $\rho=-0.77$ ). VESS scores exhibited strong and significant correlations with key soil health indicators, showing they increased with compaction and decreased with porosity, moisture content, soil organic carbon, and cation exchange capacity. The findings support VESS as a practical field tool and are effective for detecting management-induced soil degradation. We recommend its integration into the park's regular monitoring protocols to support soil conservation efforts. Promoting complex agroforestry systems is also advised. Study limitations include single-observer assessment and unmeasured environmental covariates, suggesting the need for further validation.

**Keywords:** Agroforestry management, soil physical and chemical quality, sustainable land management, tropical agroforestry, VESS

## INTRODUCTION

Soil health is crucial for biodiversity and livelihoods in Gunung Halimun Salak National Park (GHSNP), one of Java's largest remaining montane rainforests ( $\pm 87.699$  ha), and a key conservation area in Indonesia (Balai Taman Nasional Gunung Halimun Salak 2018). Soil serves as the primary medium for plant growth, consisting of minerals, organic matter, water, and air (Arifin et al. 2019). The physical properties of soil influence water availability, aeration, root development, and nutrient uptake, contributing to ecosystem productivity (Cardone et al. 2020; Hartanto et al. 2021). Local communities in GHSNP practice agroforestry systems that combine production with conservation functions. However, the quantitative effects of these systems on soil health require further assessment, presenting a knowledge gap for park management (Matos et al. 2020, 2022; Huera-Lucero et al. 2025). Conventional soil monitoring methods based on laboratory analyses are complex and costly, indicating a practical need for alternative assessment tools.

Soil degradation resulting from deforestation and agricultural conversion affects these landscapes. Deforestation influences nutrient cycles by reducing tree cover that contributes to soil nutrient retention, potentially affecting ecosystem productivity (Wahyuni and Suranto 2021). Agricultural intensification can alter soil physical properties by increasing bulk density and penetration resistance while decreasing aeration, aggregate stability, and water infiltration, which may elevate erosion risk (Hasannudin et al. 2022; Indriyati et al. 2024). Soil restoration following degradation is generally recognized as a lengthy process (Wahyunto and Dariah 2014; Sena et al. 2021). These concerns highlight the value of sustainable land management approaches. Agroforestry represents one strategy that may reduce degradation through ecological integration. The Visual Evaluation of Soil Structure (VESS) method provides one approach for assessing soil quality in these systems.

Agroforestry integrates woody perennials with agricultural crops in spatial or temporal arrangements (Sardjono et al. 2003; Gunawan et al. 2019). Trees in these systems contribute to nutrient cycling through litterfall,

potentially enhancing soil organic matter and microbial activity (Dollinger and Jose 2018; Fahad et al. 2022). Agroforestry systems can diversify production while providing multiple benefits (Lehmann et al. 2020). Trees help maintain soil nutrients, reduce erosion, and conserve soil and water while yielding products (Sanchez 1995; Cardinael et al. 2020). Research indicates agroforestry can contribute to soil fertility, hydrological regulation, and biodiversity (Udawatta et al. 2019; Fahad et al. 2022). For example, rubber-based agroforestry increases soil porosity by 13.3% and aggregate diameter by 31.5% compared to monocultures (Ngaba et al. 2024). These characteristics suggest agroforestry may help maintain soil quality, while VESS offers a method to monitor soil structure.

The Visual Evaluation of Soil Structure (VESS) method provides a field-based approach to soil quality assessment (Ball et al. 2007). This method combines observations of aggregate size, strength, porosity, and root presence into a single score (Guimarães et al. 2011). Research has documented VESS applications in agricultural and agroforestry contexts internationally (Ball et al. 2016; Silva et al. 2022) and in Indonesia (Aji et al. 2021; Briliawan et al. 2022; Purnama et al. 2022). VESS scores have demonstrated correlations with certain soil properties including bulk density, porosity, and organic carbon. However, limited research has examined VESS applications specifically in conservation areas (Thomas et al. 2024; Paltineanu et al. 2025). The relationship between VESS scores and comprehensive laboratory-measured soil properties in tropical montane conservation areas like GHSNP requires further investigation. Since soil structure affects water infiltration, root growth, and nutrient cycling (Novák and Hlaváčiková 2019), evaluating VESS in this context could provide park managers with a supplementary monitoring tool.

This study aims to analyze vegetation composition across different stand types in GHSNP, assess soil structural quality using the VESS method, and examine relationships between VESS scores and laboratory-measured soil properties. The research considers natural forest, mixed stands, and four agroforestry systems. We anticipate that VESS scores will correlate with measured soil properties and reflect differences among stand types. This investigation may contribute to developing agroforestry management practices that support conservation and livelihood objectives in the national park.

## MATERIALS AND METHODS

### Study area

This study was conducted from November 2024 to June 2025 within the Gunung Kendeng Resort area, part of the Gunung Halimun Salak National Park (GHSNP) in Indonesia (Figure 1). The research encompassed an elevational range of 800-1,300 meters above sea level (masl), corresponding to the moderate zone under Junghuhn's climate classification (600-1,500 masl). This zone was selected to ensure representation of typical ecosystem conditions within the study area. Data collection

was performed across six distinct stand types: natural forest, mixed stand, and four agroforestry systems (Damar-cardamom-lemongrass-pineapple, damar-coffee, damar-chili pepper, and damar-eggplant).

### Stands description

#### *Natural forest*

This stand is located in the jungle zone at 1,004-1,006 masl on andosol soil. Tree composition is dominated by *Macropanax dispermus*. The canopy is multi-layered. This stand is unmanaged with no human intervention. It functions as a buffer zone for the national park.

#### *Agroforestry stand: Damar-cardamom-lemongrass-pineapple*

This stand is located in the rehabilitation zone at 963-964 masl on andosol soil. The tree layer is dominated by *Agathis dammara* with a multi-layered canopy. Management is organic, utilizing litter from the forest floor. Agricultural commodities are harvested.

#### *Agroforestry stand: Damar-coffee*

This stand is located in the rehabilitation zone at 951-960 masl on andosol soil. The tree layer is dominated by *A. dammara* with a multi-layered canopy. Management is organic, utilizing litter from the forest floor. Coffee is harvested, and its seed dispersal is assisted by animals.

#### *Agroforestry stand: Damar-chili*

This stand is located in the rehabilitation zone at 868-871 masl on andosol soil. The tree layer is dominated by *A. dammara* with a sparse canopy. Management follows intensive practices with quantified inputs: herbicides and pesticides applied at 140 cc. 20 m<sup>-2</sup>, Phonska fertilizer at 2 kg. 5 m<sup>-2</sup>, and mechanical maintenance (weeding, tillage) every 30 days. Plastic mulch is used on 1-meter-wide beds. The *Agathis* canopy is thinned for livestock and agriculture, with production focused on chili.

#### *Agroforestry stand: Damar-eggplant*

This stand is located in the rehabilitation zone at 841-842 masl on andosol soil. The tree layer is dominated by *A. dammara* with a sparse canopy. Management follows intensive practices with quantified inputs: herbicides and pesticides applied at 140 cc. 20 m<sup>-2</sup>, Phonska fertilizer at 2 kg. 5 m<sup>-2</sup>, and mechanical maintenance (weeding, tillage) every 30 days. Plastic mulch is applied on 1-meter-wide beds. The *Agathis* canopy is thinned to support livestock and agricultural activities, with production focused on eggplant.

#### *Mixed stand*

This stand is located in the rehabilitation zone at 896-901 masl on andosol soil. *Altingia excelsa* dominates tree composition with a multi-layered canopy. This stand is unmanaged. It resulted from rehabilitation efforts in the 1950s.

## Procedures

### *Vegetation analysis and soil sampling*

This study used purposive sampling by creating three sample plots for each type of stand (Wasis et al. 2019). Vegetation and soil sampling were conducted using a nested plot design, with plot sizes adapted to different vegetation strata: 20×20 m for trees, 10×10 m for poles, 5×5 m for saplings, and 2×2 m for seedlings. Within each main 20×20 m plot, comprehensive data collection was performed: (i) vegetation analysis, including recording all plant species, counting individuals, and measuring stem diameter and height for trees and poles; and (ii) soil sampling, collecting both disturbed and undisturbed samples from five systematically distributed points within each main plot to ensure spatial representation and comprehensive analysis.

### *VESS procedure*

Soil structural quality was assessed using the Visual Evaluation of Soil Structure (VESS) method, following established guidelines from Ball et al. (2016). For each sampling point, a soil pit (30×30×30 cm) was excavated to extract an intact block sample (approximately 20×10×25 cm). The evaluation procedure involved: (i) identifying distinct soil layers, (ii) gently crushing soil aggregates to 1.5-2 cm to observe their internal structure, and (iii) visually assessing structural characteristics, including aggregate size, porosity, root distribution, and ease of fragmentation. These observations were synthesized into a VESS score (Sq) for each layer according to the standardized scoring chart, which integrates assessments of structural strength (resistance to fragmentation), aggregate morphology, porosity patterns, and root development into a single numerical value ranging from Sq1 (best structure—friable, highly porous with abundant roots) to Sq5 (poorest structure—dense, massive with no roots).

## Data analysis

### *Species composition*

Species identification was conducted using standard field guides and verified by a local botanist. Species composition was quantified using the Important Value Index (IVI), which synthesizes a species' relative density, relative frequency, and relative dominance to evaluate its ecological dominance within the community from Kusmana et al. (2022):  $IVI = RD + RF + RDo$  (poles and trees) and  $IVI = RD + RF$  (seedlings and saplings). Where:

### Density ( $D$ (ind. $ha^{-1}$ ))

$$D = \frac{\sum \text{Density of species}}{\text{Area of plot}}$$

### Density Relative (DR) (%)

$$RD = \frac{\text{Density of species}}{\text{Density all species}} \times 100\%$$

### Frequency (F)

$$F = \frac{\sum \text{sub plot species found}}{\sum \text{sub plot}}$$

### Frequency Relative (FR) (%)

$$FR = \frac{\text{Frequency of species}}{\text{Frequency all species}} \times 100\%$$

### Domination ( $Do$ ) ( $m^2 \cdot ha^{-1}$ ) for poles and trees

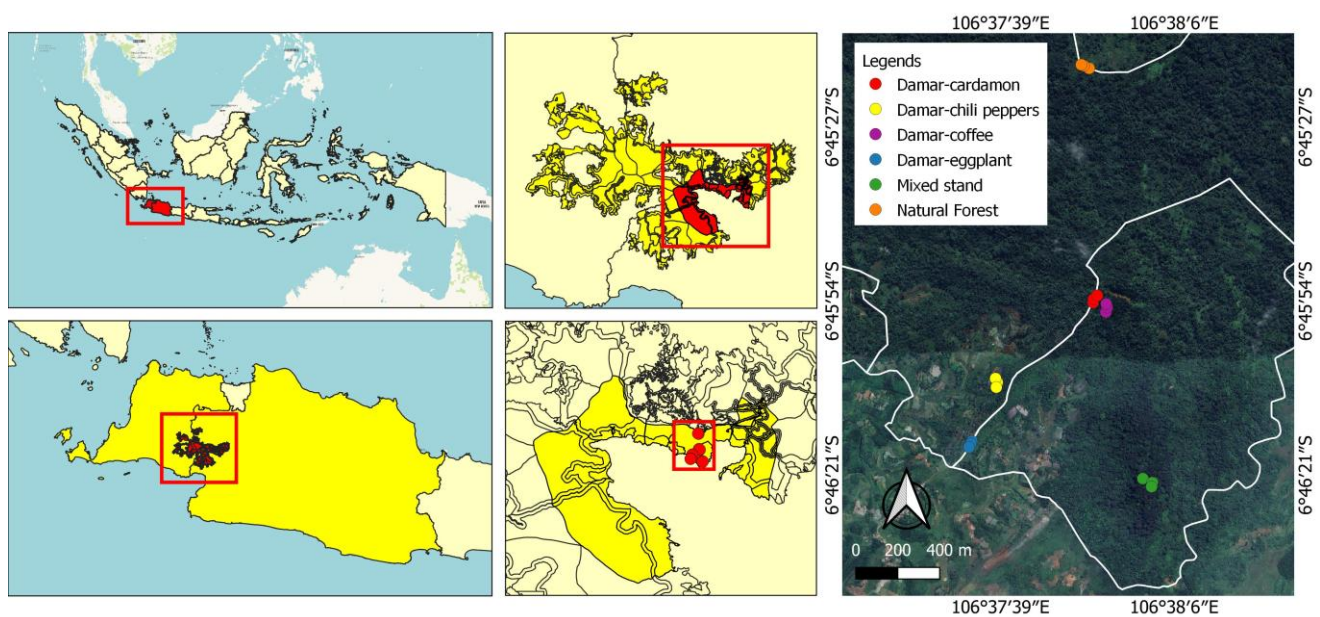
$$Do = \frac{\text{Basal area of species}}{\text{Area of plot}}$$

### Domination Relative (DoR) (%)

$$DoR = \frac{\text{Domination of species}}{\text{Domination all species}} \times 100\%$$

### Basal area of species ( $m^2$ )

$$\text{Basal area} = 0.25 \times \pi \times D^2$$



**Figure 1.** Location of the six studied stand types within the Gunung Kendeng Resort area, Gunung Halimun Salak National Park, Indonesia

### Formal definitions of vegetation parameters

Vegetation analysis was conducted across six stands for each tree growth level. Chowdhury et al. (2019) defined each parameter. Density (D) refers to the number of individuals of a species per hectare, and Density Relative (DR) is the percentage of individuals of a species relative to the total individuals of all species. Frequency (F) is the number of sampling plots where a species is recorded. Frequency Relative (FR) is the percentage frequency of a species relative to the total frequency of all species. Domination (Do) is the basal area of a species for all its individuals, a parameter applied to both poles and trees. Domination Relative (DoR) is the percentage domination of a species relative to the total domination of all species. Basal area is the total cross-sectional area of tree stems at breast height per hectare.

### Index biodiversity

Vegetation diversity was analyzed using three ecological indices: the Shannon-Wiener Diversity Index (H'), species richness (DMg), and Pielou's Evenness Index (E). The formulas and references for calculating these indices are provided in Table 1. These indices were calculated for each vegetation growth level (seedlings, saplings, poles, and trees) within every stand type.

### Formal definitions of index biodiversity

Vegetation diversity was assessed using three complementary indices. The Shannon-Wiener Index (H') quantifies overall diversity by incorporating both species richness and their relative abundance, where higher values indicate greater diversity and community balance (Peng et al. 2018; Sheng et al. 2024). The Margalef Richness Index (DMg) specifically evaluates species richness by accounting for the number of species present relative to the total individual count, providing a standardized measure for cross-community comparisons (Death 2008; Meng et al. 2023). The Pielou Evenness Index (E) assesses the distribution uniformity of individuals among species, with values approaching 1.0 indicating more equitable distribution patterns (Cui et al. 2022; Kumar et al. 2022). These indices collectively provide comprehensive insights into different aspects of vegetation community structure across the studied stand types.

### VESS calculation

The VESS score was assigned to each observed soil layer based on its structural characteristics. The VESS score for the soil profile was then calculated using a weighted average formula based on layer thickness Guimarães et al. (2011), as follows:

$$\text{VESS Sq score} = \sum_{i=1}^n \frac{Sq_i \times T_i}{TT}$$

Where: VESS Sqscore: VESS score, Sq<sub>i</sub>: VESS score a thickness to i, T<sub>i</sub>: soil sample thickness to i, TT: total thickness of the whole soil.

The resulting overall VESS score was categorized into soil structural quality classes, which indicate the urgency of management intervention needed (Ball et al. 2007). The classification criteria are presented in Table 2.

### Other soil properties measurement

Soil chemical analyses were performed on composited samples from the 0-30 cm depth, representing the biologically active zone most responsive to management practices. While the VESS assessment evaluated soil structure throughout the profile, chemical analysis focused on this surface layer (0-30 cm) due to its direct relevance to vegetation growth and management impacts. Samples were analyzed in triplicate (n=3) for each stand to ensure statistical reliability. Analytical precision was maintained through instrument calibration before each analysis batch and verification using standard reference materials. All methods followed established laboratory protocols with appropriate quality control measures. All parameters and their corresponding analytical methods are detailed in Table 3.

### Statistical test

All statistical analyses were performed using RStudio. Data normality and homogeneity of variance were tested prior to ANOVA. The data met the assumptions for parametric testing. The effect of different stand types on soil parameters (VESS score, bulk density, porosity, moisture content, pH, organic carbon, and CEC) was analyzed using one-way Analysis of Variance (ANOVA) at a significance level of  $\alpha = 0.05$ . For parameters that showed significant differences in the ANOVA results, Duncan's Multiple Range Test (DMRT) was applied as a post-hoc analysis to determine specific differences between mean values of the stand types.

**Table 1.** Methods for calculating biodiversity indices: Shannon-Wiener (H'), Margalef (DMg), and Pielou (E)

Indices	Methods	References
Shannon-Wiener Diversity Index (H')	$H' = - \sum_{i=1}^n p_i \times \ln p_i ; p_i = \frac{n_i}{N}$	Where: H': Shannon-Wiener Diversity Index value, pi: Proportion of each species (ni/N), ni: Number of individuals of species I, N: Total number of individuals (Pretzsch 2009; Utami and Putra 2020)
Margalef richness index (DMg)	$DMg = \frac{S - 1}{\ln N}$	Where: DMg: Margalef's Richness Index value, S: Number of species found, ln: Natural logarithm, N: Total number of individuals (Magurran 1988; Utami and Putra 2020)
Pielou's Evenness Index (E)	$E = \frac{H'}{\ln S}$	Where: E: Pielou's Evenness Index value, H': Shannon-Wiener Diversity Index value, ln: Natural logarithm, S: Number of species found (Magurran 1988; Utami and Putra 2020)

Principal Component Analysis (PCA) was employed as a multivariate approach to explore the integrated relationships among all soil parameters and their variations across different stand types. The PCA was performed using the correlation matrix of standardized soil variables.

The relationships between VESS scores and other soil parameters were examined using Spearman's rank correlation coefficient. Spearman correlation analysis was conducted at a 95% confidence level, with statistical significance determined at  $\alpha = 0.05$ .

## RESULTS AND DISCUSSION

### Ecological dominance and management implications

The Important Value Index (IVI) quantifies ecological structure and species dominance (Hidayat 2018; Gao et al. 2021). Table 4 shows distinct species compositions and dominance patterns among stand types. The natural forest had high species diversity, with no single species dominating all strata. A species shift occurs from *Lithocarpus* sp. in seedlings to *M. dispermus* in trees. *Macropanax dispermus* had a high IVI (120.57%) in tree strata, consistent with its known role in mature forests (Balandier et al. 2006; Ali et al. 2020; Sun et al. 2023). The low advancement of dominant lower-strata species suggests possible competition or environmental filters. Agroforestry systems were dominated by *A. dammara* in the canopy (IVI: 158.05-300.00%), with understories containing introduced species. This structure aligns with managed systems designed for economic and ecological outputs (Houehanou et al. 2011; Herrero-Jáuregui et al. 2013). *Altingia excelsa* dominated the mixed stand at the tree level (IVI: 248.50%). The high dominance of a single species may indicate lower resilience, as noted in other studies (Tovar et al. 2019; Katembo et al. 2020). Management should consider enhancing species diversity for long-term stability (Aerts and Honnay 2011; Hua et al. 2022).

Biodiversity analysis reveals distinct structural patterns across stand types (Table 5). The natural forest exhibits consistently high Shannon-Wiener index values across all vegetation levels, demonstrating a stable species distribution characteristic of mature ecosystems (Chaturvedi and Raghubanshi 2014; Fagua et al. 2021). In contrast, managed agroforestry systems show reduced diversity in upper strata due to economic species dominance. The damar-coffee system maintains moderate

understory diversity but experiences sharp declines at the tree level from *A. dammara* dominance, reflecting farmer preference for high-value species (Valencia et al. 2015; Hartoyo et al. 2024). Intensive systems like damar-chili show more severe impacts, with completely absent seedling layers and zero tree diversity, indicating regeneration failure (Koelemeijer et al. 2021).

The mixed stand presents a conservation paradox with good lower-strata diversity but extreme *A. excelsa* dominance at the tree level, potentially compromising ecosystem resilience (Draper et al. 2019). Overall, the biodiversity gradient from natural forest to intensive agroforestry clearly reflects management intensity (Scales and Marsden 2008). While complex multi-strata agroforestry maintains moderate understory diversity, no system fully replicates the structural complexity of natural forests (Udawatta et al. 2019; Santos et al. 2022).

### VESS as an early warning system for soil management

The Visual Evaluation of Soil Structure (VESS) provides a rapid field assessment of soil structure quality. It uses a Sq score based on aggregate size, porosity, and root distribution. This method suits remote areas with limited lab access (Franco et al. 2019; Aji et al. 2021; Silva et al. 2022). We focused on the upper soil layer (0-30 cm). This zone is biologically active and sensitive to management (Ball et al. 2007; Emmet-Booth et al. 2019). VESS scores involve observer subjectivity. Our study used a single observer, but we did not test inter-observer reliability. Our VESS results should be interpreted with the consideration that a single observer conducted assessments. While this approach ensured internal consistency for comparative purposes across our plots, it does not account for potential inter-observer variability. Future studies would benefit from inter-observer reliability testing to enhance the method's robustness in similar contexts.

**Table 2.** Soil structural quality classes based on the scoring VESS score

Sq score	Soil structural quality	Management needs
1-2	Good	No changes needed
2.1-3	Fair	Long-term improvements
3.1-5	Poor	Short-term improvements

**Table 3.** Soil properties and analytical methods used in the study

Parameter	Methods	References
Bulk density	Core Method	(Walter et al. 2016; Al-Shammary et al. 2018)
Porosity	Calculation of bulk density & particle density (2.65 g. cm <sup>-3</sup> for mineral soil)	(Robinson et al. 2022; Bryk and Kołodziej 2023)
Moisture content	Gravimetric Oven-Drying Method	(ASTM International 2019)
pH soil	pH H <sub>2</sub> O	(IUSS Working Group WRB 2022)
Organic carbon	Walkley and Black	(IUSS Working Group WRB 2022)
Cation Exchange Capacity (CEC)	Leaching (Ammonium acetate 1 N pH 7)	(IUSS Working Group WRB 2022)

**Table 4.** Ecological dominance patterns revealed by the Important Value Index (IVI) of the most influential species at different growth levels in each stand type

Stands	Level	Species	IVI (%)
Natural forest	Seedling	<i>Lithocarpus</i> sp.	100.00
	Sapling	<i>Macaranga rhizinoides</i> (Blume) Müll.Arg.	70.00
	Pole	<i>Macropanax dispermus</i> (Blume) Kuntze	110.38
	Tree	<i>Macropanax dispermus</i> (Blume) Kuntze	120.57
Agroforestry damar-cardamom, pineapple, lemongrass	Seedling	<i>Calliandra calothyrsus</i> Meisn.	141.67
	Sapling	<i>Persea americana</i> Mill.	200.00
	Pole	<i>Artocarpus heterophyllus</i> Lam.	127.56
	Tree	<i>Agathis dammara</i> (Lamb.) Rich. & A.Rich.	205.41
Agroforestry damar-coffee	Seedling	<i>Coffea arabica</i> L.	78.33
	Sapling	<i>Coffea arabica</i> L.	101.90
	Pole	<i>Syzygium jambos</i> (L.) Alston	113.90
	Tree	<i>Agathis dammara</i> (Lamb.) Rich. & A.Rich.	244.21
Agroforestry damar-chili pepper	Seedling	No seedlings found	No seedlings found
	Sapling	<i>Durio zibethinus</i> Murray	100.00
	Pole	<i>Maesopsis eminii</i> Engl.	127.22
	Tree	<i>Agathis dammara</i> (Lamb.) Rich. & A.Rich.	300.00
Agroforestry damar-eggplant	Seedling	<i>Coffea canephora</i> Pierre ex A.Froehner	133.33
	Sapling	<i>Garcinia mangostana</i> L.	100.00
	Pole	<i>Syzygium aromaticum</i> (L.) Merr. & L.M.Perry	94.37
	Tree	<i>Agathis dammara</i> (Lamb.) Rich. & A.Rich.	158.05
Mixed	Seedling	<i>Acer laurinum</i> Hassk.	50.00
	Sapling	<i>Acer laurinum</i> Hassk.	105.68
	Pole	<i>Acer laurinum</i> Hassk.	132.28
	Tree	<i>Altingia excelsa</i> Noronha	248.50

**Table 5.** Biodiversity indices across vegetation with different growth levels in each stand type

Stands	Level	S	N	H'	DMg	E
Natural forest	Seedling	3	6	1.01	1.12	0.92
	Sapling	4	10	1.31	1.30	0.95
	Pole	4	5	1.34	1.86	0.96
	Tree	7	20	1.61	2.00	0.83
Agroforestry damar-cardamom, pineapple, lemongrass	Seedling	2	4	0.56	0.72	0.81
	Sapling	1	1	0.00	Cannot be calculated	Cannot be calculated
	Pole	4	7	1.28	1.54	0.92
	Tree	3	8	0.61	0.60	0.56
Agroforestry damar-coffee	Seedling	9	30	1.59	2.35	0.72
	Sapling	6	35	1.05	1.40	0.58
	Pole	4	11	1.34	1.25	0.97
	Tree	3	31	0.38	0.58	0.35
Agroforestry damar-chili pepper	Seedling	0	0	No species found	No species found	No species found
	Sapling	2	2	0.69	1.44	1.00
	Pole	4	5	1.33	1.86	0.96
	Tree	1	19	0.00	Cannot be calculated	Cannot be calculated
Agroforestry damar-eggplant	Seedling	2	3	0.64	0.91	0.92
	Sapling	2	4	0.69	0.72	1.00
	Pole	4	6	1.24	1.67	0.90
	Tree	4	10	1.08	1.30	0.79
Mixed	Seedling	5	10	1.56	1.73	0.97
	Sapling	6	22	1.12	1.62	0.62
	Pole	7	23	1.43	1.91	0.73
	Tree	3	20	0.40	0.67	0.36

Note: S: Number of species that found, N: Total individual on that level, H': Shannon-Wiener Diversity Index, DMg: Margalef Richness Index, E: Pielou's Evenness Index. Biodiversity indices were not calculated for stands with only one species

Figure 2 shows variation in soil layer thickness and VESS scores across stands. This variation reflects land-use effects. Natural forest, damar-coffee, damar-cardamom, and mixed stands had good Sq scores (1.0-1.84). These

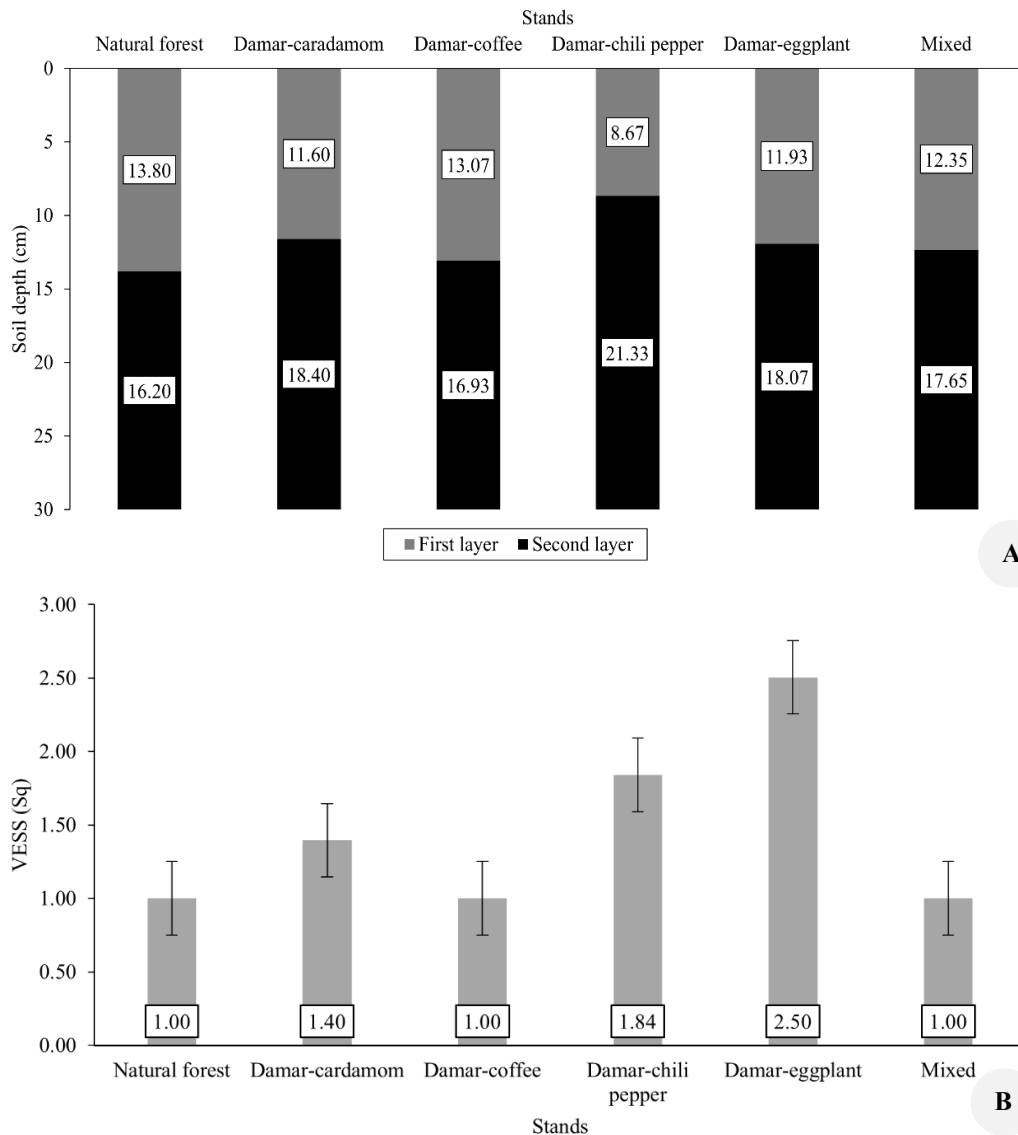
scores indicate maintained soil structure. These scores align with the aggregate sizes and forms documented in Table 6. The scores indicate maintained soil structure. Easily crumbled aggregates suggest good stability. Soil organic

matter and biological activity govern this stability (Kumar et al. 2021). Multi-strata systems mimic natural forests. They ensure continuous litter input, reduce erosion, and foster stable aggregates (Kuyah et al. 2019; Fahad et al. 2022). Soil organic matter and soil biota interact synergistically. Microbes produce binding agents sustained by organic matter (Lehmann et al. 2017; Guhra et al. 2022).

Damar-eggplant agroforestry had a higher Sq score (2.50). This score suggests early structural degradation. Intensive practices like weeding and chemical fertilization are associated with this system. These practices reduce organic inputs and disrupt soil biota (Sullivan et al. 2021). Similar declines occur in intensive vegetable systems (Çelik et al. 2020). The score difference was not statistically significant. System variability and VESS sensitivity limits in good soils explain the lack of significance (Guimarães et al. 2011; Franco et al. 2019). The numerical pattern serves as an early warning.

Intensification might initiate degradation, potentially masked by *A. dammara* dominance (Fauziyah et al. 2022).

The numerical gradient in Sq scores has ecological meaning. Scores range from best in natural forest (Sq 1.0) to worst in damar-eggplant (Sq 2.5). This pattern links to management intensity. Correlations with other soil properties support this (Table 11). VESS serves as a practical tool for proactive management (Mora-Motta et al. 2024). Stands with good scores (1-2) should maintain practices. Stands with moderate degradation need long-term strategies. Use crop diversification to boost residue inputs. Apply organic amendments like compost or manure. These actions enhance soil organic matter, aggregate stability, porosity, and erosion resistance (Cen et al. 2021; Kumar et al. 2021; Vanino et al. 2022; Maticic et al. 2024). For park managers, VESS offers a cost-effective early warning system. It enables targeted interventions to prevent severe degradation and support conservation and livelihoods.



**Figure 2.** Soil characteristics across stand types: A. Mean soil depth and B. Mean Visual Evaluation of Soil Structure (VESS) score. Higher VESS scores indicate poorer soil structural quality

**Management intensity alters soil physical properties: Early warnings and solutions**

All physical soil parameters met the assumptions of normality and homogeneity of variance (Table 7). Soil physical properties are fundamental to ecosystem functions like water infiltration, aeration, and root growth (Faucon et al. 2017; Blanco-Canqui and Ruis 2020). As presented in Table 8, our analysis revealed significant differences in bulk density, porosity, and moisture content among stand types (ANOVA,  $p < 0.05$ ). The superscript letters in the table denote statistical groupings based on Duncan's Multiple Range Test (DMRT) at  $p < 0.05$ , where values within the same column sharing a common letter are not significantly different.

For bulk density, values ranged from  $0.40 \text{ g.cm}^{-3}$  in the mixed stand to  $0.72 \text{ g.cm}^{-3}$  in the damar-eggplant system. The statistical grouping shows that the natural forest ( $0.42 \text{ g.cm}^{-3}$ ) and mixed stand ( $0.40 \text{ g.cm}^{-3}$ ) both share the letter 'a', indicating no significant difference between them, and they have the lowest bulk densities among all stands. In contrast, intensive agroforestry systems like damar-chili pepper ( $0.69 \text{ g.cm}^{-3}$ ) and damar-eggplant ( $0.72 \text{ g.cm}^{-3}$ ) also share the letter 'a', but are significantly higher than the damar-coffee system ( $0.52 \text{ g.cm}^{-3}$ , denoted 'b'). This pattern reflects a management-intensity gradient, where minimal disturbance in natural and mixed stands maintains lower bulk density, while frequent tillage and reduced organic inputs in intensive systems lead to compaction.

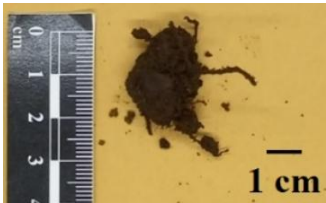
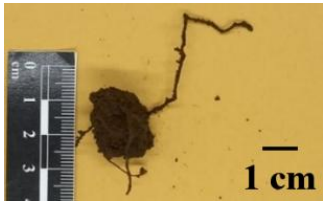
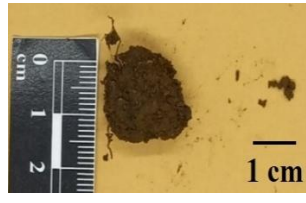
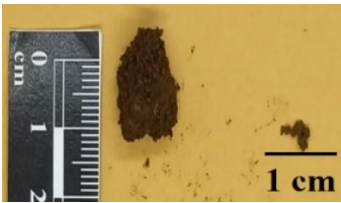

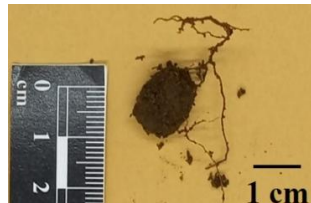
Porosity exhibited an inverse relationship with bulk density. The natural forest (84.29%) and mixed stand (84.93%) both had high porosity (shared 'a'), indicating well-structured soils with ample pore space. The damar-coffee system (80.44%, 'b') showed intermediate porosity, while intensive systems like damar-chili pepper (73.89%)

and damar-eggplant (72.72%) shared 'a' but had lower porosity, aligning with increased compaction. This suggests that management practices reducing soil organic matter may contribute to soil structure degradation, limiting aeration and water movement (Qiu et al. 2015; Zhao et al. 2021).

Moisture content varied significantly, with the natural forest (59.14%) having the highest value ('a'), followed by the mixed stand (56.80%, 'ab'). The damar-coffee system (52.97%, 'b') retained moderate moisture, while intensive systems like damar-chili pepper (41.45%) and damar-eggplant (41.35%) had the lowest values ('a'), indicating poor water retention due to compaction and reduced SOM. These trends highlight how intensive management diminishes the soil's ability to hold water, affecting plant growth and ecosystem resilience.

The observed gradients provide a crucial early warning, quantifying initial degradation trends in intensive systems and aligning with our VESS assessment. The strong positive correlation between VESS scores and bulk density ( $\rho = +0.85$ ) and very strong negative correlation with moisture content ( $\rho = -0.85$ ) provides statistical support for VESS, linking visual assessment to measurable physical degradation. This gradient appears to be associated with differential SOM management, underscored by the strong VESS-organic carbon correlation ( $\rho = -0.86$ ). Natural forest and mixed stands maintain high SOM via diverse litter input and minimal disturbance, fostering stable aggregates that resist compaction and retain water (Meurer et al. 2020; Li et al. 2024). In contrast, intensive systems (e.g., damar-eggplant) experience frequent tillage, weed removal, and low litter input, accelerating SOM decomposition, disrupting aggregates, and increasing compaction (Bonifacio et al. 2024).

**Table 6.** Soil aggregate size and form for natural forest to mixed stands. A scale bar (e.g., 1 cm) is included in the image for reference

Stands	Natural forest	Damar-cardamom	Damar-coffee
Size (cm)	2.3	2.1	1.7
Form	Granular	Granular	Granular
Documentation			
Stands	Damar-chilli pepper	Damar-eggplant	Mixed stand
Size (cm)	1.6	1.9	1.4
Form	Granular	Granular	Granular
Documentation			

Based on these results, we recommend considering the following management strategies: enrich agroforestry with tree diversity to mimic natural ecosystems; for annual crop systems, adopt minimum tillage, cover crops, and organic mulch to reduce erosion, compaction, and conserve SOM (Koudahe et al. 2022; Van Dung et al. 2023). Informed species selection is key the better condition of damar-coffee, suggesting deep-rooted perennials enhance sustainability without sacrificing economic output (Jezeer et al. 2018; Soratto et al. 2022). In conclusion, the significant physical properties gradient serves as a quantitative early warning. The strong VESS-analytical correlations validate its use for rapid assessment. Prioritizing SOM-conserving practices (litter mulch, cover crops, minimized tillage) and adopting complex, natural-

like agroforestry models could contribute to long-term productivity and resilience in the national park.

#### Management intensity drives soil chemical gradients

All chemical soil parameters met the assumptions of normality and homogeneity of variance (Table 9). Soil chemical properties are critical indicators of nutrient retention and availability. Our analysis revealed significant variations in pH, Organic Carbon (OC), and Cation Exchange Capacity (CEC) across stand types (Table 10), mirroring physical property patterns. The superscript letters in Table 9 denote statistical groupings based on Duncan's Multiple Range Test (DMRT) at  $p < 0.05$ , where values within the same column sharing a common letter are not significantly different.

**Table 7.** Results of normality tests (Shapiro-Wilk), variance homogeneity (Levene), and Analysis of Variance (ANOVA) for soil physical parameters (bulk density, porosity, and moisture content)

Parameter	Normality test	Homogeneity test	ANOVA
Bulk density	W=0.980, p=0.946	F(5,12)=0.302, p=0.902	F(5,12)=23.98, p<0.001
Porosity	W=0.980, p=0.946	F(5,12)=0.302, p=0.902	F(5,12)=23.98, p<0.001
Moisture content	W=0.936, p=0.251	F(5,12)=1.329, p=0.317	F(5,12)=28.04, p<0.001

**Table 8.** Mean bulk density, porosity, and moisture content in different stand types within Gunung Halimun Salak National Park, Indonesia. Values in the same column followed by different superscript letters are significantly different ( $p < 0.05$ , DMRT)

Stands	Bulk density (g.cm <sup>-3</sup> ) *	Porosity (%) *	Moisture content (%) *
Natural forest	0.42±0.045 <sup>c</sup>	84.29±1.71 <sup>a</sup>	59.14±0.85 <sup>a</sup>
Agroforestry damar-cardamom, pineapple, lemongrass	0.64±0.062 <sup>a</sup>	75.86±2.36 <sup>c</sup>	46.34±5.14 <sup>c</sup>
Agroforestry damar-coffee	0.52±0.023 <sup>b</sup>	80.44±0.88 <sup>b</sup>	52.97±1.69 <sup>b</sup>
Agroforestry damar-chili pepper	0.69±0.069 <sup>a</sup>	73.89±2.59 <sup>c</sup>	41.45±0.79 <sup>d</sup>
Agroforestry damar-eggplant	0.72±0.056 <sup>a</sup>	72.72±2.10 <sup>c</sup>	41.35±2.56 <sup>d</sup>
Mixed	0.40±0.021 <sup>c</sup>	84.93±0.80 <sup>a</sup>	56.80±1.13 <sup>ab</sup>

Note: \*: Significantly different at the 95% confidence level

**Table 9.** Results of normality tests (Shapiro-Wilk), variance homogeneity (Levene), and Analysis of Variance (ANOVA) for soil chemical characteristics (pH, organic carbon, and Cation Exchange Capacity - CEC)

Parameter	Normality test	Homogeneity test	ANOVA
pH	W=0.951, p=0.434	F(5,12)=0.199, p=0.957	F(5,12)=30.9, p<0.001
Organic carbon	W=0.959, p=0.591	F(5,12)=1.049, p=0.434	F(5,12)=9.86, p=0.001
CEC	W=0.947, p=0.387	F(5,12)=0.656, p=0.663	F(5,12)=6.317, p=0.004

**Table 10.** Soil chemical characteristics (pH, organic carbon, and Cation Exchange Capacity - CEC) across different stand types within Gunung Halimun Salak National Park. Values in the same column followed by different superscript letters are significantly different ( $p < 0.05$ , DMRT)

Stands	pH *	Organic carbon (%) *	CEC (cmol(+). kg <sup>-1</sup> ) *
Natural forest	5.52±0.14 <sup>b</sup>	10.04±2.30 <sup>a</sup>	33.53±6.95 <sup>a</sup>
Agroforestry damar-cardamom, pineapple, lemongrass	5.84±0.07 <sup>a</sup>	5.69±1.53 <sup>bcd</sup>	20.10±6.04 <sup>bc</sup>
Agroforestry damar-coffee	5.61±0.13 <sup>b</sup>	6.58±0.70 <sup>bc</sup>	23.10±3.44 <sup>bc</sup>
Agroforestry damar-chili pepper	5.21±0.11 <sup>c</sup>	4.47±1.17 <sup>cd</sup>	23.48±1.29 <sup>bc</sup>
Agroforestry damar-eggplant	5.14±0.03 <sup>c</sup>	3.58±0.34 <sup>d</sup>	15.66±2.18 <sup>c</sup>
Mixed	4.90±0.10 <sup>d</sup>	7.48±0.19 <sup>b</sup>	27.05±1.69 <sup>ab</sup>

Note: \*: Significantly different at the 95% confidence level

The damar-cardamom system showed the highest pH (5.84, 'a'), significantly higher than natural forest (5.52, 'b'), damar-coffee (5.61, 'b'), and substantially higher than intensive systems like damar-chili (5.21, 'c'), damar-eggplant (5.14, 'c'), and mixed stand (4.90, 'd'). This pattern suggests that specific agroforestry management, particularly with organic residues from cardamom and lemongrass, may buffer soil acidity more effectively than natural forest or intensive annual cropping systems.

The statistical groupings reveal a clear degradation gradient. Natural forest maintained the highest OC (10.04%, 'a'), significantly greater than all other stands. Mixed stand (7.48%, 'b') and damar-coffee (6.58%, 'bc') formed an intermediate group, while intensive systems showed progressive OC decline: damar-cardamom (5.69%, 'bcd'), damar-chili (4.47%, 'cd'), and damar-eggplant (3.58%, 'd'). This demonstrates that management intensity directly influences soil carbon stocks, with perennial systems conserving more OC than annual cropping systems.

CEC values followed the OC gradient closely. Natural forest had the highest CEC (33.53 cmol(+). kg<sup>-1</sup>, 'a'), with mixed stand (27.05 cmol(+). kg<sup>-1</sup>, 'ab') not significantly different. The damar-coffee (23.10 cmol(+). kg<sup>-1</sup>, 'bc'), damar-chili (23.48 cmol(+). kg<sup>-1</sup>, 'bc'), and damar-cardamom (20.10 cmol(+). kg<sup>-1</sup>, 'bc') formed a homogeneous intermediate group, while damar-eggplant showed the lowest CEC (15.66 cmol(+). kg<sup>-1</sup>, 'c'), indicating severely compromised nutrient retention capacity.

The conversion of natural forests to managed systems consistently reduces soil organic carbon and fertility (Bakhshandeh et al. 2019; Miju et al. 2025). All soils were acidic (pH 4.90-5.84), characteristic of humid tropical uplands (Wei et al. 2022), but the statistical groupings reveal a clear management-intensity gradient.

The most striking finding was the dramatic decline in soil organic carbon from natural forest (10.04%) to intensive damar-eggplant systems (3.58%). This OC loss appears to be a key factor associated with overall soil degradation (Assunção et al. 2019; Su et al. 2021), is the appears to be a major factor associated with soil degradation. The data suggest OC loss may contribute to deterioration in other parameters: loss of organic binding agents leads to poorer soil structure (higher VESS scores), increased compaction, and reduced water retention. This is strongly supported by our correlation analysis, which revealed a very strong negative correlation between VESS scores and OC ( $\rho=-0.86$ ), highlighting OC's role as a primary regulator of soil physical health (Meurer et al. 2020). In contrast, relatively high OC in damar-coffee (6.58%) and mixed (7.48%) stands demonstrates their effectiveness as carbon conservation systems, where perennial vegetation provides continuous litter input and minimal tillage reduces decomposition.

CEC values (15.66-33.53 cmol<sup>+</sup> kg<sup>-1</sup>) closely followed the OC gradient, as expected, since organic matter provides negative charges for cation retention in acidic tropical soils (Kaiser et al. 2008; Ramos et al. 2018). The strong negative VESS-CEC correlation ( $\rho=-0.77$ ) provides evidence

suggesting that degraded structure may reduce nutrient retention capacity, potentially increasing leaching risks in low-OC systems (Burakova and Bakšienė 2021).

Interestingly, the damar-cardamom-pineapple-lemongrass system exhibited the highest pH (5.84), suggesting active amelioration through organic residues and possibly lemongrass allelopathy influencing microbial communities and nitrification (Khamare et al. 2022; Tazi et al. 2024), indicating understory species composition critically influences soil chemistry. These findings underscore that soil organic carbon is the central factor controlling chemical fertility and overall soil health (Gerke 2022). We therefore recommend: promoting complex, multi-strata agroforestry models (e.g., damar-coffee) that conserve organic matter; implementing organic amendments in intensive systems; considering species-specific effects in management; and establishing long-term soil carbon monitoring. The clear chemical gradients highlight the vulnerability of intensive systems, necessitating critical evaluation and mitigation practices to ensure long-term soil fertility in this conservation area.

#### **VESS as an integrative indicator of soil physical and chemical quality**

Principal Component Analysis (PCA) reduced seven soil variables into two principal components that collectively explained 89.24% of the total variance. The first component (PC1), accounting for 73.55% of variance, was strongly correlated with soil physical properties. High positive loadings for bulk density (+0.42) and VESS score (+0.39), coupled with a strong negative loading for porosity (-0.42), established PC1 as a gradient from compacted, poorly-structured soils to well-structured, porous soils (Ball et al. 2007; Guimarães et al. 2011). The inverse relationship between bulk density and porosity reflects reduced pore space in compacted soils, limiting water retention and aeration essential for root growth and microbial activity (Li et al. 2019; Toková et al. 2020).

The second component (PC2) explained 15.89% of variance and was predominantly influenced by soil pH, shown by its strong negative loading (-0.94). These relationships are visualized in the PCA biplot (Figure 3). Sample distribution in the biplot revealed distinct clustering related to land management intensity. Natural forest and multi-strata agroforestry (damar-cardamom) grouped in the left quadrant with low PC1 scores, indicating favorable soil structure with high porosity and low VESS scores. These agroforestry systems maintained soil physical quality comparable to natural forest, with no significant differences in VESS, bulk density, and porosity (Stöcker et al. 2020; Aji et al. 2021; Purnama et al. 2022), while consistently enhancing soil organic carbon and cation exchange capacity above monoculture systems (Gusli et al. 2020; Souza et al. 2025).

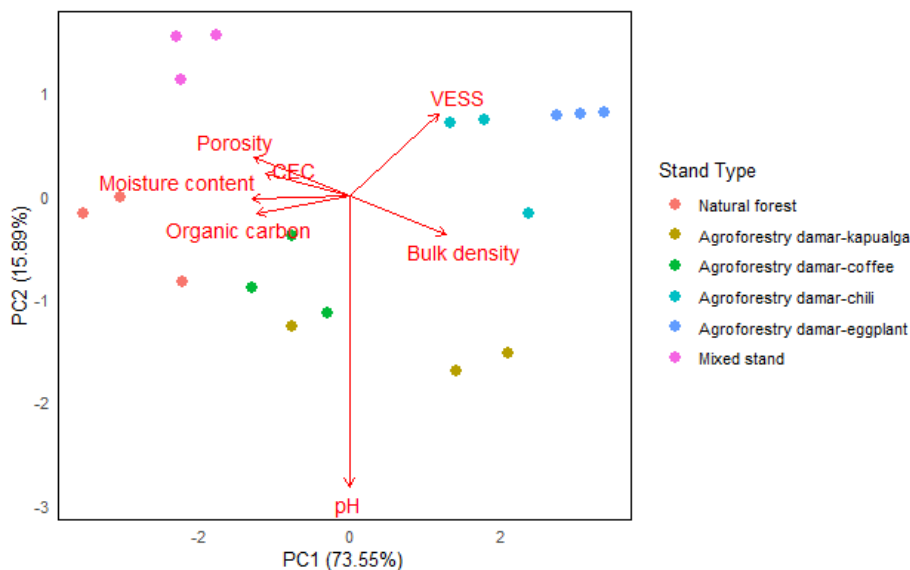
Intensive agroforestry systems (damar-chili and damar-eggplant) clustered in the right quadrant with high PC1 values, indicating degraded soil conditions with higher compaction and poorer structure. This pattern aligns with documented effects of agricultural intensification, where management practices increase bulk density while reducing

porosity, water infiltration, and aggregate stability (Bogunovic et al. 2020; Kumar et al. 2021; Cárceles Rodríguez et al. 2022). Comparative studies confirm that intensively managed lands consistently exhibit poorer soil physical conditions than natural forests and complex agroforestry systems (Akinde et al. 2020; Bogunovic et al. 2020). The antagonistic relationship between bulk density and both porosity and organic matter in the biplot reinforces evidence that declining soil organic content contributes to increased compaction and structural degradation (Lehmann et al. 2020).

VESS demonstrates integrative characteristics by combining key physical soil attributes—such as aggregate size, porosity, and root distribution into a single practical numerical score (Guimarães et al. 2011; Ball et al. 2016). In this study, correlations between VESS scores and laboratory-measured parameters (bulk density, porosity) and chemical properties (soil organic matter, cation exchange capacity), identified through PCA, support its role as an indicator reflecting both physical and related chemical soil conditions (Aji et al. 2021; Silva et al. 2022). However, this interpretation requires careful consideration, as the indirect relationship between VESS and biological processes such as microbial activity necessitates further

investigation through specific biological measurements (Lehmann et al. 2020). The application of VESS in tropical conservation landscapes such as Gunung Halimun Salak National Park also requires validation across broader spatial and temporal scales before it can be adopted as a standard monitoring tool (Moncada et al. 2014). These findings indicate the potential utility of VESS as a supportive tool in evaluating agroforestry practices, although its integration with soil chemical and biological data remains essential for a comprehensive soil health assessment (Purnama et al. 2022; Olivares et al. 2023).

The Spearman correlation analysis reveals significant relationships between physical and chemical soil properties, with the Visual Evaluation of Soil Structure (VESS) score showing consistent associations with key soil parameters. These findings align with validation studies of VESS across diverse environments (Becker et al. 2024; Leal et al. 2025). The correlation patterns suggest that soil structural quality, as indicated by VESS scores, relates to both physical-hydrological and chemical-biological soil functions. This supports VESS as a practical tool for detecting management-related changes in soil quality (Mora-Motta et al. 2024). All correlations were tested for significance at the 95% confidence level ( $p < 0.05$ ).



**Figure 3.** Principal Component Analysis (PCA) biplot of soil physical and chemical properties across different stands

**Table 11.** Spearman's rank correlation coefficients ( $\rho$ ) between the Visual Evaluation of Soil Structure (VESS) scores and soil properties

Other soil properties	VESS	Description	p-value
Bulk density	+0.85	Very strong correlation	$p < 0.001$ ( $9.035 \times 10^{-6}$ )
Porosity	-0.85	Very strong correlation	$p < 0.001$ ( $9.035 \times 10^{-6}$ )
Moisture content	-0.85	Very strong correlation	$p < 0.001$ ( $1.009 \times 10^{-3}$ )
pH	-0.18	Very weak correlation	$p > 0.05$ ( $4.686 \times 10^{-1}$ )
Organic carbon	-0.86	Very strong correlation	$p < 0.001$ ( $5.704 \times 10^{-6}$ )
CEC	-0.77	Very strong correlation	$p < 0.001$ ( $1.834 \times 10^{-4}$ )

VESS scores showed strong positive correlation with bulk density ( $\rho=+0.85$ ;  $p<0.001$ ) and strong negative correlations with porosity ( $\rho=-0.85$ ;  $p<0.001$ ) and moisture content ( $\rho=-0.85$ ;  $p<0.001$ ). These relationships indicate that visual assessment of soil structure corresponds with measurable physical properties, including compaction, pore space, and water retention capacity (Çelik et al. 2020; Aji et al. 2021). The correlation with moisture content suggests VESS assessment may reflect changes in soil hydrology, with potential implications for water management (Silva et al. 2022).

VESS scores also correlated negatively with organic carbon ( $\rho=-0.86$ ;  $p<0.001$ ) and cation exchange capacity ( $\rho=-0.77$ ;  $p<0.001$ ). These relationships are consistent with the established understanding that soil organic matter contributes to stable soil aggregates (Witzgall et al. 2021), while soil structure influences decomposition environments (Meurer et al. 2020). However, we note that unmeasured environmental factors such as slope, aspect, and parent material may also influence these relationships. The weak, non-significant correlation with pH ( $\rho=-0.18$ ) suggests soil reaction operates independently of structural differences in this context, possibly influenced by factors like fertilizer inputs or soil biota activity (Purnama et al. 2022; Olivares et al. 2023).

This study represents a single-case investigation in a specific geographical context. The correlations reported, while statistically significant, do not establish causation due to the observational nature of the study. Environmental covariates, including slope, aspect, rainfall variation, and parent material, were not systematically controlled and may confound the observed relationships. Management recommendations should therefore be interpreted as suggestive rather than definitive, requiring validation through experimental studies and long-term monitoring.

In conclusion, this study demonstrates that the Visual Evaluation of Soil Structure (VESS) method effectively differentiates soil structural quality across a management intensity gradient in Gunung Halimun Salak National Park. The three research objectives were successfully addressed. Vegetation composition analysis revealed distinct dominance patterns, with natural forest dominated by *M. dispermus* (IVI: 120.57%), agroforestry systems by *A. dammara* (IVI: 158.05-300.00%), and mixed stand by *A. excelsa* (IVI: 248.50%). VESS evaluation showed good soil structure (Sq 1.0-1.84) in natural forest and low-intensity agroforestry, with moderate degradation (Sq 2.5) in intensive systems. Principal Component Analysis confirmed VESS as an integrative indicator, with PC1 explaining 73.55% of variance along a soil structure gradient. Statistical analysis revealed strong correlations between VESS scores and laboratory-measured properties: bulk density ( $\rho=+0.85$ ;  $p<0.001$ ), porosity ( $\rho=-0.85$ ;  $p<0.001$ ), moisture content ( $\rho=-0.85$ ;  $p<0.001$ ), organic carbon ( $\rho=-0.86$ ;  $p<0.001$ ), and CEC ( $\rho=-0.77$ ;  $p<0.001$ ).

We recommend park managers consider adopting VESS as a practical monitoring tool for early detection of soil structural degradation, particularly in remote park areas with limited laboratory access. Sustainable agroforestry models, especially complex multi-strata systems like

damar-coffee, should be promoted to maintain soil quality while supporting local livelihoods. Management should prioritize soil organic matter conservation through organic amendments and reduced tillage, alongside strategic species diversification to enhance ecosystem resilience. Training programs for field staff and community farmers should be developed to standardize VESS assessment and interpretation.

This study has limitations. The assessment relied on a single observer for VESS scoring, and it did not measure environmental covariates such as microclimate or topography that could influence soil properties. Future research should address these limitations. Direct efforts should include inter-observer reliability testing for VESS to validate its consistency. Long-term monitoring is needed to incorporate environmental covariates and validate these findings across broader spatial and temporal scales within the national park. Future research should also focus on developing and validating a region-specific Soil Quality Index that integrates physical, chemical, and biological indicators to provide a more comprehensive assessment of soil health in tropical montane ecosystems.

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## REFERENCES

- Aerts R, Honnay O. 2011. Forest restoration, biodiversity, and ecosystem functioning. *BMC Ecol* 11: 29. DOI: 10.1186/1472-6785-11-29.
- Aji BDS, Wijayanto N, Wasis B. 2021. Visual Evaluation of Soil Structure (VESS) method to assess soil properties of agroforestry system in Pangalengan, West Java. *Jurnal Manajemen Hutan Tropika* 27 (1): 80-88. DOI: 10.7226/jtftm.27.2.80.
- Akinde BP, Olakayode AO, Oyedele DJ, Tijani FO. 2020. Selected physical and chemical properties of soil under different agricultural land-use types in Ile-Ife, Nigeria. *Heliyon* 6 (9): e05090. DOI: 10.1016/j.heliyon.2020.e05090.
- Ali A, Mattsson E, Nissanka SP, Wang LQ. 2020. Topmost trees and foremost species underlie tropical forest structure, diversity and biomass through opposing mechanisms. *For Ecol Manag* 473: 118299. DOI: 10.1016/j.foreco.2020.118299.
- Al-Shammary AAG, Kouzani AZ, Kaynak A, Khoo SY, Norton M, Gates W. 2018. Soil bulk density estimation methods: A review. *Pedosphere* 28 (4): 581-596. DOI: 10.1016/s1002-0160(18)60034-7.
- Arifin M, Putri ND, Sandrawati A, Harryanto R. 2019. Pengaruh posisi lereng terhadap sifat fisika dan kimia tanah pada inceptisols di

- Jatinangor. SoilREns 16 (2): 37-44. DOI: 10.24198/soilrens.v16i2.20858. [Indonesian]
- Assunção SA, Pereira MG, Rosset JS, Berbara RLL, Garcia AC. 2019. Carbon input and the structural quality of soil organic matter as a function of agricultural management in a tropical climate region of Brazil. *Sci Total Environ* 658: 901-911. DOI: 10.1016/j.scitotenv.2018.12.271.
- ASTM International. 2019. Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass. ASTM International, West Conshohocken.
- Bakhshandeh E, Hossieni M, Zeraatpisheh M, Francaviglia R. 2019. Land use change effects on soil quality and biological fertility: A case study in northern Iran. *Eur J Soil Biol* 95: 103119. DOI: 10.1016/j.ejsobi.2019.103119.
- Balai Taman Nasional Gunung Halimun Salak. 2018. Rencana Pengelolaan Jangka Panjang Taman Nasional Gunung Halimun Salak. Balai Taman Nasional Gunung Halimun Salak, Sukabumi. [Indonesian]
- Balandier P, Collet C, Miller JH, Reynolds PE, Zedaker SM. 2006. Designing forest vegetation management strategies based on the mechanisms and dynamics of crop tree competition by neighbouring vegetation. *Forestry* 79 (1): 3-27. DOI: 10.1093/forestry/cpi056.
- Ball BC, Batey T, Munkholm LJ. 2007. Field assessment of soil structural quality - A development of the Peerkamp test. *Soil Use Manag* 23 (4): 329-337. DOI: 10.1111/j.1475-2743.2007.00102.x.
- Ball BC, Guimarães RML, Cloy JM, Hargreaves PR, Shepherd TG, McKenzie BM. 2016. Visual soil evaluation: A summary of some applications and potential developments for agriculture. *Soil Tillage Res* 173: 114-124. DOI: 10.1016/j.still.2016.07.006.
- Becker RK, Giarola NFB, de Paula AL, Schiebelbein BE, da Luz FB. 2024. Soil health assessment in Brazilian subtropical oxisol under land use and long-term tillage systems. *Braz Arch Biol Technol* 67 (SPE1): e2024230789. DOI: 10.1590/1678-4324-PSSM-2024230789.
- Blanco-Canqui H, Ruis SJ. 2020. Cover crop impacts on soil physical properties: A review. *Soil Sci Soc Am J* 84 (5): 1527-1576. DOI: 10.1002/saj2.20129.
- Bogunovic I, Viduka A, Magdic I, Telak LJ, Francos M, Pereira P. 2020. Agricultural and forest land-use impact on soil properties in Zagreb Periurban Area (Croatia). *Agronomy* 10 (9): 1331. DOI: 10.3390/agronomy10091331.
- Bonifacio E, Said-Pullicino D, Stanchi S, Potenza M, Belmonte SA, Celi L. 2024. Soil and management effects on aggregation and organic matter dynamics in vineyards. *Soil Tillage Res* 240:106077. DOI: 10.1016/j.still.2024.106077.
- Briiliawan BD, Wijayanto N, Wasis B. 2022. Visual soil structure quality and its correlation to quantitative soil physical properties of upland rice site in *Falcataria mouluccana* agroforestry system. *Biodiversitas* 23 (4): 1894-1903. DOI: 10.13057/biodiv/d230423.
- Bryk M, Kotodziej B. 2023. Pedotransfer functions for estimating soil bulk density using image analysis of soil structure. *Sensors* 23 (4): 1852. DOI: 10.3390/s23041852.
- Burakova A, Bakšiene E. 2021. Leaching losses of main nutrients by incorporating organic fertilisers into light texture soils haplic luvisol. *Environ Eng Res* 26 (4): 200190. DOI: 10.4491/eer.2020.190.
- Cárceles Rodríguez B, Durán-Zuazo VH, Soriano Rodríguez M, García-Tejero IF, Gálvez Ruiz B, Cuadros Távira S. 2022. Conservation agriculture as a sustainable system for soil health: A review. *Soil Syst* 6 (4): 87. DOI: 10.3390/soilsystems6040087.
- Cardinael R, Mao Z, Chen C, Hinsinger P. 2020. Belowground functioning of agroforestry systems: Recent advances and perspectives. *Plant Soil* 453 (1-2): 1-13. DOI: 10.1007/s11104-020-04633-x.
- Cardone L, Castronuovo D, Perniola M, Scranò L, Cicco N, Candido V. 2020. The influence of soil physical and chemical properties on saffron (*Crocus sativus* L.) growth, yield and quality. *Agronomy* 10 (8): 1154. DOI: 10.3390/agronomy10081154.
- Çelik İ, Günel H, Acar M, Acir N, Bereket Barut Z, Budak M. 2020. Evaluating the long-term effects of tillage systems on soil structural quality using visual assessment and classical methods. *Soil Use Manag* 36 (2): 223-239. DOI: 10.1111/sum.12554.
- Cen R, Feng W, Yang F, Wu W, Liao H, Qu Z. 2021. Effect mechanism of biochar application on soil structure and organic matter in semi-arid areas. *J Environ Manag* 286: 112198. DOI: 10.1016/j.jenvman.2021.112198.
- Chaturvedi RK, Raghubanshi AS. 2014. Species composition, distribution, and diversity of woody species in a tropical dry forest of India. *J Sustain For* 33 (8): 729-756. DOI: 10.1080/10549811.2014.925402.
- Chowdhury MA, Islam KN, Hafiz N, Islam K. 2019. Diversity of trees in a community-managed forest: The case of Komolchori VCF, Khagrachari, Bangladesh. *Geol Ecol Landsc* 3 (2): 95-103. DOI: 10.1080/24749508.2018.1508980.
- Cui R, Qi S, Wu B, Zhang D, Zhang L, Zhou P, Ma N, Huang X. 2022. The influence of stand structure on understory herbaceous plant species diversity of *Platycladus orientalis* plantations in Beijing, China. *Forests* 13 (11): 1921. DOI: 10.3390/f13111921.
- Death R. 2008. Margalef's Index. In: Jørgensen SE, Fath BD (eds). *Encyclopedia of Ecology*. Elsevier, Oxford. DOI: 10.1016/B978-008045405-4.00117-8.
- Dollinger J, Jose S. 2018. Agroforestry for soil health. *Agrofor Syst* 92 (2): 213-219. DOI: 10.1007/s10457-018-0223-9.
- Draper FC, Asner GP, Honorio Coronado EN et al. 2019. Dominant tree species drive beta diversity patterns in western Amazonia. *Ecology* 100 (4): e02636. DOI: 10.1002/ecy.2636.
- Emmet-Booth JP, Forristal PD, Fenton O, Bondi G, Holden NM. 2019. Visual soil evaluation – Spade vs. profile methods and the information conveyed for soil management. *Soil Tillage Res* 187: 135-143. DOI: 10.1016/j.still.2018.12.002.
- Fagua JC, Jantz P, Burns P, Massey R, Buitrago JY, Saatchi S, Hakkenberg C, Goetz SJ. 2021. Mapping tree diversity in the tropical forest region of Chocó-Colombia. *Environ Res Lett* 16 (5): 054024. DOI: 10.1088/1748-9326/abf58a.
- Fahad S, Chavan SB, Chichaghare AR et al. 2022. Agroforestry systems for soil health improvement and maintenance. *Sustainability* 14 (22): 14877. DOI: 10.3390/su142214877.
- Faucon MP, Houben D, Lambers H. 2017. Plant functional traits: Soil and ecosystem services. *Trends Plant Sci* 22 (5): 385-394. DOI: 10.1016/j.tplants.2017.01.005.
- Fauziyah LA, Mawardani SI, Febriyanti S, Kurniawati I, Perdana Y. 2022. Repong damar as a mitigation effort for the Ulun Saibatin landslide disaster in the Regency of Pesisir Barat. *Asian J Humanit Cult Res* 1 (1): 40-50. DOI: 10.53402/ajhcr.v1i1.64.
- Franco HHS, Guimarães RML, Tormena CA, Cherubin MR, Favilla HS. 2019. Global applications of the Visual Evaluation of Soil Structure method: A systematic review and meta-analysis. *Soil Tillage Res* 190: 61-69. DOI: 10.1016/j.still.2019.01.002.
- Gao S, Dong G, Jiang X, Nie T, Yin H, Guo X. 2021. Quantification of natural and anthropogenic driving forces of vegetation changes in the three-river headwater region during 1982-2015 based on geographical detector model. *Remote Sens* 13 (20): 4175. DOI: 10.3390/rs13204175.
- Gerke J. 2022. The central role of soil organic matter in soil fertility and carbon storage. *Soil Syst* 6 (2): 33. DOI: 10.3390/soilsystems6020033.
- Guhra T, Stolze K, Totsche KU. 2022. Pathways of biogenically excreted organic matter into soil aggregates. *Soil Biol Biochem* 164: 108483. DOI: 10.1016/j.soilbio.2021.108483.
- Guimarães RML, Ball BC, Tormena CA. 2011. Improvements in the visual evaluation of soil structure. *Soil Use Manag* 27 (3): 395-403. DOI: 10.1111/j.1475-2743.2011.00354.x.
- Gunawan, Wijayanto N, Budi SW. 2019. Karakteristik sifat kimia tanah dan status kesuburan tanah pada agroforestri tanaman sayuran berbasis *Eucalyptus* sp. *Jurnal Silviculture Tropika* 10 (2): 63-69. DOI: 10.29244/j-siltrop.10.2.63-69. [Indonesian]
- Gusli S, Sumeni S, Sabodin R, Muqfi IH, Nur M, Hairiah K, Useng D, van Noordwijk M. 2020. Soil organic matter, mitigation of and adaptation to climate change in cocoa-based agroforestry systems. *Land* 9 (9): 323. DOI: 10.3390/land9090323.
- Hartanto N, Zulkarnain Z, Wicaksono AA. 2021. Analisis beberapa sifat fisik tanah sebagai indikator kerusakan tanah pada lahan kering. *J Trop AgriFood* 4 (2): 107-112. DOI: 10.35941/jatf.4.2.2022.7001.107-112. [Indonesian]
- Hartoyo APP, Mosa SA, Winata B, Rusniarsyah L, Peniwidiyanti, Izzbilhaq. 2024. Tree species diversity and management in agroforestry pohpohan (*Pilea melastomoides*): The case in the traditional zone of Gunung Halimun Salak National Park, Indonesia. *Biotropia* 31 (3): 380-390. DOI: 10.11598/btb.2024.31.3.2281.
- Hasannudin DAL, Nurrochmat DR, Ekayani M. 2022. Agroforestry management systems through landscape-lifescape integration: A case study in Gowa, Indonesia. *Biodiversitas* 23 (4): 1864-1874. DOI: 10.13057/biodiv/d230420.

- Herrero-Jáuregui C, Guariguata MR, Cárdenas D, Vilanova E, Robles M, Licona JC, Nalvarte W. 2013. Assessing the extent of “conflict of use” in multipurpose tropical forest trees: A regional view. *J Environ Manag* 130: 40-47. DOI: 10.1016/j.jenvman.2013.08.044.
- Hidayat M. 2018. Analisis vegetasi dan keanekaragaman tumbuhan di Kawasan Manifestasi Geotermal IE Suum Kecamatan Mesjid Raya Kabupaten Aceh Besar. *BIOTIK: Jurnal Ilmiah Biologi Teknologi dan Kependidikan* 5 (2): 114-125. DOI: 10.22373/biotik.v5i2.3019. [Indonesian]
- Houehanou TD, Assogbadjo AE, Kakai RG, Houinato M, Sinsin B. 2011. Valuation of local preferred uses and traditional ecological knowledge in relation to three multipurpose tree species in Benin (West Africa). *For Policy Econ* 13 (7): 554-562. DOI: 10.1016/j.forpol.2011.05.013.
- Hua F, Adrian Bruijnzeel L, Meli P et al. 2022. The biodiversity and ecosystem service contributions and trade-offs of forest restoration approaches. *Science* 376 (6595): 839-844. DOI: 10.1126/science.abl4649.
- Huera-Lucero T, Torres B, Bravo-Medina C, García-Nogales B, Vicente L, López-Piñero A. 2025. Comparative analysis of soil biological activity and macroinvertebrate diversity in Amazonian Chakra agroforestry and tropical rainforests in Ecuador. *Agriculture* 15 (8): 830. DOI: 10.3390/agriculture15080830.
- Indriyati LT, Santoso S, Irianti E. 2024. Dampak pertanian organik dan konvensional pada biodiversitas dan sifat kimia tanah pada budi daya tanaman padi sawah. *Jurnal Ilmu Pertanian Indonesia* 29 (3): 331-341. DOI: 10.18343/jipi.29.3.331. [Indonesian]
- IUSS Working Group WRB. 2022. World Reference Base For Soil Resources. International Soil Classification System for Naming Soils and Creating Legends for Soil Maps. 4th Edition. International Union of Soil Sciences (IUSS), Vienna.
- Jezeer RE, Santos MJ, Boot RGA, Junginger M, Verweij PA. 2018. Effects of shade and input management on economic performance of small-scale Peruvian coffee systems. *Agric Syst* 162: 179-190. DOI: 10.1016/j.agsy.2018.01.014.
- Kaiser M, Ellerbrock RH, Gerke HH. 2008. Cation exchange capacity and composition of soluble soil organic matter fractions. *Soil Sci Soc Am J* 72 (5): 1278-1285. DOI: 10.2136/sssaj2007.0340.
- Katembo JM, Libalah MB, Boyemba FB, Dauby G, Barbier N. 2020. Multiple stable dominance states in the Congo Basin forests. *Forests* 11 (5): 553. DOI: 10.3390/F11050553.
- Khamare Y, Chen J, Marble SC. 2022. Allelopathy and its application as a weed management tool: A review. *Front Plant Sci* 13: 1034649. DOI: 10.3389/fpls.2022.1034649.
- Koelmeijer IA, Tack AJM, Zewdie B, Nemomissa S, Hylander K. 2021. Management intensity and landscape configuration affect the potential for woody plant regeneration in coffee agroforestry. *Agric Ecosyst Environ* 313: 107384. DOI: 10.1016/j.agee.2021.107384.
- Koudahe K, Allen SC, Djaman K. 2022. Critical review of the impact of cover crops on soil properties. *Intl Soil Water Conserv Res* 10 (3): 343-354. DOI: 10.1016/j.iswcr.2022.03.003.
- Kumar M, Mitra S, Mazumdar SP, Majumdar B, Saha AR, Singh SR, Pramanick B, Gaber A, Alsanie WF, Hossien A. 2021. Improvement of soil health and system productivity through crop diversification and residue incorporation under jute-based different cropping systems. *Agronomy* 11 (8): 1622. DOI: 10.3390/agronomy11081622.
- Kumar P, Dobriyal M, Kale A, Pandey AK, Tomar RS, Thounaojam E. 2022. Calculating forest species diversity with information-theory-based indices using Sentinel-2A sensors of Mahavir Swami Wildlife Sanctuary. *PLoS One* 17 (5): e0268018. DOI: 10.1371/journal.pone.0268018.
- Kusmana C, Istomo, Winata B, Hilwan I. 2022. *Ekologi Hutan Indonesia*. IPB Press, Bogor. [Indonesian]
- Kuyah S, Whitney CW, Jonsson M, Sileshi GW, Öborn I, Muthuri CW, Luedeling E. 2019. Agroforestry delivers a win-win solution for ecosystem services in sub-Saharan Africa. A meta-analysis. *Agron Sustain Dev* 39 (5): 47. DOI: 10.1007/s13593-019-0589-8.
- Leal O dos A, Miguel P, Rodrigues MF, Guimarães RML, Pinto LFS, Silva TP, Pinto MAB, Nachtigal SD, Stumpf L. 2025. First validation of the method: Visual Evaluation of Soil Structure in coal mining area using a long-term field revegetation experiment as testbed. *Soil Tillage Res* 246: 106347. DOI: 10.1016/j.still.2024.106347.
- Lehmann A, Zheng W, Rillig MC. 2017. Soil biota contributions to soil aggregation. *Nat Ecol Evol* 1 (12): 1828-1835. DOI: 10.1038/s41559-017-0344-y.
- Lehmann LM, Smith J, Westaway S, Pisanelli A, Russo G, Borek R, Sandor M, Gliga A, Smith L, Ghaley BB. 2020. Productivity and economic evaluation of agroforestry systems for sustainable production of food and non-food products. *Sustainability* 12 (24): 10236. DOI: 10.3390/su122410236.
- Li S, Li Q, Wang C, Li B, Gao X, Li Y, Wu D. 2019. Spatial variability of soil bulk density and its controlling factors in an agricultural intensive area of Chengdu Plain, Southwest China. *J Integr Agric* 18 (2): 290-300. DOI: 10.1016/S2095-3119(18)61930-6.
- Li W, Li J, Wu Y, Guo K, Feng X, Liu X. 2024. Soil organic matter and bulk density: driving factors in the vegetation-mediated restoration of coastal saline lands in North China. *Agronomy* 14 (9): 2007. DOI: 10.3390/agronomy14092007.
- Magurran AE. 1988. *Ecological Diversity and Its Measurement*. Springer Dordrecht, Bangor. DOI: 10.1007/978-94-015-7358-0.
- Maticic M, Dugan I, Bogunovic I. 2024. Challenges in Sustainable Agriculture—The Role of Organic Amendments. *Agriculture* 14 (4): 643. DOI: 10.3390/agriculture14040643.
- Matos PS, Cherubin MR, Damian JM, Rocha FI, Pereira MG, Zonta E. 2022. Short-term effects of agroforestry systems on soil health in Southeastern Brazil. *Agrofor Syst* 96 (5-6): 897-908. DOI: 10.1007/s10457-022-00749-4.
- Matos PS, Fonte SJ, Lima SS, Pereira MG, Kelly C, Damian JM, Fontes MA, Chaer GM, Brasil FC, Zonta E. 2020. Linkages among soil properties and litter quality in agroforestry systems of Southeastern Brazil. *Sustainability* 12 (22): 9752. DOI: 10.3390/su12229752.
- Meng X, Fan S, Dong L, Li K, Li X. 2023. Response of understory plant diversity to soil physical and chemical properties in urban forests in Beijing, China. *Forests* 14 (3): 571. DOI: 10.3390/f14030571.
- Meurer KHE, Chenu C, Coucheney E, Herrmann AM, Keller T, Kätterer T, Svensson DN, Jarvis N. 2020. Modelling dynamic interactions between soil structure and the storage and turnover of soil organic matter. *Biogeosciences* 17 (20): 5025-5042. DOI: 10.5194/bg-17-5025-2020.
- Miju C, Kiflu A, Gizachew S. 2025. Effects of land use/land cover change on soil physicochemical properties and soil carbon stock in Kochore district, southern Ethiopia. *Arab J Geosci* 18 (2): 41. DOI: 10.1007/s12517-025-12181-w.
- Moncada MP, Penning LH, Timm LC, Gabriels D, Comelis WM. 2014. Visual examinations and soil physical and hydraulic properties for assessing soil structural quality of soils with contrasting textures and land uses. *Soil Tillage Res* 140: 20-28. DOI: 10.1016/j.still.2014.02.009.
- Mora-Motta D, Llanos-Cabrera MP, Chavarro-Bermeo JP, Ortiz-Moreno FA, Silva-Olaya AM. 2024. Visual evaluation of soil structure is a reliable method to detect changes in the soil quality of Colombian Amazon pasturelands. *Soil Sci Soc Am J* 88 (2): 527-539. DOI: 10.1002/saj2.20637.
- Ngaba MJY, Mgelwa AS, Gurmesa GA, Uwiragiye Y, Zhu F, Qiu Q, Fang Y, Hu B, Rennenberg H. 2024. Meta-analysis unveils differential effects of agroforestry on soil properties in different zoniobioses. *Plant Soil* 496 (1-2): 589-607. DOI: 10.1007/s11104-023-06385-w.
- Novák V, Hlaváčiková H. 2019. *Applied Soil Hydrology*. Springer Cham, Bratislava. DOI: 10.1007/978-3-030-01806-1.
- Olivares BO, Lobo D, Rey JC, Vega A, Rueda MA. 2023. Relationships between the Visual Evaluation of Soil Structure (VESS) and soil properties in agriculture: A meta-analysis. *Sci Agropecu* 14 (1): 67-78. DOI: 10.17268/sci.agropecu.2023.007.
- Paltaneanu C, Mocanu V, Vizitiu O, Domnariu H, Dumitru S. 2025. Soil organic carbon to clay ratio and bulk density related to some basic soil variables in Romania. *Soil Use Manag* 41 (1): e70065. DOI: 10.1111/sum.70065.
- Peng Y, Fan M, Song J, Cui T, Li R. 2018. Assessment of plant species diversity based on hyperspectral indices at a fine scale. *Sci Rep* 8 (1): 4776. DOI: 10.1038/s41598-018-23136-5.
- Pretzsch H. 2009. *Forest Dynamics, Growth and Yield from Measurement to Model*. Springer Berlin, Heidelberg. DOI: 10.1007/978-3-540-88307-4.
- Purnama TJ, Wijayanto N, Wasis B. 2022. Assessing soil properties in various agroforestry lands in Kuningan District, West Java, Indonesia using Visual Evaluation of Soil Structure (VESS). *Biodiversitas* 23 (6): 3012-3021. DOI: 10.13057/biodiv/d230628.
- Qiu J, Khalloufi S, Martynenko A, Van Dalen G, Schutysen M, Almeida-Rivera C. 2015. Porosity, bulk density, and volume reduction during drying: Review of measurement methods and coefficient determinations. *Dry Technol* 33 (14): 1681-1699. DOI: 10.1080/07373937.2015.1036289.

- Ramos FT, Dores EFDC, Weber OLDS, Beber DC, Campelo JH, Maia JCDS. 2018. Soil organic matter doubles the cation exchange capacity of tropical soil under no-till farming in Brazil. *J Sci Food Agric* 98 (9): 3595-3602. DOI: 10.1002/jsfa.8881.
- Robinson DA, Thomas A, Reinsch S, Lebron I, Feeney CJ, Maskell LC, Wood CM, Seaton FM, Emmett BA, Cosby BJ. 2022. Analytical modelling of soil porosity and bulk density across the soil organic matter and land-use continuum. *Sci Rep* 12 (1): 7085. DOI: 10.1038/s41598-022-11099-7.
- Sanchez PA. 1995. Science in agroforestry. *Agrofor Syst* 30 (1-2): 5-55. DOI: 10.1007/BF00708912.
- Santos M, Cajaiba RL, Bastos R, Gonzalez D, Petrescu Bakiş AL, Ferreira D, Leote P, Barreto da Silva W, Cabral JA, Gonçalves B, Mosquera-Losada MR. 2022. Why do agroforestry systems enhance biodiversity? Evidence from habitat amount hypothesis predictions. *Front Ecol Evol* 9: 630151. DOI: 10.3389/fevo.2021.630151.
- Sardjono MA, Djogo T, Arifin HS, Wijayanto N. 2003. Klasifikasi dan pola kombinasi komponen agroforestri. In: Widiyanto, Utami SR, Hairiah K (eds). *Agroforestri di Indonesia*. World Agroforestry Centre (ICRAF), Bogor. [Indonesian]
- Sena KL, Yeager KM, Barton CD, Lhotka JM, Bond WE, Schindler KJ. 2021. Development of mine soils in a chronosequence of forestry-reclaimed sites in Eastern Kentucky. *Minerals* 11 (4): 422. DOI: 10.3390/min11040422.
- Sheng Q, Dong L, Liu Z. 2024. Driving forces of herbaceous species diversity in natural broadleaf forests in Maoershan from Northeast China. *Front Plant Sci* 15: 1449421. DOI: 10.3389/fpls.2024.1449421.
- Silva IMD, Rodrigues S, Lima H, Queiroz HM, Pereira Valani G, da Silva AP. 2022. Visual evaluation of soil structure in organic smallholder farms in the eastern Amazon: A useful tool to assess soil quality. *Arch Agron Soil Sci* 68 (9):1251-1260. DOI: 10.1080/03650340.2021.1884225.
- Soratto RP, Perdoná MJ, Parecido RJ, Pinotti RN, Gitari HI. 2022. Turning biennial into biannual harvest: Long-term assessment of Arabica coffee-macadamia intercropping and irrigation synergism by biological and economic indices. *Food Energy Secur* 11 (2): e365. DOI: 10.1002/fes3.365.
- Souza FED de, Oliveira J de N dos S, Santos CRC dos, Ferreira EV de O, Silva RTL da, Paula MT de, Alves JDN, Oliveira JSR de, Rodrigues JI de M, Martins WBR. 2025. Physical and chemical soil quality and litter stock in agroforestry systems in the Eastern Amazonia. *Agric Ecosyst Environ* 382: 109479. DOI: 10.1016/j.agee.2025.109479.
- Stöcker CM, Bamberg AL, Stumpf L, Monteiro AB, Cardoso JH, de Lima ACR. 2020. Short-term soil physical quality improvements promoted by an agroforestry system. *Agrofor Syst* 94 (5): 2053-2064. DOI: 10.1007/s10457-020-00524-3.
- Su F, Xu S, Sayer EJ, Chen W, Du Y, Lu X. 2021. Distinct storage mechanisms of soil organic carbon in coniferous forest and evergreen broadleaf forest in tropical China. *J Environ Manag* 295: 113142. DOI: 10.1016/j.jenvman.2021.113142.
- Sullivan P, Billings S, Hirmas D et al. 2021. Embracing the dynamic nature of soil structure: A paradigm illuminating the role of life in critical zones of the Anthropocene. *Earth-Sci Rev* 225: 103873. DOI: 10.1016/j.earscirev.2021.103873.
- Sun Z, Sonsuthi A, Jucker T et al. 2023. Top canopy height and stem size variation enhance aboveground biomass across spatial scales in seasonal tropical forests. *Plants* 12 (6): 1343. DOI: 10.3390/plants12061343.
- Tazi A, Zinedine A, Rocha JM, Errachidi F. 2024. Review on the pharmacological properties of lemongrass (*Cymbopogon citratus*) as a promising source of bioactive compounds. *Pharmacol Res - Nat Prod* 3: 100046. DOI: 10.1016/j.prenap.2024.100046.
- Thomas A, Seaton F, Dhiedt E, Cosby BJ, Feeney C, Lebron I, Maskell L, Wood C, Reinsch S, Emmett BA, Robinson DA. 2024. Topsoil porosity prediction across habitats at large scales using environmental variables. *Sci Total Environ* 922: 171158. DOI: 10.1016/j.scitotenv.2024.171158.
- Toková L, Igaz D, Horák J, Aydın E. 2020. Effect of biochar application and re-application on soil bulk density, porosity, saturated hydraulic conductivity, water content and soil water availability in a silty loam haplic luvisol. *Agronomy* 10 (7): 1005. DOI: 10.3390/agronomy10071005.
- Tovar C, Harris DJ, Brncic T, Willis KJ. 2019. Tropical monodominant forest resilience to climate change in Central Africa: A *Gilbertiodendron dewevrei* forest pollen record over the past 2,700 years. *J Veg Sci* 30 (3): 575-586. DOI: 10.1111/jvs.12746.
- Udawatta RP, Rankoth LM, Jose S. 2019. Agroforestry and biodiversity. *Sustainability* 11 (10): 2879. DOI: 10.3390/su11102879.
- Utami I, Putra ILI. 2020. *Ekologi Kuantitatif Metode Sampling dan Analisis Data Lapangan*. Penerbit K-Media, Yogyakarta. [Indonesian]
- Valencia V, West P, Sterling EJ, García-Barrios L, Naem S. 2015. The use of farmers' knowledge in coffee agroforestry management: Implications for the conservation of tree biodiversity. *Ecosphere* 6 (7): art122. DOI: 10.1890/es14-00428.1.
- Van Dung T, Van Dang L, Ngoc NP, Hung NN. 2023. Soil fertility and pomelo yield are influenced by soil conservation practices. *Open Agric* 8 (1): 20220181. DOI: 10.1515/opag-2022-0181.
- Vanino S, Di Bene C, Piccini C, Fila G, Pennelli B, Zornoza R, Sánchez-Navarro V, Alvaro-Fuentes J, Hüppi R, Six J, Farina R. 2022. A comprehensive assessment of diversified cropping systems on agro-environmental sustainability in three Mediterranean long-term field experiments. *Eur J Agron* 140: 126598. DOI: 10.1016/j.eja.2022.126598.
- Wahyuni H, Suranto S. 2021. Dampak deforestasi hutan skala besar terhadap pemanasan global di Indonesia. *JiIP: Jurnal Ilmiah Ilmu Pemerintahan* 6 (1): 148-162. DOI: 10.14710/jiip.v6i1.10083. [Indonesian]
- Wahyunto, Dariah A. 2014. Degradasi lahan di Indonesia: Kondisi existing, karakteristik, dan penyeragaman definisi mendukung gerakan menuju satu peta. *Jurnal Sumberdaya Lahan* 8 (2): 81-93. DOI: 10.2018/jsdl.v8i2.6470. [Indonesian]
- Walter K, Don A, Tiemeyer B, Freibauer A. 2016. Determining soil bulk density for carbon stock calculations: A systematic method comparison. *Soil Sci Soc Am J* 80 (3): 579-591. DOI: 10.2136/sssaj2015.11.0407.
- Wasis B, Saharjo BH, Putra EI. 2019. Impacts of peat fire on soil flora and fauna, soil properties, and environmental damage in Riau Province, Indonesia. *Biodiversitas* 20 (6): 1770-1775. DOI: 10.13057/biodiv/d200639.
- Wei H, Yang J, Liu Z, Zhang J. 2022. Data integration analysis indicates that soil texture and pH greatly influence the acid buffering capacity of global surface soils. *Sustainability* 14 (5): 3017. DOI: 10.3390/su14053017.
- Witzgall K, Vidal A, Schubert DI, Höschen C, Schweizer SA, Buegger F, Pouteau V, Chenu C, Mueller CW. 2021. Particulate organic matter as a functional soil component for persistent soil organic carbon. *Nat Commun* 12 (1): 4115. DOI: 10.1038/s41467-021-24192-8.
- Zhao C, Zhou W, Hu QH, Xu H, Zhang C. 2021. Porosity measurement of granular rock samples by modified bulk density analyses with particle envelopment. *Mar Pet Geol* 133: 105273. DOI: 10.1016/j.marpetgeo.2021.105273.