

Soil Health, Carbon Storage, and Ecosystem Service Valuation in Coffee Agroforestry Systems of Bener Meriah, Aceh

Sri Julidar¹, Halus Satriawan*² , Ernawita² , Orang Kaya Hasnanda Syahputra³

¹Students of the Natural Resources and Environmental Management Study Programme, Universitas Almuslim, Bireuen, 24261, Indonesia

²Natural Resources and Environmental Management Study Programme, Universitas Almuslim, Bireuen, 24261, Indonesia

³Faculty of Forestry, Universitas Sumatera Utara, Medan, Indonesia

*Corresponding Author: halussatriawan@umuslim.ac.id

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ABSTRACT

Agroforestry has been promoted as a sustainable land-use model to reconcile agricultural production with ecosystem service provision. This study evaluates soil health indicators and their economic valuation in coffee agroforestry versus monoculture systems in Bener Meriah, Aceh, Indonesia. Forty soil samples were analyzed for physical, chemical, and biological parameters, including bulk density, porosity, soil organic carbon (SOC), total nitrogen (N), available phosphorus (P), and soil organisms. Results indicate that coffee agroforestry consistently improves soil physical, chemical, and biological properties compared to monoculture systems, leading to enhanced carbon storage, nutrient retention, and hydrological regulation. These improvements translate into higher indirect economic values of ecosystem services, highlighting the multifunctional benefits of agroforestry for sustainable coffee production. These findings confirm that coffee agroforestry enhances soil health, supports multiple ecosystem services, and delivers higher economic benefits than monoculture. Agroforestry thus represents a multifunctional and sustainable landscape model for coffee production in tropical regions.

Keyword: Carbon Sequestration, Coffee Agroforestry, Ecosystem Service Valuation, Nutrient Retention, Soil Health



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1. Introduction

Coffee is one of the most important plantation commodities with a very high global trade value, ranking second after petroleum and natural gas, with production increasing by 200% since 1950 [1]. Coffee consumption continues to grow in major importing countries as well as in producing countries, including Indonesia. Bener Meriah District in Aceh Province is recognized as one of Indonesia's main coffee-producing centers, with a plantation area of 46,167 ha, most of which is managed by smallholder farmers with an average landholding of 1–2 ha. These smallholder plantations support the livelihoods of more than 30,000 households, highlighting the strategic role of coffee in both local and regional economies.

Nevertheless, the sustainability of coffee production in Bener Meriah faces multiple challenges. Climate change and declining soil fertility have contributed to fluctuations in production, while land-use change driven by population pressure has further exacerbated the problem. Globally, long-term coffee production is projected to fall short of demand due to the direct and indirect impacts of climate change [2]. Rising temperatures and altered rainfall patterns disrupt coffee growth, reduce land suitability [3], and increase the

risk of pest and disease outbreaks [4]. Consequently, coffee landscapes are predicted to shift from lowland to upland areas bordering natural ecosystems, thereby increasing potential conflicts between production and conservation. At the same time, the intensification of coffee cultivation through monoculture practices further threatens ecosystem quality.

Addressing these challenges requires strategies that balance increased production with the preservation of ecosystem services. One promising approach is the development of multifunctional coffee-based landscapes through the integration of multipurpose tree species (MPTS). Agroforestry systems have been widely recognized for providing diverse ecosystem services, including carbon sequestration, pest control, product diversification, soil enrichment, pollination and seed dispersal, biodiversity conservation, and improvements in air and water quality [5]. From an economic perspective, agroforestry represents a viable land-use system to reduce poverty, ensure food security, and generate environmental benefits that support social, economic, and ecological sustainability [6].

In Bener Meriah, coffee agroforestry systems are commonly shaded with *Leucaena leucocephala* (lamtoro), a nitrogen-fixing tree that supplies essential nutrients for coffee plants while fostering a microenvironment conducive to soil microbial activity and nutrient mineralization. Sustainable coffee farming emphasizes not only long-term productivity but also ecological functions such as soil and water conservation and biodiversity preservation. The ecological processes within agroforestry systems, including nutrient and water cycling, energy flow, and population regulation, closely resemble those occurring in tropical forest ecosystems [7]. The study sites are characterized by two dominant soil types, namely Humic Psammentic Dystrudepts and Typic Hapludands. Dystrudepts are Inceptisols with moderate weathering, relatively low organic matter content, and limited nutrient retention capacity, commonly found in sloping upland areas. In contrast, Hapludands belong to Andisols derived from volcanic ash, characterized by high organic matter content, high porosity, and strong phosphorus fixation capacity. These contrasting soil properties provide an appropriate basis for evaluating the performance of coffee agroforestry and monoculture systems under different pedo-environmental conditions. Therefore, this study explicitly compares coffee agroforestry and coffee monoculture systems within each soil type (Dystrudepts and Hapludands), while also examining how differences in soil characteristics influence the magnitude of ecosystem services generated under agroforestry management.

2. Method

2.1. Research Location

This study was conducted in smallholder coffee plantations in Bener Meriah District. The data collection sites were determined in areas that represent the coffee plantation centers where shade trees are applied, which are identified as agroforestry practices.

2.2. Tools and Materials

The data used in this research were classified into two categories, namely primary and secondary data. Primary data included: (1) information on farming practices and farmers' socio-economic aspects, (2) soil samples for evaluating physical, chemical, and biological soil properties, and (3) litter samples for estimating carbon stocks. Secondary data consisted of: (1) climate data from the Redelong Meteorological Station, (2) topographic data (digital elevation model) and administrative boundaries from the Geospatial Information Agency (BIG), (3) soil type data from the Center for Agricultural Land Resources Instrument Standardization (BBPSI SDLP), and (4) land cover data from the Ministry of Environment and Forestry (MoEF).

The tools used in this research were also grouped into two categories: tools for collecting primary data and tools for data processing. Primary data collection tools included questionnaires, GPS, and soil sampling equipment. Data processing was carried out using a computer equipped with Microsoft Office software.

2.3. Data Collection

The soil sampling sites were determined through surveys or systematic exploration to obtain a comprehensive overview of the study area. Both intact and composite soil samples were collected from the topsoil layer (0–15 cm), as root activity and soil management practices are most dominant at this depth, making soil physical, chemical, and biological properties relatively more dynamic, except for soil texture

which remains stable. This depth range was also selected to ensure a more measurable volume of soil for analysis.

A total of 40 samples were collected using a randomized block design, covering two management systems (coffee agroforestry and coffee monoculture), two soil types (Humic Psammentic Dystrudept and Typic Hapludand), five sampling points per management system, and two replicates per location. Interviews with local communities were also conducted to obtain data on substitute goods prices in local markets, which were then used to calculate the indirect use value of soil health.

2.4. Data Analysis

This study assessed soil health conditions in coffee plantations managed under agroforestry and monoculture systems, while also developing a framework to estimate the economic value of soil health. The research activities were conducted in two stages. First, soil health parameters in coffee plantations with different management systems were evaluated based on the indicators summarized in Table 1. Second, the economic value of soil health was calculated using a revealed preference method with direct proxies, linked to the economic value of ecosystem services associated with soil health parameters.

2.4.1. Soil health evaluation

Several key parameters were analyzed, including bulk density, porosity, total nitrogen, available phosphorus, total fungi, total microbes, total invertebrates, and soil organic carbon. Each soil health parameter was interpreted using established thresholds and comparative benchmarks reported in the literature for tropical agricultural soils. Rather than classifying parameters into rigid categories (e.g., high, medium, low), this study emphasizes relative differences between management systems within the same soil type, which is considered more appropriate for site-specific ecosystem service valuation. These parameters were chosen because of their strong relationship with the provision of ecosystem services. For instance, bulk density and porosity are associated with water regulation services, soil organic carbon supports climate regulation services, total nitrogen and available phosphorus are linked to nutrient retention, while total microbes, fungi, and invertebrates contribute to habitat services.

Bulk density, porosity, and invertebrates were analyzed using undisturbed soil samples, while other parameters were measured from composite soil samples. Factors such as micronutrients, pH, base saturation, and cation exchange capacity were not included, as they potentially correlate with the parameters studied and their impacts on ecosystem services were considered less significant. Organic matter is a key driver of soil health, influencing nutrient availability, soil aggregation, and biological activity, which ultimately supports multiple ecosystem services (Thiele-Bruhn et al., 2012; Lehmann et al., 2020).

2.4.2. Economic value of soil health

Soil health is regarded as natural capital that can increase or decrease depending on management decisions, for instance through agroforestry or monoculture practices. From a neoclassical economic perspective, soil can be considered an asset that provides returns in the form of ecosystem services. However, ecosystem services are not only influenced by soil conditions, but also by climate, topography, and human activities.

To estimate the economic value of soil health, a quantitative model linking soil conditions with the ecosystem services they support is required. Using this approach, the economic value of soil health can be calculated through ecosystem service valuation methods. In this study, the estimation focused on the indirect use value (IUV) of soil health, thereby not encompassing the total economic value of ecosystem services. The economic value of soil health was then derived from its contribution to ecosystem service provision using ecosystem service valuation approaches. The measured soil physical, chemical, and biological parameters under different land-use systems and soil types are summarized in Table 1.

Table 1. Soil health parameters, the ecosystem services they support, and the valuation methods used to estimate the economic value of each soil health parameter.

No	Parameter	Ecosystem Service	Economic Valuation	Equation
1	Soil Organic Carbon	Climate Regulation	Carbon Incentive	SOC is soil organic carbon (kg/ha), M_{rCO_2} and M_{rC} are the molecular weights of carbon dioxide and carbon, respectively, and CI is the carbon incentive (Rp/kg CO ₂).
2	Total Nitrogen	Nutrient Retention	Replacement Cost	$EVTN = TN \div 46\% N \times FPUrea$, where TN is total nitrogen (kg/ha), 46% N is the nitrogen content in urea, and FPUrea is the price of urea fertilizer (Rp/kg).
3	Available Phosphorus	Nutrient Retention	Replacement Cost	$EVAP = AP \div 46\% P \times FPTSP$, where AP is available phosphorus (kg/ha), 46% P is the phosphorus content in TSP, and FPTSP is the price of TSP fertilizer (Rp/kg).
4	Gravitational Water	Water Regulation	Replacement Cost	$EVGW = GW \times V \times WP$, where GW is gravitational water (%), V is soil volume (m ³ /ha), and WP is the water tariff (Rp/m ³).
5	Available Water	Water Regulation	Production Function	$EVAWC = AWC \times V \times WU \times DBP$, where AWC is available water (%), V is soil volume (m ³ /ha), WU is crop water requirement (kg/m ³), and DBP is the price of dried cocoa beans (Rp/kg).
6	Total Microbes	Nutrient Retention	Production Function	$SB = \beta_0 + \beta_1 SOM + \beta_2 TN + \beta_3 AP + \beta_4 pH$ (Pedotransfer function).
7	Total Fungi	Habitat Provision & Nutrient Cycling	Replacement Cost / Contingent Valuation	Estimated through the role of mycorrhizal fungi in enhancing phosphorus availability and supporting plant productivity [8].
8	Total Invertebrates	Soil Biodiversity & Decomposition	Replacement Cost / Benefit Transfer	Estimated through their contribution to organic matter decomposition, nutrient turnover, and soil structure improvement.

3. Result and Discussion

3.1. Soil Health Parameters

This study does not classify soil parameters into categorical classes (high, medium, low), as such classifications may vary across soil orders and climatic zones. Instead, the analysis focuses on management-induced differences that are directly linked to ecosystem service performance (Table 2).

Table 2. Soil health parameters in coffee agroforestry and coffee monoculture

No	Soil Health Parameter	Dystrudepts – Agroforestry	Dystrudepts – Monoculture	Hapludand – Agroforestry	Hapludand – Monoculture
Field Observation					
1	Organic Carbon (%)	1.53	1.30	2.87	1.23
2	Total Nitrogen (%)	0.25	0.15	0.20	0.15
3	Available Phosphorus (ppm)	163.0	134.0	149.1	135.0
4	Bulk Density (kg·m ⁻³)	1.40	1.80	1.40	1.40
5	Total Porosity (% v/v)	93.0	67.0	76.5	59.5
6	Total Microbes (10 ⁵ cfu·g ⁻¹)	52.5	27.1	40.8	25.2
7	Total Fungi (cfu·g ⁻¹)	335	106	210	101
8	Total Invertebrates (ind·ring ⁻¹)	24	15	20	16
Calculated Properties					
1	Field Capacity (%)	36.4	33.9	34.4	25.5
2	Permanent Wilting Point (%)	10.1	9.5	11.4	8.9
3	Available Water Content (%)	16.7	16.8	14.4	11.9
4	Gravitational Water (%)	16.1	15.5	13.2	10.7

The concept of soil health encompasses a broader scope than soil quality. Soil not only functions as a medium for agricultural production but also plays a crucial role in ensuring environmental sustainability through the provision of various ecosystem services [9], [10]. A soil can be categorized as healthy when its physical, chemical, and biological aspects are able to function optimally to support productivity while simultaneously enhancing ecosystem services. In general, soil physical parameters are related to soil particle structure and porosity, chemical parameters include organic matter content and nutrient availability, while biological parameters are associated with the population and diversity of soil organism. Based on laboratory analysis, the coffee agroforestry system on Humik Psammentic Dystrudept and Typic Hapludand soils showed significant improvements in all soil health parameters compared to monoculture. This was evident from higher levels of soil organic carbon, total nitrogen, available phosphorus, microbial populations, fungi, and invertebrates, as well as improved porosity, while bulk density was lower. These findings indicate that agroforestry better supports the sustainability of ecosystem functions compared to monoculture [11], [12].

One key factor contributing to improved soil health in agroforestry is the higher organic matter input derived from litter and biomass of shade trees. Organic matter is an essential element that influences nearly all aspects of soil health by enhancing nutrient availability, improving soil structure, and supporting soil organism diversity [13]. High organic matter content also creates favorable conditions for plant growth through improved water retention and soil fertility [14]. Furthermore, soil organisms such as microbes, fungi, and invertebrates derive energy from organic matter, which contributes to decomposition, pest control, and nutrient cycling, thereby forming a synergistic loop that reinforces soil health [8].

3.2. Economic Valuation of Soil Health

The improvement of soil health through coffee agroforestry is believed to strengthen multiple ecosystem services, particularly regulating services, which in turn provide higher indirect economic value.

3.2.1. Soil Organic Carbon as a Climate Regulation Support

Healthy soils act as effective carbon sinks, storing large reserves of organic carbon and making a significant contribution to climate change mitigation [15], [16]. Compared to monoculture, coffee agroforestry systems have higher soil organic carbon reserves. In monoculture coffee fields, soil organic carbon content was recorded at only 1.30% in Dystrudepts and 1.23% in Hapludand soils, equivalent to 27.30 t C/ha (100.91 t CO₂e/ha) and 25.83 t C/ha (94.79 t CO₂e/ha), respectively. In contrast, coffee agroforestry increased soil organic carbon content to 1.53% in Dystrudepts and 2.87% in Hapludand soils,

with reserves reaching 32.1 t C/ha (117.8 t CO₂e/ha) and 60.3 t C/ha (221.3 t CO₂e/ha). This difference is closely linked to the amount of litter input and decomposer activity. The low input of organic matter in monoculture systems, both from litter and organic fertilizers, reduces soil organic carbon reserves. Conversely, agroforestry systems are able to maintain higher carbon stocks even without additional organic fertilizer, thanks to the decomposition of shade tree litter [17].

The indirect benefits of soil organic carbon can be estimated through incentive-based economic mechanisms, either in the form of compensation for those who sequester and store carbon or penalties for those who release it into the atmosphere. Since 2022, the Government of Indonesia has set a carbon incentive rate of Rp. 30,000 per ton of CO₂-equivalent as the basis for national carbon trading and carbon tax policies [18]. Using this approach, the indirect economic value of soil organic carbon can be estimated for various land-use systems. For example, in monoculture coffee grown on Dystrudepts, the economic value is estimated at around Rp. 3,027,300 per hectare, while in Hapludand soils it reaches Rp. 2,483,700 per hectare. Meanwhile, coffee agroforestry shows higher values, namely Rp. 3,534,000 per hectare in Dystrudepts and Rp. 6,639,000 per hectare in Hapludand soils. These findings are consistent with global meta-analyses confirming that coffee agroforestry systems consistently increase soil carbon stocks compared to coffee monoculture, thus contributing more significantly to climate change mitigation [19], [20]. Therefore, agroforestry not only functions as a sustainable agricultural adaptation strategy but also provides tangible socio-economic value through Payment for Ecosystem Services (PES) schemes, since the benefits of soil carbon storage are widely shared at the global level [21].

3.2.2. Soil Porosity as a Water Regulation Support

Based on the principle of the water balance, soil plays an important role in distributing rainfall into three main hydrological components: surface runoff, infiltration that subsequently contributes to groundwater recharge, and soil water storage utilized through evapotranspiration. The proportion of each component is strongly influenced by soil physical characteristics, particularly pore space distribution. Drainage pores, which consist of macropores, function as flow pathways for gravitational water, thereby determining the potential for groundwater recharge. Conversely, available water pores, or mesopores, serve as the primary reservoir for supporting plant evapotranspiration [22].

The results of this study show that pore distribution differs between land-use systems (Figure 1). In Hapludand soils, drainage pores in coffee agroforestry systems reached 13.20% of soil volume, higher than coffee monoculture which was only 10.70%. A clearer difference was observed in Dystrudepts, where coffee agroforestry had drainage pores of 16.10%, slightly higher than coffee monoculture at 15.50%. These findings indicate that agroforestry systems tend to improve soil structure by increasing macropores, which in turn enhance infiltration capacity and groundwater recharge [23]. Thus, the higher the proportion of drainage pores, the greater the soil's potential to store and channel gravitational water into deeper layers. This highlights that coffee agroforestry not only contributes to climate change mitigation through increased carbon stocks but also enhances adaptation by improving hydrological ecosystem services, particularly in supporting sustainable groundwater availability [24], [15].

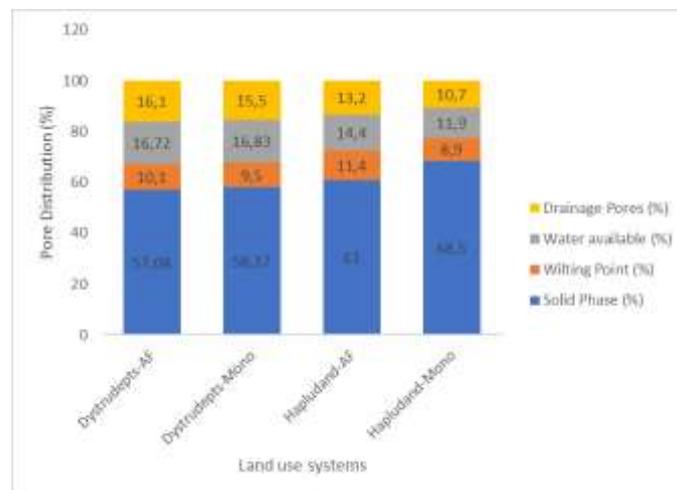


Figure 1. Distribution of pore space across land-use systems and soil types

The calculation results show that coffee agroforestry systems on both soil types (Dystrudepts and Hapludands) are able to enhance the soil's capacity to retain water, both in drainage pores and available water pores, compared to coffee monoculture systems. In Dystrudept soils, the volume of available water reached 501.6 m³/ha under agroforestry, slightly higher than in monoculture (505 m³/ha), while the volume of drainage pores was also greater (483 m³/ha vs. 465 m³/ha). Meanwhile, in Hapludand soils the differences between agroforestry and monoculture were more pronounced. Coffee agroforestry had a drainage pore capacity of 396 m³/ha, higher than monoculture coffee (321 m³/ha), and available water of 432 m³/ha compared to 357 m³/ha in monoculture. This indicates that Hapludand soils are more responsive to agroforestry systems in improving soil hydrological functions. These findings are consistent with [25], who reported that coffee agroforestry increases available water capacity compared to open systems (monoculture) at surface soil depth.

This improvement demonstrates that the presence of shade trees in agroforestry systems enhances soil structure through the accumulation of organic matter and soil biota activity, which in turn increases both macropores and mesopores [26]. Moreover, the increase in macroporosity directly contributes to higher infiltration rates and groundwater recharge potential.

Ecologically, the higher proportion of drainage pores in agroforestry systems indicates that the land has a greater capacity to store and channel gravitational water into deeper soil layers. Thus, agroforestry contributes not only to greater soil water availability for plants (available water), but also to water resource sustainability through aquifer recharge. This reinforces the argument that agroforestry provides higher hydrological ecosystem services compared to monoculture farming systems [27], [28]. Therefore, agroforestry improves not only available water capacity (important for evapotranspiration and drought stress), but also the soil's ability to absorb gravitational water and recharge aquifers [29]. This supports the argument that enhancing soil hydrological services requires soil structure modification through agroforestry and interventions such as biopores.

Table 3. Indirect Use Value of Groundwater in Coffee Agroforestry vs. Monoculture Systems

Soil Classification	Planting System	Drainage Pore Volume (m ³ /ha)	Available Water Volume (m ³ /ha)	Total Water Volume (m ³ /ha)	Water Use Value (Rp/ha)
Dystrudepts	Agroforestry	483	501.60	984.60	Rp1,329,210
	Monoculture	465	505	970	Rp1,309,500
Hapludand	Agroforestry	396	432	828	Rp1,117,800
	Monoculture	321	357	678	Rp915,300

Based on Table 3, the calculations show that the coffee agroforestry system consistently has a higher groundwater use value compared to the monoculture system, both in Dystrudept and Hapludand soils. In Dystrudept soils, the total volume of water that can be stored reached 984.6 m³/ha with an economic value of Rp. 1,329,210/ha, slightly higher than the monoculture system which stored only 970 m³/ha with a value of Rp. 1,309,500/ha. A more pronounced difference was observed in Hapludand soils, where agroforestry was able to store 828 m³/ha of water with a value of Rp. 1,117,800/ha, compared to monoculture which stored only 678 m³/ha with a value of RP. 915,300/ha.

The increase in groundwater use value in agroforestry systems is attributed to improved soil structure facilitated by shade trees, which add organic matter inputs, enhance soil biota activity, and improve soil aggregation. These conditions lead to increased macroporosity (drainage pores) and mesoporosity (available water), thereby enhancing the soil's capacity to store and channel water [30]. Thus, agroforestry not only plays a role in maintaining water availability for coffee plants but also supports the sustainability of water resources by increasing groundwater recharge potential.

The economic value, calculated based on the basic household groundwater tariff (Rp. 1,350/m³), illustrates that soil hydrological functions can be converted into tangible ecosystem service values. This value reflects the contribution of agroforestry in providing environmental services that benefit society at large, not only farmers. This finding is consistent with [25], who reported that coffee agroforestry systems increase available water capacity compared to unshaded coffee systems.

3.2.3. Soil Nutrients as a Support for Nutrient Retention

Soil nutrient content (soil organic carbon, nitrogen, and phosphorus) plays a vital role in supporting nutrient retention, namely the soil's ability to store and supply nutrients for plants in a sustainable manner. The data show that coffee agroforestry systems consistently enhance nutrient availability compared to monoculture systems. Higher soil organic carbon in agroforestry, particularly in Hapludand soils, is closely linked to the organic matter inputs from litter and the roots of shade trees. Organic matter functions as an agent for soil aggregate formation, increases cation exchange capacity (CEC), and improves soil pore distribution, thereby optimizing nutrient retention [31].

The increase in total nitrogen under agroforestry also highlights the role of shade trees in the nitrogen cycle, both through the addition of N-rich litter and through interactions with soil microbes that support mineralization. In Dystrudepts–Agroforestry, total N reached 0.25%, compared to only 0.15% in Dystrudepts–Monoculture. A similar pattern was observed in Hapludand soils, although the difference was smaller (0.20% vs. 0.15%). The higher total N under agroforestry shows a strong relationship with soil organic carbon, as the decomposition of organic matter produces mineral nitrogen readily available for plant uptake. This is consistent with the findings of [12], who reported that agroforestry improves nitrogen cycling efficiency and reduces nitrogen losses through leaching.

Available phosphorus was also higher in agroforestry compared to monoculture. In Dystrudepts–Agroforestry, available P was recorded at 163 ppm, higher than in Dystrudepts–Monoculture (134 ppm). In Hapludand soils, agroforestry recorded 149.10 ppm, also higher than monoculture (135.02 ppm). The greater P availability in agroforestry is likely due to the role of soil fungi, particularly mycorrhizae, in enhancing the dissolution of bound phosphates. Research by [8] emphasized that mycorrhizal associations can significantly increase P availability, thereby improving the soil's capacity to supply nutrients to plants. Thus, it can be concluded that nutrient retention is better in coffee agroforestry systems compared to monoculture. This is not only due to the higher input of organic matter but also because of more active soil biological interactions, making agroforestry more sustainable in supporting land productivity and mitigating soil degradation.

The analysis further shows that the higher nitrogen (N) and phosphorus (P) content in coffee agroforestry systems contributes significantly to the increase in the economic value of soil nutrients. Using the replacement cost approach, the economic value of nutrients in Dystrudepts–Agroforestry was estimated at Rp. 88.55 million/ha, much higher than Dystrudepts–Monoculture, which was only Rp. 55.90 million/ha. Similarly, in Hapludand–Agroforestry, the economic value of nutrients reached Rp. 72.26 million/ha, higher than Hapludand–Monoculture at Rp. 55.97 million/ha. This difference is primarily attributed to the significantly higher contribution of total nitrogen in agroforestry systems.

The increase in nitrogen reserves in agroforestry systems is linked to the role of shade trees in enriching N-rich litter and supporting soil microbial activity that accelerates mineralization. As shown in this study, total N content in Dystrudepts–Agroforestry reached 0.25% compared to 0.15% in monoculture. This finding is consistent with [32], who reported that agroforestry consistently improves nitrogen cycle efficiency and reduces nutrient losses through leaching.

From the phosphorus perspective, agroforestry also demonstrated advantages with higher available P values. For instance, Dystrudepts–Agroforestry had 163 ppm of phosphorus, higher than monoculture with 134 ppm. When converted to synthetic fertilizer costs, this equates to Rp. 12.46 million/ha, compared to only Rp. 10.24 million/ha for monoculture. The role of soil fungi, particularly mycorrhizae, is an important factor in enhancing the dissolution of bound phosphate, thereby improving P availability for plants. This aligns with [8], who emphasized that mycorrhizal associations can significantly increase P availability, especially in tropical soils that are generally P-deficient.

Overall, these results demonstrate that agroforestry systems are not only superior in nutrient retention but also provide higher economic value when assessed through ecosystem service valuation approaches. In other words, agroforestry practices can substitute a substantial portion of chemical fertilizer functions in the long run while reducing farmers' dependency on external inputs. This condition not only supports the ecological sustainability of soils but also strengthens the economic benefits of smallholder farmers through reduced production costs [33].

3.2.4. Soil Organisms as a Support for Nutrient Retention

Observations showed that the total microbial population in Dystrudepts–Agroforestry reached 52.5×10^5 cfu/g, much higher than in monoculture systems (27.1×10^5 cfu/g). In Hapludand soils, a similar pattern was observed with 40.8×10^5 cfu/g under agroforestry compared to only 25.2×10^5 cfu/g in monoculture. This indicates that the presence of soil organisms is strongly influenced by the management system, where agroforestry consistently increases microbial activity compared to monoculture.

Pedotransfer estimates provided further insights into the determining factors of microbial abundance. Regression coefficients showed that total nitrogen was the most dominant variable, with an influence of +762.8 on microbial populations. This aligns with field data, where total N content in Dystrudepts–Agroforestry was higher (0.25%) compared to Dystrudepts–Monoculture (0.15%). High nitrogen supports microbial activity through the availability of essential elements for metabolism, as reported by [32] who noted that agroforestry strengthens nitrogen cycling through the addition of N-rich litter and interactions with nitrogen-fixing microbes.

In addition, soil organic carbon also contributed positively to microbial abundance, with a regression coefficient of +1.42. In Hapludand–Agroforestry, soil organic carbon content reached 2.87%, much higher than in Hapludand–Monoculture (1.23%). The availability of organic matter serves as the main energy source for microbes, accelerating decomposition and humification processes, thereby enhancing nutrient retention in the soil [34].

Interestingly, the model showed a negative relationship between available phosphorus (AP) and total microbes, with a coefficient of -1.77 . However, this pattern is not fully consistent with soil ecology theory, as agroforestry in fact also increased phosphorus availability. For example, in Dystrudepts–Agroforestry, available P was recorded at 163 ppm, higher than in Dystrudepts–Monoculture (134 ppm). This regression outcome was likely due to the limited sample size ($n=4$) and multicollinearity between C, N, and P, and therefore may not fully reflect biological mechanisms. Recent studies by Lehmann et al. (2020) emphasized the crucial role of soil fungi, particularly mycorrhizae, in enhancing the dissolution of bound phosphate and strengthening microbe–plant interactions.

Overall, the data show that soil organisms are more active in coffee agroforestry systems, both in Dystrudept and Hapludand soils. The higher activity of microbes (52.5 vs. 27.1 ; 40.8 vs. 25.2), fungi (335 vs. 106 ; 210 vs. 101), and invertebrates (24 vs. 15 ; 20 vs. 16) indicates that agroforestry systems not only add nutrient inputs from organic matter but also reinforce soil biological processes. Thus, nutrient retention is better in agroforestry, supporting sustainable land productivity while reducing the risk of soil degradation.

4. Conclusion

This study demonstrates that coffee agroforestry systems consistently outperform monoculture systems in enhancing soil health, supporting ecosystem services, and generating indirect economic values. Agroforestry significantly increased soil organic carbon, with stocks reaching 32.10 t C/ha (117.80 t CO₂e/ha) in Dystrudepts and 60.30 t C/ha (221.30 t CO₂e/ha) in Hapludands, compared to only 27.30 t C/ha and 25.8 t C/ha under monoculture. This improvement translates into higher carbon incentive values of up to Rp. 6.64 million/ha, highlighting the role of agroforestry in climate regulation. Nutrient retention was also superior under agroforestry, with total nitrogen increasing to 0.25% in Dystrudepts–Agroforestry versus 0.15% in Dystrudepts–Monoculture, and available phosphorus reaching 163 ppm compared to 134 ppm. These improvements resulted in higher nutrient replacement costs, estimated at Rp. 88.55 million/ha in Dystrudepts–Agroforestry compared to only Rp. 55.90 million/ha in monoculture. Similarly, soil organisms were more abundant, with microbial populations reaching 52.5×10^5 cfu/g in Dystrudepts–Agroforestry compared to 27.1×10^5 cfu/g in monoculture, reinforcing biological nutrient cycling. From a hydrological perspective, agroforestry increased drainage porosity to 16.1% in Dystrudepts and 13.20% in Hapludands, enhancing groundwater recharge potential. The total groundwater value reached 984.6 m³/ha (Rp. 1.33 million/ha) in Dystrudepts–Agroforestry and 828 m³/ha (Rp. 1.12 million/ha) in Hapludands, consistently higher than monoculture systems. Overall, these findings confirm that coffee agroforestry provides multifunctional benefits by improving soil health, strengthening climate and water regulation, and delivering higher economic values through ecosystem service valuation. Thus, agroforestry represents a sustainable landscape model for coffee production in Bener Meriah, Aceh, balancing ecological conservation with economic viability for smallholder farmers.

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