

Potential aboveground carbon storage in the community forest area of Tawangmangu, Karanganyar District, Indonesia

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¹Department of Environmental Science, Faculty of Mathematics and Natural Sciences, Universitas Sebelas Maret. Jl. Ir. Sutami 36A Surakarta 57126, Central Java, Indonesia. Tel./fax.: +62-271-663375, ✉email: volatileoils@gmail.com

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Abstract. *Setyasih DMD, Putri RAS, Raharjo YAA, Izdihar RS, Kusumaningrum L, Setyawan AD. 2025. Potential aboveground carbon storage in the community forest area of Tawangmangu, Karanganyar District, Indonesia. Asian J For 9: 108-114.* Forests are ecologically significant landscapes characterized by tree cover and high biodiversity. They play an important role in carbon sequestration and storage, contributing to climate regulation. Tawangmangu sub-district with its significant portion of forest land holds considerable potential for carbon sequestration. This study aims to assess the carbon storage potential and tree species composition in three villages within the Tawangmangu sub-district—Plumbon, Nglebak, and Sepanjang. Data were collected using a random sampling technique, with 20 plots (20 × 20 m) established at each site. Data such as identification of species and the circumference of each tree were measured. The collected data were analyzed using the Shannon-Wiener diversity index, biomass index, and carbon storage potential. A total of 30 tree species from 18 families were identified across the three villages, with the Fabaceae family being the most dominant. The species diversity index (H') values were 2.147 for Plumbon, 1.278 for Nglebak, and 2.456 for Sepanjang, indicating moderate species diversity and relatively stable ecosystem productivity. Biomass calculations revealed values of 462.81 kg/ha in Plumbon, 807.28 kg/ha in Nglebak, and 145.13 kg/ha in Sepanjang. Corresponding carbon stock estimates were 212,892 kg in Plumbon, 371,348 kg in Nglebak, and 66,759 kg in Sepanjang. The data indicate a positive correlation between biomass and carbon stock values. The variation in carbon storage across sites is likely influenced by species composition and site-specific ecological factors affecting carbon sequestration efficiency.

Keywords: Allometric equation, biomass, carbon sequestration, Central Java, tree diversity

INTRODUCTION

The Food and Agriculture Organization of the United Nations (FAO) defines a forest as a land area exceeding 0.5 hectares, with a tree canopy cover of more than 10% and a minimum tree height of 5 meters (Qin et al. 2021). Forests play a crucial role at local, regional, and global scales, supporting an estimated 1.6 billion people by providing livelihoods and income opportunities (Frick et al. 2018; Mukul et al. 2020). In addition to serving as habitats for diverse plant and animal species, forests offer essential ecological services, including climate regulation, carbon sequestration, biodiversity conservation, and oxygen production (Nurrochmat and Abdulah 2014). Furthermore, forests contribute to economic growth through the sustainable use of biodiversity resources (Mayasari et al. 2024).

Forests play a vital role in soil protection, preventing erosion, regulating atmospheric oxygen, and capturing and storing atmospheric carbon (Oulaana et al. 2023). Their ecological, economic, and social functions make them indispensable to maintaining environmental stability and supporting human well-being (Guntur et al. 2023). However, despite their ecological and economic significance, forest ecosystems face increasing threats from anthropogenic activities, including deforestation and forest

degradation. Major drivers of forest loss include agricultural expansion, encroachment, and land-use conversion (Wahyuni and Suranto 2021). Deforestation is responsible for approximately 18-20% of global anthropogenic greenhouse gas (GHG) emissions (Mwakalukwa et al. 2023), contributing significantly to climate change. The loss of forest cover reduces carbon reserves, further exacerbating atmospheric carbon accumulation (Sumarlin et al. 2021).

Forests play a key role in climate change mitigation by absorbing and storing atmospheric carbon (Arianasari et al. 2021). Carbon sequestration occurs through photosynthesis, wherein plants absorb atmospheric carbon alongside water, facilitated by chlorophyll and sunlight (Rizaldi et al. 2021; Kusumaningrum and Izdihar 2022). Absorbed carbon is subsequently converted into organic matter and stored in biomass, with approximately 47% of total biomass consisting of carbon (Susanto et al. 2021; Fadillah et al. 2023). Over time, a portion of this stored carbon is released back into the atmosphere, contributing to the dynamic carbon cycle (Matuszkiewicz et al. 2021). Carbon stocks refer to the total amount of carbon stored in forests and other ecosystems, with fluctuations influenced by human-induced landscape modifications and vegetation changes (Selvia et al. 2023). Forest degradation diminishes carbon sequestration capacity, intensifying climate change effects (Nedhisa and Tjahjaningrum 2019). The live biomass

structure of a degraded forest is considerably altered, with proportionately more stems and coarse roots, and less leaves and fine roots, compared to a normal forest which may cause the lower carbon sequestration of the degraded forest than the undisturbed forest (Pandey et al. 2020). Therefore, quantifying carbon stocks is crucial for assessing forest health and the impacts of deforestation and degradation (Mauya et al. 2019). The carbon storage potential of forests is influenced by multiple factors, including stand density, aboveground biomass, species composition, and forest type (Choden et al. 2021).

Indonesia is one of the Southeast Asian countries with diverse topography. Tawangmangu Sub-district, located in Karanganyar District, Central Java, Indonesia has a mountainous topography due to its position on the slopes of Mount Lawu (Irianto et al. 2022). These environmental conditions support agroforestry practices, making the region suitable for horticultural crop cultivation, including fruit and vegetable farming (Negari et al. 2023). While a significant portion of forest land remains intact in Tawangmangu, it serves both ecological and economic functions for local communities. Given the extent of its forest cover, Tawangmangu sub-district holds considerable potential for carbon sequestration. This study aims to quantify carbon storage in three villages within the sub-district—Plumbon, Nglebak, and Sepanjang—and to identify the dominant tree species contributing to carbon sequestration in these areas.

MATERIALS AND METHODS

Study area

The research was conducted in March 2024 in three villages within Tawangmangu Sub-district, Karanganyar District, Central Java Province, Indonesia, i.e.: Plumbon

Village ($-7.652017^{\circ}\text{S}$, $111.102693^{\circ}\text{E}$), Nglebak Village ($-7.666431^{\circ}\text{S}$, $111.107943^{\circ}\text{E}$), and Sepanjang Village ($-7.676738^{\circ}\text{S}$, $111.103774^{\circ}\text{E}$) (Figure 1). These villages are situated at the foothills of Mount Lawu and are located at similar altitudes, with Plumbon Village at 781 meters above sea level (m asl.), Nglebak Village at 863 m asl., and Sepanjang Village at 927 m asl. (Dinas Kominfo Kabupaten Karanganyar 2019). Geographically, the research area is positioned at approximately $7^{\circ}36'43''\text{S}$ and $111^{\circ}3'27''\text{E}$, covering a total area of 70.03 km² (Dinas Kominfo Kabupaten Karanganyar 2019). Tawangmangu Sub-district is characterized by hilly terrain with steep slopes and extensive forest cover (Sihombing and Agustinus 2023). The region experiences a cool climate, with nighttime temperatures ranging from 8 to 12°C and daytime temperatures fluctuating between 15 and 30°C (Prasetyo 2023). The area receives an average annual rainfall of 7,231.4 mm, with peak precipitation occurring between February and April (Shobirin 2020).

Procedures

In this study, primary data were collected through direct field observations. The data collection employed a random sampling method using 20 × 20 cm plots for tree measurements (Mwakalukwa et al. 2023), with a total of 60 plots across the research sites. Specifically, 20 plots were established in Plumbon Village, 20 in Nglebak Village, and 20 in Sepanjang Village. Within each plot, tree species were identified, and the circumference of each tree was measured. Trees classified at the tree level had a diameter greater than 20 cm (Haryadi 2017). The random sampling method is a statistical technique used to select a subset of data that is representative of a larger population. This approach ensures that each member of the population has an equal probability of being selected, thereby minimizing bias (Iliyasa and Etikan 2021).

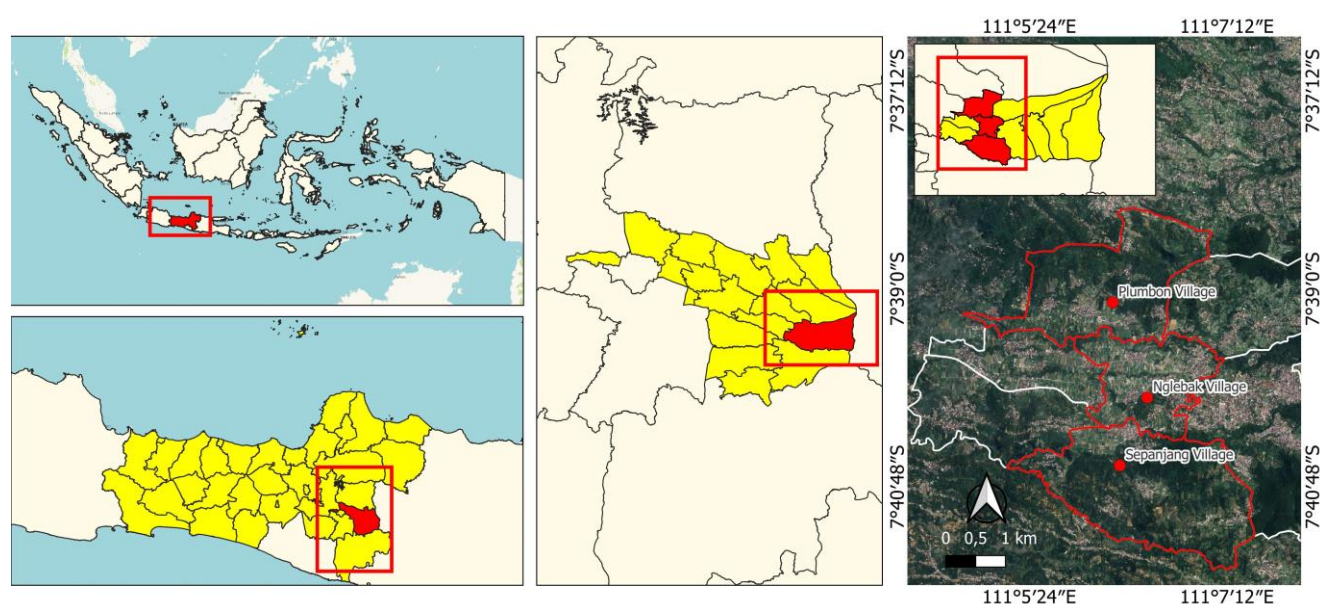


Figure 1. Research location in Tawangmangu Sub-district, Karanganyar District, Central Java, Indonesia: A. Plumbon Village, B. Nglebak Village, C. Sepanjang Village

Table 1. Biomass calculation formulas for certain species

Species	Allometric equation	Reference
<i>Pinus merkusii</i> Jungh. & de Vriese	$B = 0.0936 \times D^{2.4323}$	Siregar (2021)
<i>Schima wallichii</i> (DC.) Korth.	$B = 0.0936 \times D^{2.4323}$	Suhendang (2002)
<i>Toona sureni</i> (Blume) Merr.	$B = VK \times 390 \text{ kg/m}^3$; $VK = 0.00013 \times D^{2.057}$	P3HH (2008)
<i>Swietenia mahagoni</i> (L.) Jacq.	$B = 0.048 \times D^{2.68}$	Adinugroho and Sidiyasa (2006)
<i>Artocarpus heterophyllus</i> Lam.	$B = 0.1792 \times D^{2.25112}$	Brown (1997)
<i>Tectona grandis</i> L.f.	$B = 0.370 \times D^{2.125}$	Aminudin (2008)
<i>Acacia mangium</i> Willd.	$B = 0.134741 \times D^{2.38}$	Irawan et al. (2020)

Data analysis

The collected data were analyzed to determine the diversity index and the potential carbon storage.

Index of diversity

The diversity index is a quantitative measure used to assess species richness and evenness within a given area or population (Augousti et al. 2021). Vegetation diversity was evaluated using the Shannon-Wiener index (Odum 1971):

$$\text{Index of Diversity (H')} = \Sigma \left[\frac{n_i}{N} \log \frac{n_i}{N} \right]$$

Where:

n_i : Number of individuals of a species

N : Total number of individuals of all species

Shannon-Wiener species diversity level:

$H' < 1$: Low diversity

$1 < H' < 3$: Medium diversity

$H' > 1$: high diversity

Biomass

Biomass refers to the total dry weight of organic matter, expressed in kilograms or tons. Estimating the carbon stored in a tree requires first determining its biomass. Different species exhibit varying allometric relationships, necessitating species-specific allometric equations for accurate biomass estimation. The allometric equations for selected species identified in the study area are presented in Table 1.

For species lacking a specific biomass estimation formula, the allometric equation developed by Brown (1997) can be applied to estimate the biomass of trees growing in humid tropical regions:

$$B = \exp [-2.134 + 2.53 \ln (D)]$$

Where:

B : Biomass (kg)

D : Diameter of tree (cm)

To determine the biomass in a specific area, the formula by Danarto (2020) was used:

$$\text{Biomass per unit area} = \text{Total Biomass (kg)} / \text{Area (ha)}$$

Carbon storage potential

According to Hairiah and Rahayu (2007), carbon stocks are estimated from biomass, with approximately 46% of the total biomass considered as carbon. Thus, the amount

of stored carbon is estimated by multiplying the biomass by 0.46. The calculated carbon stock, initially expressed in kilograms, was then converted into tons for standardization.

$$\text{Stored carbon} = \text{Biomass per unit area} \times 0.46$$

RESULTS AND DISCUSSION

Vegetation found in community forest area

Vegetation refers to the assemblage of tree species within a specific location, where interactions occur between different species, environmental conditions, and other living organisms (Agustina et al. 2022). In this study, 30 tree species belonging to 18 families were identified across 20 plots in Plumbon Village, Nglebak Village, and Sepanjang Village. The Fabaceae family had the highest species representation, with six species recorded. A comprehensive list of tree species found in the research area is presented in Table 2.

The tree species identified at the research site contribute to the composition and vegetation structure, providing ecological and economic benefits to the local community (Safitri et al. 2018). The study area, located on the slopes of Mount Lawu, contains vegetation that plays a crucial role in maintaining soil stability and preventing landslides (Indrajaya and Handayani 2008). In addition to their role in soil conservation, several tree species, such as pine (*Pinus merkusii* Jungh. & de Vriese), teak (*Tectona grandis* L.f.), acacia (*Acacia decurrens* (J.C.Wendl.) Willd.), and mahogany (*Swietenia mahagoni* (L.) Jacq), are valuable for timber production, serving as raw materials for furniture and paper manufacturing (Asmaini et al. 2023). The local community also cultivates fruit-bearing trees, including durian (*Durio zibethinus* L.), jackfruit (*Artocarpus heterophyllus* Lam.), mango (*Mangifera indica* L.), and avocado (*Persea americana* Mill.), primarily for fruit production. This practice has led to increased tree diversity within the research site. According to Table 2, the most abundant tree species in Plumbon Village was mahogany (*Swietenia mahagoni* (L.) Jacq), with 90 recorded individuals, while the least common species—*Alstonia scholaris* (L.) R.Br. (*pulai* tree), *Syzygium myrtifolium* Walp. (*pucuk merah* tree), *Terminalia catappa* L. (*ketapang* tree), and *Carica papaya* L. (*papaya* tree)—had only one individual each. In Nglebak Village, pine (*Pinus merkusii* Jungh. & de Vriese) was the dominant species, with 168 individuals, whereas *Alstonia scholaris* (L.) R.Br.

(pulai tree) and *Leucaena leucocephala* (Lam.) de Wit (*Petai cina* tree) were the least common, each represented by a single individual. In Sepanjang Village, the most frequently encountered species was *Toona sureni* (Blume) Merr. (Suren tree), with 47 individuals, while the least abundant species—*Breynia androgyna* (L.) Chakrab. & N.P.Balakr. (*katuk* tree), *Persea americana* Mill. (avocado tree), *Alstonia scholaris* (L.) R.Br. (*pulai* tree), *Mangifera foetida* Lour. (*pakel* tree), and *Mangifera indica* L. (mango tree)—each had only one recorded individual. Mahogany and pine trees dominate the area due to their adaptability to colder climates and high rainfall conditions, making them suitable for widespread cultivation. These species are frequently incorporated into agroforestry systems as shade trees. In contrast, less dominant tree species are mainly found in community gardens, where tree diversity is higher compared to monoculture plantations.

Tree diversity in Plumbon Village and Sepanjang Village exhibits relatively similar Shannon-Wiener diversity index values. However, Nglebak Village has a significantly lower diversity index compared to the other two locations. The species diversity in all three areas falls within the moderate diversity category, with values in the range of $1 < H' < 3$. Sepanjang Village recorded the highest species diversity with an H' value of 2.456, followed by Plumbon Village at 2.147, while Nglebak Village had the

lowest diversity at 1.278. A higher number of species in an area generally corresponds to greater species diversity (Setiarno et al. 2020). Sepanjang Village contained 21 plant species, Plumbon Village had 20 species, and Nglebak Village had the least, with 13 species. Species diversity is influenced by plant distribution patterns and the adaptability of species within an area (Sari and Mukti 2019). The moderate species diversity observed across the three research locations suggests sufficient productivity (Amarullah et al. 2017) and indicates that the ecosystem remains relatively stable with moderate ecological pressure (Prastiyo et al. 2019). Additionally, environmental factors such as light availability, soil pH, temperature, and pollution levels also influence plant diversity in the study area (Sihombing et al. 2024). Generally, a higher diversity index corresponds to greater stability within the tree community. However, high species diversity does not necessarily correlate with increased carbon storage potential (Ananda and Sutrisno 2022). This is because carbon sequestration values are not directly influenced by vegetation diversity (Salina 2019).

Diversity index (H') in the community forest area

The calculation of tree diversity shows different results in each research location (Table 3).

Table 2. Composition of tree vegetation in the forest area of Plumbon, Nglebak, and Sepanjang Villages, Tawangmangu, Karanganyar, Indonesia

Scientific name	Local name	Family	Amount of vegetation		
			Plumbon	Nglebak	Sepanjang
<i>Pinus merkusii</i> Jungh. & de Vriese	<i>Pinus</i>	Pinaceae	11	168	13
<i>Swietenia mahagoni</i> (L.) Jacq.	<i>Mahoni</i>	Meliaceae	90	17	0
<i>Toona sureni</i> (Blume) Merr.	<i>Suren</i>	Meliaceae	46	15	47
<i>Durio zibethinus</i> L.	<i>Durian</i>	Malvaceae	3	7	9
<i>Acacia decurrens</i> (J.C.Wendl.) Willd.	<i>Akasia Gunung</i>	Fabaceae	0	5	0
<i>Artocarpus heterophyllus</i> Lam.	<i>Nangka</i>	Moraceae	8	2	10
<i>Tectona grandis</i> L.f.	<i>Jati</i>	Lamiaceae	11	0	12
<i>Cocos nucifera</i> L.	<i>Kelapa</i>	Arecaceae	3	3	5
<i>Acer laurinum</i> Hassk.	<i>Huru bodas</i>	Sapindaceae	6	0	10
<i>Mangifera indica</i> L.	<i>Mangga</i>	Anacardiaceae	3	0	1
<i>Carica papaya</i> L.	<i>Pepaya</i>	Caricaceae	1	0	0
<i>Hibiscus tiliaceus</i> L.	<i>Waru</i>	Malvaceae	7	3	32
<i>Terminalia catappa</i> L.	<i>Ketapang</i>	Combretaceae	1	0	10
<i>Mangifera foetida</i> Lour.	<i>Pakel</i>	Anacardiaceae	0	0	1
<i>Syzygium myrtifolium</i> Walp.	<i>Pucuk merah</i>	Myrtaceae	1	2	2
<i>Gmelina arborea</i> Roxb. ex Sm.	<i>Jati putih</i>	Lamiaceae	3	0	0
<i>Parkia speciosa</i> Hassk.	<i>Petai</i>	Fabaceae	9	0	40
<i>Gnetum gnemon</i> L.	<i>Melinjo</i>	Gnetaceae	2	0	0
<i>Myristica magnifica</i> Bedd.	<i>Pala hutan</i>	Myristicaceae	27	0	3
<i>Dalbergia latifolia</i> Roxb.	<i>Sonokeling</i>	Fabaceae	2	0	0
<i>Alstonia scholaris</i> (L.) R.Br.	<i>Pulai</i>	Apocynaceae	1	1	1
<i>Schima wallichii</i> (DC.) Korth.	<i>Puspa</i>	Theaceae	0	15	0
<i>Leucaena leucocephala</i> (Lam.) de Wit	<i>Petai cina</i>	Fabaceae	0	1	0
<i>Acacia mangium</i> Willd.	<i>Akasia</i>	Fabaceae	58	5	0
<i>Breynia androgyna</i> (L.) Chakrab. & N.P.Balakr.	<i>Katuk</i>	Phyllanthaceae	0	0	1
<i>Persea americana</i> Mill.	<i>Alpukat</i>	Lauraceae	0	0	1
<i>Syzygium aromaticum</i> (L.) Merr. & L.M.Perry	<i>Cengkeh</i>	Myrtaceae	0	0	16
<i>Archidendron pauciflorum</i> (Benth.) I.C.Nielsen	<i>Jengkol</i>	Fabaceae	0	0	2
<i>Artocarpus camansi</i> Blanco	<i>Kluwih</i>	Moraceae	0	0	2
<i>Syzygium jambos</i> (L.) Alston	<i>Jambu mawar</i>	Myrtaceae	0	0	6

Table 3. The results of the calculation of the Shannon-Wiener diversity index (H')

Location	Diversity index value (H')	Description
Plumbon Village	2.147456643	Medium
Nglebak Village	1.278676037	Medium
Sepanjang Village	2.456086473	Medium

Table 4. The result of biomass calculation

Location	Biomass value (kg)	Biomass per unit area (kg/ha)
Plumbon Village	212844.91	462.81
Nglebak Village	221541.01	807.28
Sepanjang Village	83768.67	145.13

Table 5. The results of the calculation of the carbon stock value

Location	Carbon storage (kg/ha)
Plumbon Village	212.8926
Nglebak Village	371.3488
Sepanjang Village	66.7598

Biomass estimation in the community forest area

Based on the biomass calculations presented in Table 4, Nglebak Village exhibited the highest total biomass, amounting to 221,541.01 kg. The biomass per unit area in Nglebak Village was 807.28 kg/ha, nearly double that of Plumbon Village, despite the total biomass values not differing significantly. This indicates that Plumbon Village has a larger overall area than Nglebak Village. Conversely, the lowest biomass and biomass per unit area were recorded in Sepanjang Village, where the number of trees per plot was lower than in the other villages. Additionally, Sepanjang Village exhibited greater plant species diversity within plots, as evidenced by Table 3, which shows the highest diversity index among the three villages. Tree diameter is a key factor influencing biomass values, with larger diameters corresponding to higher biomass. The average tree diameters in the study locations were 28.02 cm in Plumbon Village, 20.85 cm in Nglebak Village, and 24.6 cm in Sepanjang Village. Biomass is defined as the total mass of living organisms within a given area or species, typically expressed in dry weight and encompassing both above- and below-ground biomass (Konstantinavičienė and Vitunskienė 2023). In the context of trees, biomass includes the dry weight of wood, leaves, and roots. The greater the biomass of a tree, the higher its carbon storage potential (Darmawan et al. 2022). Thus, biomass directly influences a tree's capacity for carbon sequestration. Biomass per unit area represents the amount of biomass contained within a one-hectare area and is calculated by dividing the total biomass by the total area of the study site (Danarto 2020). The study sites covered the following

areas: Plumbon Village (459.9 ha), Nglebak Village (274.43 ha), and Sepanjang Village (577.21 ha).

Estimation of carbon storage potential in the community forest area

Based on the calculation of the carbon storage across the three research locations, presented in Table 5, Nglebak Village had the highest carbon storage value, while Sepanjang Village had the lowest carbon storage value. The carbon storage in Nglebak Village was 371.35 kg/ha, followed by Plumbon Village with 212.89 kg/ha, and Sepanjang Village with 66.76 kg/ha. These differences in carbon storage values correspond to variations in biomass per unit area among the three villages. Since Nglebak Village exhibited the highest biomass per unit area, its carbon storage value was also the highest. Conversely, Sepanjang Village had the lowest carbon storage value due to its lower biomass per unit area. Carbon storage represents the absolute amount of carbon contained in plant biomass (Roziaty and Suparti 2022). The amount of carbon stored in an area is influenced by multiple factors, including plant species diversity, land cover density, plant height, soil type, tree diameter, and effective land management (Karuru et al. 2021). Differences in carbon storage values among the three locations can be attributed to variations in these factors, which impact the extent of carbon uptake by different plant species. Carbon sequestration within plant biomass plays an important role in mitigating atmospheric carbon levels, thereby contributing to air regulation and pollution reduction. Furthermore, carbon storage in plants serves as an ecological indicator of ecosystem stability and functionality. In addition to its environmental benefits, stored carbon also acts as an energy reserve for trees, supporting their growth and physiological processes.

Based on the research and data analysis conducted, it was determined that across 20 plots in each village, a total of 30 species from 18 different families were recorded, with the Fabaceae family being the most dominant. The Shannon-Wiener diversity index (H') values for each village were 2.147 in Plumbon Village, 1.278 in Nglebak Village, and 2.456 in Sepanjang Village. These values indicate moderate species diversity, signifying sufficient productivity and a relatively stable ecosystem. The biomass values, calculated based on tree diameter measurements, were 462.81 kg/ha in Plumbon Village, 807.28 kg/ha in Nglebak Village, and 145.13 kg/ha in Sepanjang Village. Correspondingly, the carbon stock values were 212,892 kg in Plumbon Village, 371,348 kg in Nglebak Village, and 66,759 kg in Sepanjang Village. The data indicate a positive correlation between biomass and carbon stock values. However, no significant correlation was observed between species diversity (H') and carbon stock. The variations in carbon storage across the three locations may be attributed to differences in vegetation cover and density in each village. These findings highlight the influence of structural forest attributes on carbon sequestration potential, emphasizing the importance of biomass accumulation in determining carbon storage capacity.

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