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Full Length Research Article

Estimating Vegetation Density Dynamics, Tree Diversity, and Carbon Stock in the Agroforestry System of the Community Forest in Bogor Regency, Indonesia

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ABSTRACT

Mitigation actions to address climate change are essential to prevent future adverse impacts, with woody species in forests playing a pivotal role in carbon storage, as exemplified by the agroforestry systems commonly practiced in community forests of Bogor Regency, which integrate woody species and crops. This study aimed to analyze changes in vegetation density using the Normalized Difference Vegetation Index (NDVI) approach, analyze stand structure and composition, and estimate above-ground carbon stocks in the agroforestry land of community forest in Tenjolaya Sub-District, Bogor Regency. The methods used were spatial analysis with NDVI, vegetation analysis, and carbon stock estimation using allometric and destructive methods. The plot size was 50 m × 50 m, totaling 21 plots. NDVI analysis resulted in low density (0.59–0.67), moderate density (0.67–0.78), and high density (0.78–0.85). This study found 178 plant species across 40 families, with Fabaceae and Myrtaceae being the most dominant. The carbon stock is 27.69 tons carbon/ha. Carbon stock is significantly influenced by tree density, number of species, and basal area values. A well-managed community forest has high ecological, economic, and social potential through the development of agroforestry, which can maintain biodiversity and environmental sustainability while storing carbon stocks.

1. Introduction

Climate change is indicated by broad, long-term patterns in temperature, precipitation, and other factors, such as pressure and humidity in the environment (Abbass et al. 2022; Heriyanto et al. 2023). It presents a complex, global, inter-governmental challenge, affecting the environmental, ecological, socio-economic, and socio-political systems (Baldos et al. 2023; Feliciano et al. 2022; Filho et al. 2021). Climate change shows rising temperatures in various regions globally (Schuurmans 2021; Uyttendaele et al. 2015; Wu et al. 2016; Yadav et al. 2015). Preventing the effects of climate change can be achieved by reducing emissions and increasing carbon stock.

As stated in the Enhanced Nationally Determined Contribution (ENDC) document, Indonesia aims to cut greenhouse gas (GHG) emissions by 31.89% and by 43.20% with international support to prevent a global temperature increase of 2°C and to limit it to 1.5°C (UNFCCC 2022). The forest and other land use (FOLU) sector is essential in efforts to reduce emissions in Indonesia. Aside from being a store of carbon stocks, forests also act as a giant carbon sink. Forests can store at least ten times more than other vegetation types (van der Sande et al. 2017). Agroforestry is an optimal and sustainable land management system that combines forestry (woody) and crops (Hartoyo et al. 2022). It can be practiced through various methods, such as windbreaks or shelterbelts (arranging trees to shield crops from wind), alley cropping (growing crops between spaced tree rows), forest farming (cultivating shade-tolerant crops within natural forest stands), and silvopastoral management (growing grasses under trees for livestock feed) (Moreno and Rolo 2019; Mudge 2019; Wyatt et al. 2019; Zamora et al. 2019). Agroforestry practices consider the community's environmental, physical, social, economic, and cultural aspects (Mukhlis et al. 2022). By addressing these factors, agroforestry can alleviate pressure and reduce forest disturbances, such as clearing forest land. Regarding carbon stocks, land-using agroforestry systems are more profitable than monoculture and seasonal crop-based agriculture. Trees with high biomass and litter vary and occur continuously (Hartoyo et al. 2019; Hartoyo et al. 2022).

Bogor Regency has an enormous forest potential of 28,351.4 ha spread across nine sub-watersheds, which are administratively located in 40 sub-districts in Bogor Regency. Tenjolaya, Ciawi, Cigudeg, Pamijahan, Rumpin, Jasinga, and Cisarua Sub-Districts have a community forest area percentage of 10–19% (Safe'i and Sukmara 2019). In this paper, community forest is defined as forests on private lands or outside of state forest areas. Community forests greatly contribute to the economic well-being of local communities. Regarding management, these forests are overseen by the local community without government intervention. Community forest utilization can be done in various ways, such as monoculture and agroforestry systems (Ramli et al. 2021; Sulistiyowati et al. 2023). Community forests serve multiple purposes to enhance economic and food security, such as timber and fruit production and other non-timber forest products. Agroforestry has been implemented in various regions of Indonesia.

The agroforestry system entails a combination of forestry and agricultural practices that directly benefit the community (Arafah and Hidrawati 2022). The local community in the Tenjolaya Sub-District, West Java, has implemented the agroforestry system in community forests. However, database-related information on the potential of agroforestry, especially in terms of tree diversity and carbon stock, is necessary.

Additionally, there is a need to monitor changes in vegetation density, stand structure, and composition to understand better the dynamics of agroforestry systems and their contribution to ecosystem services. Monitoring these aspects provides essential insights for decision-making in community forest management. Remote sensing through the Normalized Difference Vegetation Index (NDVI) can be utilized to monitor and assess forests. NDVI is the simplest and most commonly used objective measure of vegetation density, frequently employed to determine greenness exposure in urban environments and forested areas for environmental health studies (Gascon et al. 2016; Jimenez et al. 2022; Reid et al. 2018; Rugel et al. 2017).

Based on this background, this study aimed to analyze changes in vegetation density using the NDVI approach, evaluate stand structure and composition, and estimate above-ground carbon stocks in the agroforestry of community forest in Tenjolaya Sub-District, Bogor Regency. These objectives aim to comprehensively understand agroforestry's ecological and carbon sequestration potential to inform sustainable forest management practices.

2. Materials and Methods

2.1. Research Location

The study was carried out in the community forest in Situ Daun Village, Tenjolaya Sub-District, Bogor Regency, West Java, Indonesia. The study was conducted between July and September 2023. Tenjolaya District has an area of 4,126.99 ha consisting of 7 villages, namely Tapos I, Tapos II, Gunung Malang, Cinangneng, Central Cibitung, Gunung Mulya, and Situ Daun. The community forest for the research location is 450 meters above sea level and has an area of 16 ha. Several forest areas apply an agroforestry system in their land use. Some agricultural commodities in the research location are cassava (*Manihot esculenta*), cucumber (*Cucumis sativus*), long beans (*Vigna cylindrica*), taro (*Colocasia esculenta*), and *leunca* (*Solanum nigrum*). A map of research locations is presented in **Fig. 1**.

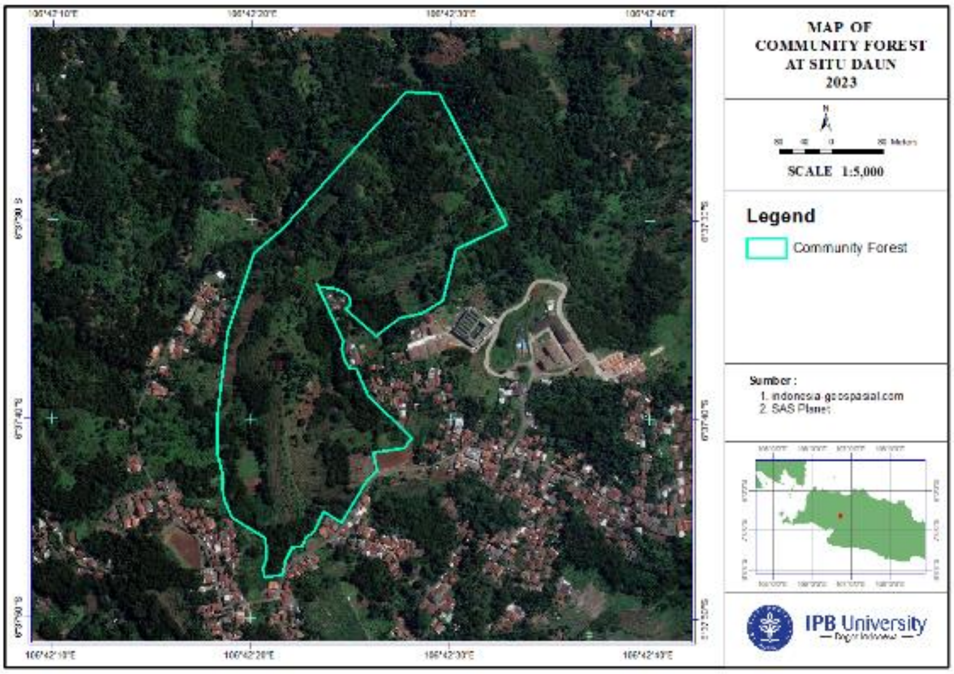

Fig. 1. The map of research locations at the community forest in Situ Daun Village.

Situ Daun Village, Tenjolaya Subdistrict, Bogor, has a wet tropical climate characterized by varying temperatures, humidity and rainfall throughout the year (**Table 1**). Over the last ten years (2012–2022), the average daily temperature was recorded at 24.83°C with an average relative humidity of 85.40%. Average annual rainfall reached 2,534.59 mm, with an average daily rainfall intensity of 6.68 mm/day. Based on the Schmidt and Ferguson climate classification, the study site belongs to the "Very Wet" climate type, with 9 wet months and 1 dry month. Meanwhile, according to the Oldeman classification, the site has climate type C3, characterized by 5 wet and 4 dry months (**Table 2**). This combination of temperature, humidity, and rainfall suggests that the study area has favorable environmental conditions for forest and agroforestry management.

Table 1. The average temperature, humidity, and rainfall at the research site

Year*	Temperature (%/day)	Humidity (%/day)	Rainfall (mm/year)	Rainfall (mm/day)
2012	24.69	83.44	1,761.33	5.27
2013	24.68	86.19	2,784.38	5.27
2014	24.74	85.81	2,816.02	5.27
2015	24.83	83.25	2,061.91	5.27
2016	25.02	87.31	3,042.77	10.55
2017	24.71	86.25	2,641.99	5.27
2018	24.86	83.69	2,067.19	5.27
2019	25.20	81.88	2,083.01	5.27
2020	25.02	86.94	2,984.77	10.55
2021	24.73	87.25	3,034.84	8.31
2022	24.68	87.38	2,602.33	7.14
Average	24.83	85.40	2,534.59	6.68

Note: *the data was obtained from the POWER Project's Hourly 2.4.3 version on 18 December 2024.

Table 2. Climate classification at the research site for 10 years

Climate classification	Total wet months*	Total dry months*	Total humid months*	Climate type
Schmidt and Ferguson	9	1	2	Very Wet
Oldeman	5	4	-	C3

Note: *the data was obtained from the POWER Project's Hourly 2.4.3 version on 18 December 2024.

The soil characteristics at the study site show the dominance of the clay fraction with a value of 50.59%, followed by the dust (29.91%) and sand (19.50%) fractions (**Table 3**). Based on this proportion, the soil texture at the study site is classified as clay. Clay soils have a high water and nutrient retention capacity, thus supporting optimal vegetation growth, including in agroforestry systems. This condition is important to carbon stock estimation, as soil structure and texture influence the ecosystem's carbon sequestration and biological activity.

Table 3. Soil fraction and texture at the research site (Poggio et al. 2021)

Soil Fraction	Value	Soil Texture
Clay	50.59	
Silt	29.91	Clay
Sand	19.50	

2.2. Procedures

2.2.1. Normalized Difference Vegetation Index (NDVI) at the Community Forest in Situ Daun Village

This study used spatial analysis to estimate vegetation density in the community forest in Situ Daun Village. The images used in this study were surface reflectance base maps downloaded from the Planet website (https://www.planet.com/). The chosen image for processing is the image in May 2023. Furthermore, the image was analyzed using NDVI and ArcMap 10.8 software; the bands used for processing were band 4 (NIR) and band 3 (Red). The main steps of image processing using ArcMap 10.8 were (i) Image input, (ii) Image pre-processing including clipping and compositing bands, (iii) Classifying NDVI in the Area of Interest into three density levels using natural breaks (Jenks), namely low density, medium density, and high density, and (iv) Perform plot distribution. Natural breaks or jenks optimization is a classification method for categorizing data based on inherent groupings. The Jenks method minimizes the variance within classes while maximizing the variance between classes. This results in class boundaries determined by significant differences in the data values, making it effective for datasets with uneven distributions. Classification values are generated by natural breaks/jenks optimization, so the values depend on the data used (Chen et al. 2013).

Sampling was conducted using a stratified random sampling method. 21 sample plots were distributed across the study area, with 7 plots at each density level. For comparison, images from 2013 were utilized to assess changes in land cover within the study area. The NDVI value was calculated using the following Equation 1:

$$NDVI = \frac{(NIR-RED)}{(NIR+RED)} \quad (1)$$

where *NDVI* is the Normalized Difference Vegetation Index, *NIR* is the Near Infrared band, and *RED* is the Red band.

This study categorized vegetation density into three classes: low, moderate, and high (**Table 4**).

Table 4. NDVI classification using natural breaks (Jenks)

NDVI Class	NDVI Value
Low density	0.593645632–0.67307135
Moderate density	0.67307135–0.78029607
High density	0.78029607–0.846815109

2.2.2. Plot establishment

Vegetation analysis was carried out in several stages. The first stage was establishing the sample plots. The sample plot used in this study was 50 m × 50 m with three sub-plots. The 50 m × 50 m plot was used to plot the vegetation at the tree level, the 25 m × 25 m sub-plot was used to plot the vegetation at the pole level, the 12.5 m × 12.5 m sub-plot was used to observe the saplings, and the plots of 6 m × 6 m were used to observe seedlings and understorey plants. The plot used in the study is shown in **Fig. 2**.

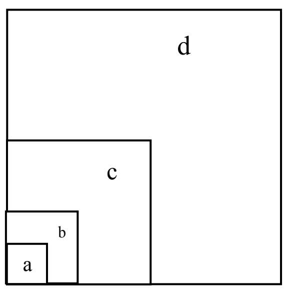

Fig. 2. Sampling plot design: (a) 6 m × 6 m, (b) 12.5 m × 12.5 m, (c) 25 m × 25 m, and (d) 50 m × 50 m.

2.2.3. Tree species diversity

The study measured vegetation structure and composition across various growth levels, including trees, poles, saplings, seedlings, and understorey. Seedlings represent the initial germination phase and have a height of fewer than 1.5 meters, while saplings are taller (≥ 1.5 m) but have a diameter below 10 cm. The pole represents the growth stage of a tree with a diameter ranging from 10 cm to 20 cm. Conversely, trees are characterized by a diameter of 20 cm or more (Heriyanto et al. 2020). Data on tree performance, including total height, branch-free height, and diameter at breast height (DBH), were collected for saplings, poles, and mature trees. Meanwhile, information on species composition and abundance was recorded for the understorey and seedlings.

2.2.4. Carbon stock estimation

Carbon stock assessments were carried out using destructive and non-destructive methods. The destructive approach measured carbon stocks in understorey, seedlings, and litter. For understorey and seedlings, harvesting occurred within 2 m × 2 m subplots, excluding root material. The harvested understorey and seedlings within the subplot were weighed in the field to determine the total wet weight (BBt). Subsequently, a 300-gram sample was extracted from the total wet weight to obtain the wet weight of the sample (BBc). The same procedure was applied to assess the litter carbon pool. Samples were processed using an oven at 105 °C for 24 hours for litter and 48 hours for understorey and seedlings to obtain the dry weight of the sample (BKc). To calculate the total dry weight (BKt), divide the dry weight of the sample by its wet weight and then multiply by the wet weight (BSN 2019).

The allometric method or non-destructive method was employed to estimate carbon stocks for saplings, poles, and mature trees. The diameter and height measurements were calculated using the allometric equation to estimate biomass and carbon stock (BSN 2019). In addition, the biomass estimation uses the allometric formula, which requires species information carried out through the ICRAF Database.

2.3. Data Analysis

2.3.1. Importance value index (IVI)

IVI values are essential at each growth stage to determine vegetation composition. The importance value index (IVI) is a quantitative metric used to assess the overall significance of each species within the community structure (Ismail et al. 2017). A higher IVI value indicates greater species contribution in each area. IVI values at the pole and tree levels can be calculated by summing the relative density (RD), relative frequency (RF), and relative dominance (RDo). Calculating IVI by adding RD and RF for understorey, seedlings, and saplings is acceptable. The values of RF, RD, and RDo were derived using Equations 2–9:

$$Density = \frac{Total\ number\ of\ individuals}{Plot\ size} \tag{2}$$

$$Relative\ Density\ (RD) = \frac{Number\ of\ individuals\ of\ the\ species}{Number\ of\ individuals\ of\ all\ species} \times 100 \tag{3}$$

$$Frequency\ (F) = \frac{Number\ of\ plot\ where\ species\ found}{Total\ plot\ size} \quad (4)$$

$$Relative\ Frequency\ (RF) = \frac{Number\ of\ occurence\ of\ the\ species}{Number\ of\ occurence\ of\ all\ species} \times 100 \quad (5)$$

$$Dominance\ (Dm) = \frac{Total\ basal\ area\ of\ the\ species}{Total\ plot\ size} \quad (6)$$

$$Relative\ Dominance\ (RDo) = \frac{Total\ basal\ area\ of\ the\ species}{Total\ basal\ area\ of\ all\ species} \times 100 \quad (7)$$

$$IVI\ (\%) = RD + RF\ (For\ understorey,\ seedlings\ and\ saplings) \quad (8)$$

$$IVI\ (\%) = RD + RF + RDo\ (For\ pole\ and\ tree) \quad (9)$$

2.3.2. Species diversity index (H')

Vegetation analysis data were processed to obtain the species diversity index (H'), species richness index (R), species dominance index (C), and species evenness index (E). The H' value indicates the level of species diversity in an area. There are three categories of the diversity index: high species diversity (H' > 3), medium diversity (1 ≤ H' ≤ 3), and low diversity (H' < 1), as described in Equation 10 (Ontoy and Padua 2014).

$$H' = -\sum_{i=1}^{n} pi\ ln\ pi \quad (10)$$

where *H'*and species diversity index, *pi* is ni/N, *ni* is the total number of individuals of type-i, and *n* is the total number of individuals of all types.

2.3.3. Species dominance index (I)

$$C = \sum \left(\frac{ni}{N}\right)^2 \quad (11)$$

where *C* is the species dominance index, *ni* is the number of individuals per species, and *N* is the number of individuals of all species.

2.3.4. Species richness index (R)

$$R = \frac{(S-1)}{ln(N)} \quad (12)$$

where *R* is the species richness index, *S* is the number of types found, and *N* is the total number of individuals encountered.

2.3.5. Species evenness index (E)

$$E = \frac{H'}{H_{max}} \quad (13)$$

where E is species evenness index, and H_{max} is ln S.

2.3.6. Tree biomass measurement

Standing biomass measurements were conducted using the allometric method. This method involves assessing plant growth through exponential or logarithmic relationships between plant organs that change proportionally and harmoniously (Wirabuana et al. 2020). The allometric model used in this study is presented in **Table 5**.

Table 5. Allometric model

Type of forest	Species	Allometric model	Source
Plantation forest	*Pinus merkusii*	$BBA = 0.0936*D^{2.4323}$	Krisnawati et al. (2012)
Plantation forest	*Paraserianthes falcataria*	$BBA = 0.1126*D^{2.3445}$	Krisnawati et al. (2012)
Plantation forest	*Tectona grandis*	$W = 0.370*D^{2.125}$	Krisnawati et al. (2012)
Moist stand forest	Mixed species	$AGB = BJ*\exp(-1.499+2.148*\ln(D)+0.207(\ln(D))^2 -0.0281(\ln(D))^3)$	Chave et al. (2005)

2.3.7. Measurement of understory, seedling and litter biomass

Destructive methods were used to obtain the undergrowth, seedlings, and litter carbon pool biomass. The data of total wet weight (BBt), sample wet weight (BBc), and sample dry weight (BKc) were entered into a formula to obtain the total dry weight. The formula in Equation 14 is as follows (BSN 2019):

$$BKt = \frac{BKc}{BBc} \times BBt \tag{14}$$

where BKt is the total dry weight (g), BBc is the wet weight of the sample (g), BKc is the dry weight of the sample (g), and BBt is the total wet weight (g).

2.3.8. Carbon formulas

The biomass value was multiplied by 0.47 to estimate the carbon stock value. This conversion factor, derived from the carbon concentration in organic material (47%), is used to convert biomass to carbon stock (BSN 2019). The formula is given in Equation 15:

$$C = B \times 0.47 \tag{15}$$

where C is carbon stock (ton C/ha), and B is biomass (ton/ha).

2.3.9. Normality and heteroscedasticity test

A normality test is required to perform statistical correlation analysis to assess the data distribution. The normality test can determine whether the correlation model's residuals follow a normal distribution. In this study, the Kolmogorov-Smirnov test was employed to check normality. Data are normally distributed if the significance value is more than 5% (Sig > 0.05) and not normally distributed if the significance value is less than 5% (Sig < 0.05).

2.3.10. Correlation test

The Pearson correlation test examined the relationship between NDVI and various parameters, including the number of species, tree density, Shannon-Wiener index, basal area, and carbon concentration. The correlation value indicates the linear relationship between two variables (Baniya et al. 2018). A non-zero value signifies the presence of a relationship. The correlation coefficient ranges from -1 to 1.

3. Results and Discussion

3.1. Vegetation Cover Using the Normalized Difference Vegetation Index (NDVI) at the Community Forest in Situ Daun Village

Situ Daun is a village in Tenjolaya District, Bogor Regency, West Java. The community forest in Situ Daun Village has an area of 16 ha, with several areas implementing an agroforestry system. Several efforts to implement an agroforestry system have been carried out in community forests located in Situ Daun Village, one of which was planted by the local community. Monitoring is essential to assess plantation outcomes. One effective method is to analyze vegetation density using the Normalized Difference Vegetation Index (NDVI). The NDVI calculates vegetation greenness from satellite image indices, measuring vegetation's relative abundance and spatial distribution within a value range of -1 to 1 (Gascon et al. 2016; Labib et al. 2020).

Based on classification results using Landsat 8 imagery, the high-density class has the most significant area compared to the other two density levels in 2023, 10.82 ha or 70.20% of the total area. After that, it is followed by moderate (17.73%) and low (4.03%) density classes. Changes in each density class can be seen when comparing the NDVI results in 2013 and 2023. The area of the high-density class has increased from the previous 1.34 to 10.82 ha (**Table 6**). Meanwhile, the area of the other two density classes experienced a decrease. In 2013, the low and moderate-density classes had an area of 2.82 ha and 11.44 ha, while in 2023, the area of the low-density class will be 0.23 ha, and the moderate-density class will be 4.36 ha (**Fig. 3**). These changes could be one of the indications of the impact of planting carried out in community forest areas.

Table 6. Change of vegetation cover area

Density	Area according to year (ha)	
	2013	2023
Low density	2.82	0.23
Moderate density	11.44	4.36
High density	1.34	10.82

The community forest studied in Situ Daun Village is managed by the forest farmer group "Tunas Lestari". Information obtained from the head of the farmer group stated that woody plant species are routinely planted every year to restore the landscape of Situ Daun Village. In addition 2018, agroforestry land development with an area of ± 7 ha was also carried out by the forest farmer group with assistance from the West Java Provincial Forestry Service. These things allow for changes in vegetation cover, where high vegetation density increased over 10 years while medium and low vegetation density decreased (Ivetic et al. 2021) (**Fig. 4**).

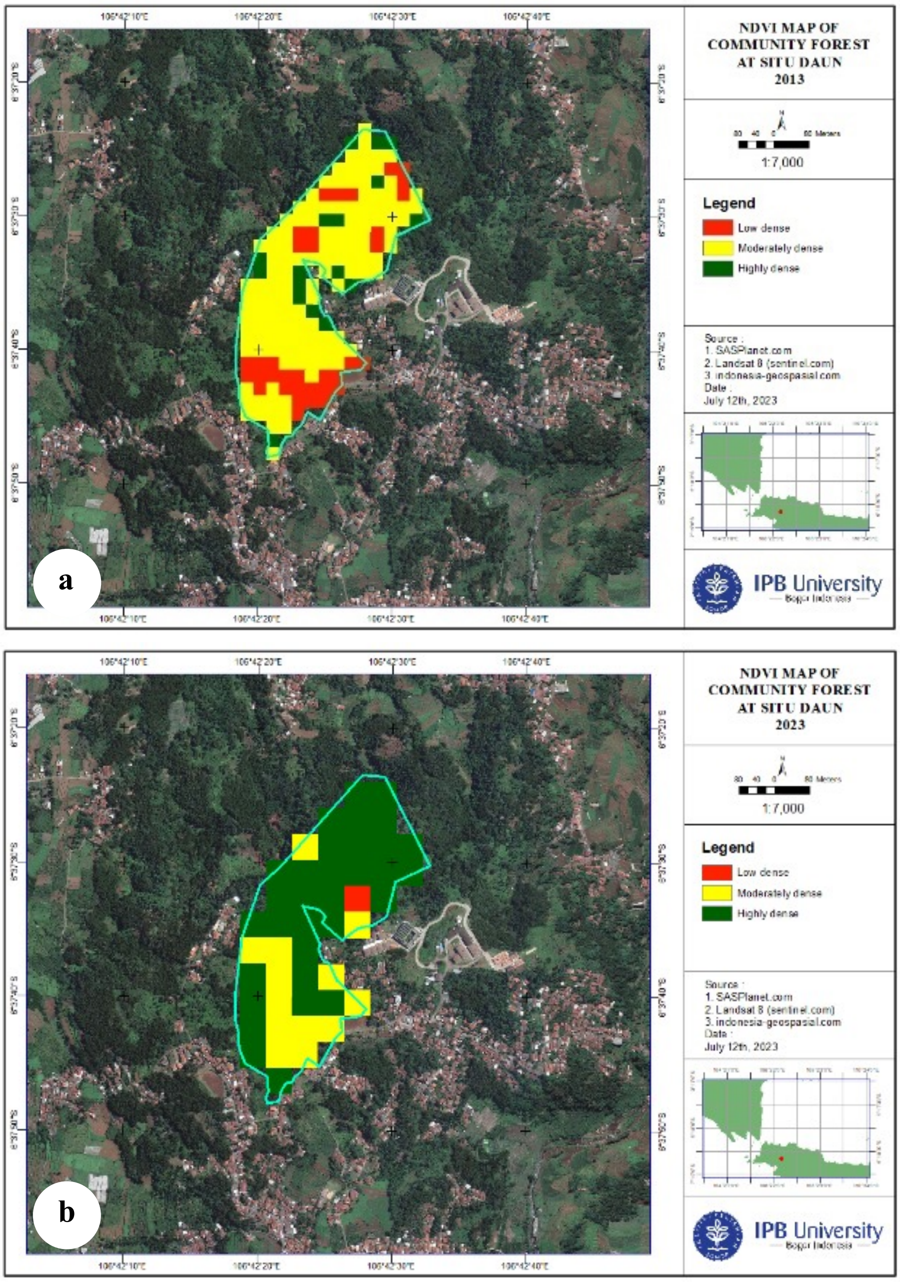

Fig. 3. NDVI map of community forest at Situ Daun Village in (a) 2013 and (b) 2023.

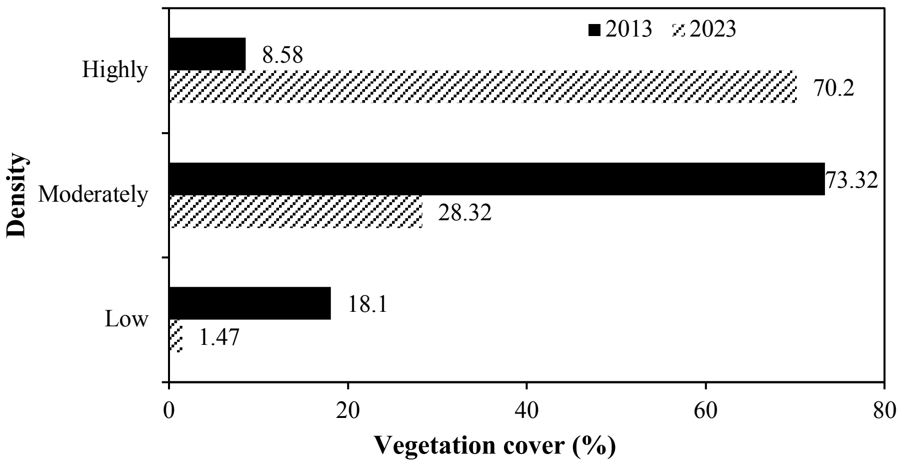

Fig. 4. Percentage of vegetation cover at community forest in Situ Daun Village.

3.2. Vegetation Composition

Vegetation analysis across 21 plots revealed the species composition and abundance at the research site. A total of 178 plant species from 40 families were identified. The low-density area had the highest species count, with 69 species, while the high-density area had the lowest, with 53 species. *Pinus merkusii* was the most abundant species, with 260 individuals for 21 sampling plots. The most represented families were Fabaceae with five species, and Myrtaceae with six species. The species count is detailed in **Table 7**.

Table 7. Species found at community forest

Growth level	Density (individuals)		
	Low	Moderate	High
Tree	11	12	11
Pole	8	7	10
Sapling	12	9	14
Seedling	3	5	4
Understorey	48	35	29
Total in each class	69	56	53
Total		178	

Across different density levels, the number of understory plant species consistently outnumbers those at other growth stages. At the low-density level, the diversity peaks with 48 understory species. The higher number of understory species at low vegetation density levels is due to the greater sunlight reaching the forest floor. Plants growing under the shade/canopy of other plants are strongly influenced by the canopy size of taller plants and the canopy density of high-density stands (Triatmojo et al. 2024). These things can cause less sunlight to be received by lower/shaded plants. Furthermore, light is an important environmental factor as an energy source, and its availability is strongly related to understory species richness (Dormann et al. 2020). This result is consistent with the number of understory species at the medium vegetation density level, lower than the low-density level, and the number of understory species at the high-density level, lower than the medium and low-density levels (**Table 7**).

This variation in species richness is linked to the Importance Value Index (IVI), which gauges a species' role, dominance, and overall significance in its ecosystem (Jadhav 2021). The IVI is a reflection of a species' ecological importance: a higher IVI underscores its pivotal role within the ecosystem. **Tables 8-10** present detailed IVI values for each density class.

Table 8 shows three types of plants with the largest IVI values at each growth level at high density. A higher IVI value reflects an increase in species significance within an area. The IVI reveals the structural importance of species within an ecosystem (Abunie and Dalle 2018); thus, species with elevated IVI values are considered more crucial than those with lower values (Maua et al. 2020).

A high IVI indicates dominance and ecological success (Jadhav 2021). IVI results at the high-density level showed varying values ranging from 12.68% for the lowest to 84.58% for the highest IVI value. These values indicate that no plant species has a dominant influence at the high-density level. Although pine has the highest IVI value (84.58%), it is not yet a dominant species, but rather a species that has an important role in the ecosystem but shares its ecological space with other species such as Kecapi, Cengkih, and Harendong Gede (Sambou et al. 2022). Another interesting result is that Harendong Gede (*B. axinanthera*) has high IVI values at the pole, sapling and seedling levels, but not at the tree level. This can be caused by *B. axinanthera* seedlings adapting better to the environment, including sunlight, water, soil conditions, nutrients, and so on (Ismail et al. 2021). Solfiyeni et al. (2023) reported that *B. axinanthera* is an invasive alien species that grows quickly but reduces the diversity and number of other species in the environment. *B. axinanthera* can form a monodominant canopy that prevents other species from growing and has allelopathic substances such as flavonoids that inhibit the growth of other seedlings (Dillis et al. 2017; Solfiyeni et al. 2023). If the dominance of *B. axinanthera* is not controlled, its aggressive growth could lead to monocultures that significantly alter the structure and composition of plant communities.

Table 8. Importance value index (IVI) at high density

Growth level	Local name	Scientific name	IVI (%)
Understorey	Rumput Jari	*Digitaria sanguinalis*	40.45
	Kancing Palsu	*Spermacoce remota*	16.19
	Pakis Merak	*Selaginella willdenowii*	12.68
Seedling	Kecapi	*Sandoricum koetjape*	67.11
	Harendong Gede	*Bellucia axinanthera*	46.05
	Singalawang	*Petiveria alliacea*	46.05
Sapling	Harendong Gede	*Bellucia axinanthera*	55.56
	Petai	*Parkia speciosa*	22.22
	Jengkol	*Archidendron pauciflorum*	18.52
Pole	Harendong Gede	*Bellucia axinanthera*	58.77
	Cengkih	*Syzygium aromaticum*	54.24
	Kecapi	*Sandoricum koetjape*	51.97
Tree	Pinus	*Pinus merkusii*	84.58
	Cengkih	*Syzygium aromaticum*	58.85
	Mahoni	*Swietenia macrophylla*	42.65

Table 9 shows the undergrowth IVI values and each medium-density class growth level. At the pole and tree growth stages, Pine (*Pinus merkusii*) achieved the highest Importance Value Index (IVI), with impressive values of 169.92% at the pole level and 170.09% at the tree level. In contrast, the species with the highest IVI at the seedling and sapling stages was Simpur (*Dillenia indica*), with an IVI of 88.42%. Several types, namely *Pinus merkusii*, *Bellucia axinanthera*, and *Parkia speciosa*, are found in the high-density class and are also found in the medium-density class. Regarding sapling growth rate in two density classes, *Bellucia axinanthera* had the highest IVI value. The high IVI of this species can be caused by several things, such as the fruit of the *harendong gede* or tangkalak guava, which is eaten by animals such as birds which are a medium for spreading this species (Tampati et al. 2023). According to Jadhav (2021), a high Importance Value Index (IVI) signifies a species' robust regenerative capacity and broad ecological adaptability. The *harendong* type, known for its prolific seed production and rapid growth, exemplifies a pioneer species adept at thriving in areas with expansive open canopies. This rapid spread occurs through the expansion of tree branches in the early growth period (Poorter and Werger 1999).

P. merkusii has the highest IVI value at the pole and tree level, which is > 100%. This value indicates that pine at the pole and tree level in medium vegetation density strongly dominates other species. *P. merkusii* is an important and native species in Indonesian forest ecosystems that is ecologically beneficial through supporting land rehabilitation and erosion control, and economically through *P. merkusii* resin or *gondorukem* (Imanuddin et al. 2020). The high presence of *P. merkusii* in the research location was initiated due to the planting of woody plants by forest farmer groups to maintain the environmental conditions of Situ Daun Village. *P. merkusii* is a species that grows optimally at an altitude of 200–2000 m above sea level, with annual rainfall between 1200–3000 mm, temperatures between 15–32°C, daily humidity ranging from 82%–86%, and can grow in various types of soil (Sallata 2013). The environmental conditions at the study site are very compatible with the optimal environment for the growth of *P. merkusii*, which is 400 m above sea level, annual rainfall of 2534 mm, and an average temperature of 25°C (**Table 1**). In addition, the dominance of *P. merkusii* at the pole and tree levels is also caused by allelopathic compounds released by *P. merkusii* into the environment that can interfere with the growth of other species (Bertolacci et al. 2018; Santonja et al. 2019). Some studies state that extracts of allelopathic compounds in the form of pinene and tannins have been shown to inhibit the growth of *Digitaria sanguinalis* and *Lepidum sativum* (Kimura et al. 2015), as well as *Amaranthus viridis*, *Echinochloa colonum*, and *Oryza sativa* (Senjaya and Surakusumah 2008).

Table 9. Importance value index (IVI) at moderate density

Growth level	Local name	Scientific name	IVI (%)
Understorey	Jukut Pahit	*Axonopus compressus*	23.47
	Goletrak	*Spermacoce latifolia*	16.24
	Rumput Setaria	*Setaria parviflora*	15.35
Seedling	Simpur	*Dillenia indica*	88.42
	Harendong Gede	*Bellucia axinanthera*	44.51
	Meranti	*Shorea* spp.	34.76
Sapling	Harendong Gede	*Bellucia axinanthera*	60.14
	Mahoni Daun Besar	*Swietenia macrophylla*	25.36
	Petai	*Parkia speciosa*	25.36
Pole	Pinus	*Pinus merkusii*	169.92
	Cemara Udang	*Casuarina equisetifolia*	44.48
	Mahoni Daun Besar	*Swietenia macrophylla*	24.11
Tree	Pinus	*Pinus merkusii*	170.09
	Cengkih	*Syzygium aromaticum*	34.82
	Cemara Udang	*Casuarina equisetifolia*	23.68

Table 10 shows the undergrowth IVI values and each low-density class growth level. The type with the highest IVI in the understory is Aur-aur (*Commelina diffusa*) 22.4%. Apart from the medium density class, Goletrak (*Spermacoce latifoliai*) is also included in the type with the highest IVI in the understory. This understory type has another name, patima grass, which belongs to the Rubiaceae family. The abundance of this type can be an opportunity for its use as a medicinal plant. Liu et al. (2022) highlighted that *S. latifolia* is a plant abundant in structurally diverse chemicals, making it a promising candidate for further exploration in medicinal and healthcare applications. In comparison, Pine emerges as the species with the highest IVI across all tree growth rates and density classes. This can happen because this type results from planting, which has a spacing to become the boundary of the community forest area in Situ Daun Village. Planting can influence the frequency of certain species, which also influences IVI. The high IVI of the types presented in **Tables 8** and **9** shows that these types have wide adaptability and tolerance to environmental conditions.

Table 10. Importance value index (IVI) at low density

Growth level	Local Name	Scientific Name	IVI (%)
Understorey	Aur-aur	*Commelina diffusa*	22.4
	Goletrak	*Spermacoce latifolia*	14.02
	Rumput Gajah	*Axonopus compressus*	11.97
Seedling	Sengon	*Falcataria moluccana*	83.33
	Beringin	*Ficus benjamina*	66.67
	Buah Luwingan	*Ficus hispida*	50.00
Sapling	Petai	*Parkia speciosa*	41.21
	Harendong Gede	*Bellucia axinanthera*	22.53
	Rambutan	*Nephelium lappaceum*	21.98
Pole	Melinjo	*Gnetum gnemon*	70.29
	Pinus	*Pinus merkusii*	62.56
	Cengkih	*Syzygium aromaticum*	47.64
Tree	Pinus	*Pinus merkusii*	147.14
	Cengkih	*Syzygium aromaticum*	42.04
	Beringin	*Ficus benjamina*	15.15

In addition to the IVI, understanding species biodiversity through various indices is crucial. These include the species diversity index (H'), species dominance index (C), species richness index (R), and species evenness index (E). The species diversity index for Community Forests is detailed in **Table 11**.

Table 11. Species diversity index (H')

Growth Level	Vegetation Density Class											
	Low				Moderate				High			
	H'	C	R	E	H'	C	R	E	H'	C	R	E
Understorey	3.01	0.08	5.89	0.38	2.69	0.76	4.31	0.76	2.36	0.16	3.55	0.30
Seedling	1.01	0.39	1.12	0.56	1.03	0.46	0.81	0.74	1.31	0.29	1.02	0.45
Sapling	2.25	0.13	3.38	0.69	1.83	0.23	2.55	0.83	2.24	0.28	3.40	0.59
Pole	1.84	0.19	2.20	0.58	1.53	0.29	2.04	0.74	1.98	0.16	2.27	0.50
Tree	1.35	0.45	2.02	0.27	0.97	0.59	2.17	0.39	1.74	0.22	2.29	0.40

The species diversity index is instrumental in characterizing community structure. The findings indicate that the diversity of species within the Situ Daun Village community forest is moderate. Notably, the highest H' value, reflecting the greatest diversity, was observed in the undergrowth of the low-density class, with a value of 3.01. This result can occur because at low density the intensity of light obtained by undergrowth is greater than at high density. The diversity of understorey plant species is influenced by light rather than water availability (Zangy et al. 2021). Conversely, the lowest H' value was recorded at the tree growth level in the medium-density class, with a value of 0.97. The diversity of plant species is influenced by factors such as climate and local site conditions (Zhang et al. 2014).

Species diversity is related to the species dominance index (C). A high C value indicates dominance is centered on a particular type. Conversely, dominance is not centered on a particular type if the C value is low. The analysis results of the type of dominance index (C) of community forests in Situ Daun Village show that the undergrowth in the medium density class has the highest

C value, namely 0.76. These results show that species dominate the understory in the medium-density class. Meanwhile, in other results, there is no dominant type. Natan et al. (2023) explain that a species dominance index (C) in the range of $0 < C < 0.5$ suggests that no single species dominates the community. Conversely, a C value between 0.5 and 1 indicates the presence of a dominant species.

The species richness index (R) quantifies the number of species present in a community. A higher R-value indicates a greater number of species. This index helps assess species richness based on the variety of species within the ecosystem (Thukral 2017). An R-value below 3.5 signifies low species richness, whereas an R-value ranging from 3.5 to 5 indicates high species richness. The analysis of the species richness index reveals that undergrowth consistently exhibits the highest R-value across all density classes. This finding correlates with the number of species identified at the research site, as detailed in **Table 7**. In all three density classes, the most species were found in the understory, resulting in a higher R-value for this growth stage than others. Additionally, only the R-value for undergrowth fell into the high species richness category across all density classes.

The species evenness index (E) measures the distribution uniformity of individuals among species within a community, with values ranging from 0 to 1. Analysis reveals that undergrowth in the medium-density class exhibits the highest E value, indicating a more even species distribution than other density classes. Conversely, the lowest E value was recorded at the tree growth level in the low-density class, at 0.27. This low evenness is likely due to the dominance of pine, a result of selective planting. Factors influencing evenness include the suitability of the growing environment and species enrichment activities (Wandi et al. 2016).

3.3. Vegetation Structure

Vegetation structure can be examined from both vertical and horizontal perspectives. The horizontal stand structure reflects the spatial distribution of individual species within their habitat, while the vertical stand structure illustrates the distribution of trees across various canopy layers. **Fig. 5** displays the density of individual trees for each regeneration stage. **Fig. 5** shows that not all densities have an inverted "J" curve. The inverted "J" curve at medium density is notably steeper compared to those at high and low densities. The highest density of trees was observed at the seedling growth stage in both medium and high-density classes. According to Maua et al. (2020), a classic inverse-J curve distribution indicates robust regeneration of woody plant species, suggesting a healthy forest and sustainable utilization practices.

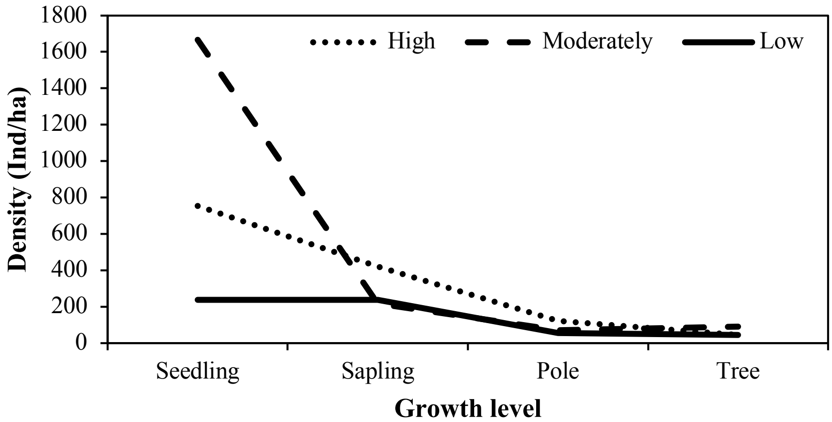

Fig. 5. The density of individual trees with their regeneration.

Meanwhile, in the low-density class, the growth rate of seedlings and saplings has the same density, namely 238 ind/ha, so it does not form an inverted "J" curve. Several factors, such as the environment, can influence this condition. This pattern may also be influenced by anthropogenic activities such as firewood extraction, grazing, charcoal burning, and pole removal (Maua et al. 2020). Additionally, the relatively open canopy cover in the low-density class affects light intensity and temperature, further impacting vegetation dynamics. Air temperature influences garden physiological activities such as photosynthesis, respiration, and transpiration. The ongoing decline in density with increasing growth stages reflects natural selection processes, which diminish the number of individuals surviving within each diameter class. The distribution of individuals across diameter classes is detailed in **Table 12**.

Table 12. Individual density per hectare by diameter class (individuals/ha)

Class	Diameter (cm)							
	10–19	20–29	30–39	40–49	50–59	60–69	70–119	Basal area (m^2/ha)
High	50	45	23	7	3	1	-	7.14
Moderately	31	71	68	13	3	3	-	14.2
Low	24	79	48	12	2	-	1	12.33

The number of individuals for each diameter class in each vegetation density class. Individual density decreases with increasing diameter in the high vegetation density class (**Table 12**). In the low and medium-density classes, the highest number of individuals was found in the 20–29 cm diameter class, with a subsequent decrease as diameter size increased. Notably, the low-density class featured a single individual in the largest diameter range of 70–119 cm. In contrast, the high-density and medium-density classes had one and three individual trees in the 60–69 cm diameter range, respectively. The basal area calculations reveal that the medium-density class has the highest basal area, at 14.2 m^2/ha. This indicates that trees in the medium-density class have, on average, larger diameters than those in other density classes. The basal area represents the total cross-sectional area of each live tree, measured at diameter at breast height (DBH), and is reported per unit area (Bettinger et al. 2017). **Fig. 6** illustrates the horizontal structure of the vegetation. The absence of an inverted "J" curve in this visualization suggests that the forest has been disturbed. Such disturbances may be attributed to anthropogenic activities, including firewood extraction, grazing, charcoal burning, and pole removal (Maua et al. 2020).

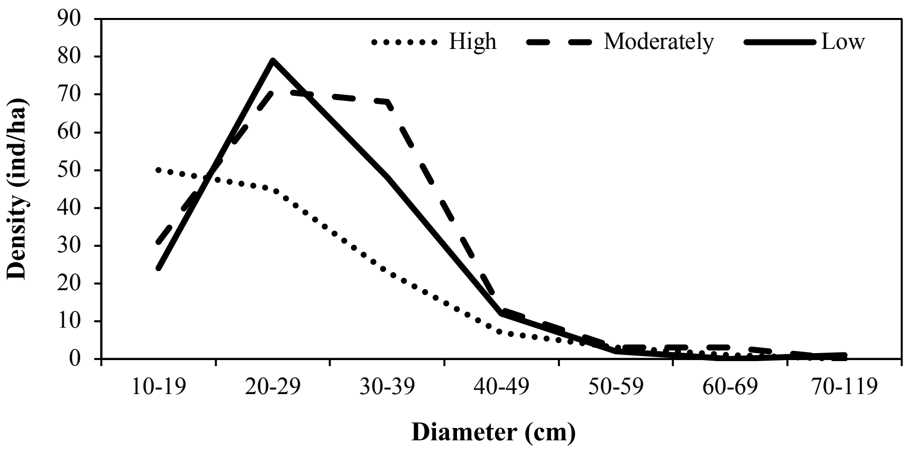

Fig. 6. Distribution of individual trees based on diameter class

3.4. Carbon Stock

The existence of forests provides benefits for many living creatures on earth. Some benefits of forests include wood, non-timber forest products, and animals. Indirectly, forests also provide environmental services such as regulating water management, beautifying aesthetics, and absorbing carbon. Forests absorb carbon from the atmosphere through photosynthesis, and this carbon can remain stored for extended periods in trees and other forest vegetation, both above and below ground, as well as in forest products used or deposited in landfills (Catanzaro and D'Amato 2019). Mokopen et al. (2021) explain that the forest carbon cycle begins with carbon fixation through photosynthesis. Organic compounds are then immobilized in tissue formation and transformed into biomass, subsequently degraded by microbes, plants, and animals through respiration. Forest carbon sequestration can be classified within each forest ecosystem into categories: above-ground biomass, belowground biomass, litter biomass, ground cover plants, and soil carbon storage.

Fig. 7 shows the high density of vegetation in community forests where leaves are not directly proportional to the stored carbon reserves. The highest carbon reserves in Situ Daun community forests are stored in the medium-density class, namely 31.09 tons C/ha. Meanwhile, the lowest carbon reserves are stored in the high-density class, 24.05 tons C/ha.

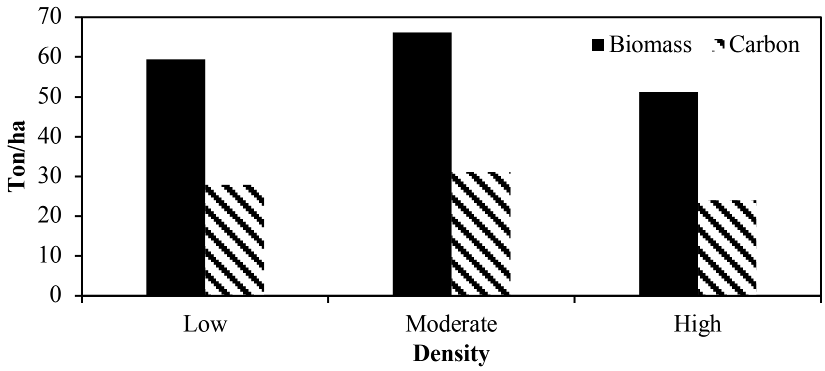

Fig. 7. Comparison of carbon (ton /ha) and biomass (ton /ha) in each density.

The potential for carbon absorption by an ecosystem is influenced by the type and condition of the ecosystem, including species composition, structure, and age distribution (Heriyanto et al. 2020). Additionally, the amount of carbon reserves is affected by the diameter of the vegetation stems. Carbon stocks were affected by mean diameter (Dimobe et al. 2019) and vegetation density. However, density alone does not account for total carbon storage if tree diameters are small. This observation aligns with the average diameter data for each density class. The high-density class has the lowest average diameter compared to the other two density classes, namely 18.91 cm. Meanwhile, the average diameter in the medium and low-density classes was 26.94 cm and 25.12 cm, respectively. Meanwhile, the total carbon reserves at the research location were 27.69 tons C/ha.

This study's results are greater than those reported by Mokopen et al. (2021), where the total carbon stock in a community forest in Thailand of 1600 m^2 was found to be 25.10 tons C/ha. Other carbon stock results such as in community forests in Pekon Kelungu, Tanggamus Regency, Indonesia with a sample area of 18000 m^2 were 100.79 tons C/ha (Ristiara et al. 2017). The results of research by Aprianto et al. (2016) who calculated carbon stocks in the agroforestry system in Tanggamus Regency, Indonesia obtained a total carbon stock of 123.33 tons C/ha, 265.20 tons

C/ha, and 146.20 tons C/ha for 3 community forests. According to IPCC (2022), carbon stock figures for primary forest, agroforestry and secondary forest land categories can differ significantly based on factors such as soil type, climate and land management practices. However, when looking at the IPCC (2019) guidelines, a good carbon stock value for primary tropical forests in Asia is 194.15 tons C/ha, secondary forests > 20 years is 61.85 tons C/ha, and secondary forests < 20 years is 21.43 tons C/ha. This shows that the value of carbon stocks at the research site is relatively good because with forest conditions < 20 years, but has more carbon stocks than secondary forests > 20 years, which is 83.08 tons C/ha.

3.4.1. Relationship between NDVI and tree density, number of species, shannon-wiener index, base area (LBDS), and carbon concentration

The analysis used in this research is correlation analysis. Data needs to be screened before statistical tests are carried out. The distribution of data variables is one of the assumptions for using parametric statistics (Turner et al. 2020). The classic assumption test performed in this research includes normality and heteroscedasticity tests, with results presented in **Table 13**.

Table 13. Normality and heteroscedasticity tests

Variables	Signification	
	Normality	Heteroscedasticity
Carbon stock	0.2	0.912
Vegetation density	0.2	0.082
Number of species	0.2	0.532
Shannon-Wiener	0.128	0.98
Basal Area	0.2	0.674

The normality test results indicate that all the variables tested are normally distributed. A normal distribution is characterized by a normality value greater than the test level of 0.05. The heteroscedasticity test results for all variables show a significance value greater than 0.05, indicating the absence of heteroscedasticity. The Pearson correlation test was conducted based on these findings. **Table 14** illustrates that the correlation between all variables is positive. A positive correlation coefficient indicates a directly proportional relationship between variables, whereas a negative correlation coefficient signifies an inversely proportional relationship. The most significant correlation coefficient value is observed between the number of species and the Shannon-Wiener index, with a value of 0.90. This indicates a relatively strong correlation between these two variables. Kumar et al. (2022) reported that ecosystems with a Shannon-Wiener index greater than 2 are classified as medium to highly diverse species. Similarly, Maua et al. (2020) found that South Nandi's Forest falls into the high diversity category with a Shannon-Wiener index of 2.63. The following variables with a strong correlation are carbon reserves with basal area and carbon reserves with density with a correlation coefficient of 0.78.

The NDVI value is not significantly correlated with other variables (**Table 14**). This shows that the NDVI value cannot be used to estimate carbon stock variables, density, number of species, Shannon-Wiener index, and basal area. The discrepancy in NDVI values with tree density is likely due to field conditions, such as a more significant number of trees in plots in the low-density class. Plot 15, classified in the low-density category, contains a greater number of trees—87 in total—compared to Plot 6 in the high-density class, which has only 30 trees. This difference in tree density significantly impacts the carbon reserves stored at the research location.

Table 14. Pearson test between variables on Community Forest in Situ Daun

Variables	Carbon stock (ton C/ha)	Density (Individual/ ha)	Number of species	Shannon-Wiener	Basal area (m^2/ha)	NDVI
Carbon stock (Ton C/ha)	1	-	-	-	-	-
Density (Ind/ha)	0.63**	1	-	-	-	-
Number of species	0.49*	0.64**	1	-	-	-
Shannon-Wiener index	0.34	0.54*	0.90**	1	-	-
Basal Area (m^2/ha)	0.78**	0.70**	0.33	0.15	1	-
NDVI	0.51	0.25	0.29	0.08	0.13	1

Notes: *Correlation is significant at the 0.05 level (2-tailed), ** The correlation is significant at the 0.01 level (2-tailed).

Regression analysis is employed to estimate the value of one variable based on others within a linear equation framework. In this analysis, NDVI is treated as the dependent variable, while carbon stocks, tree density, Shannon-Wiener Index, number of species, and basal area serve as independent variables. The regression analysis results between NDVI and other variables are illustrated in **Fig. 8**.

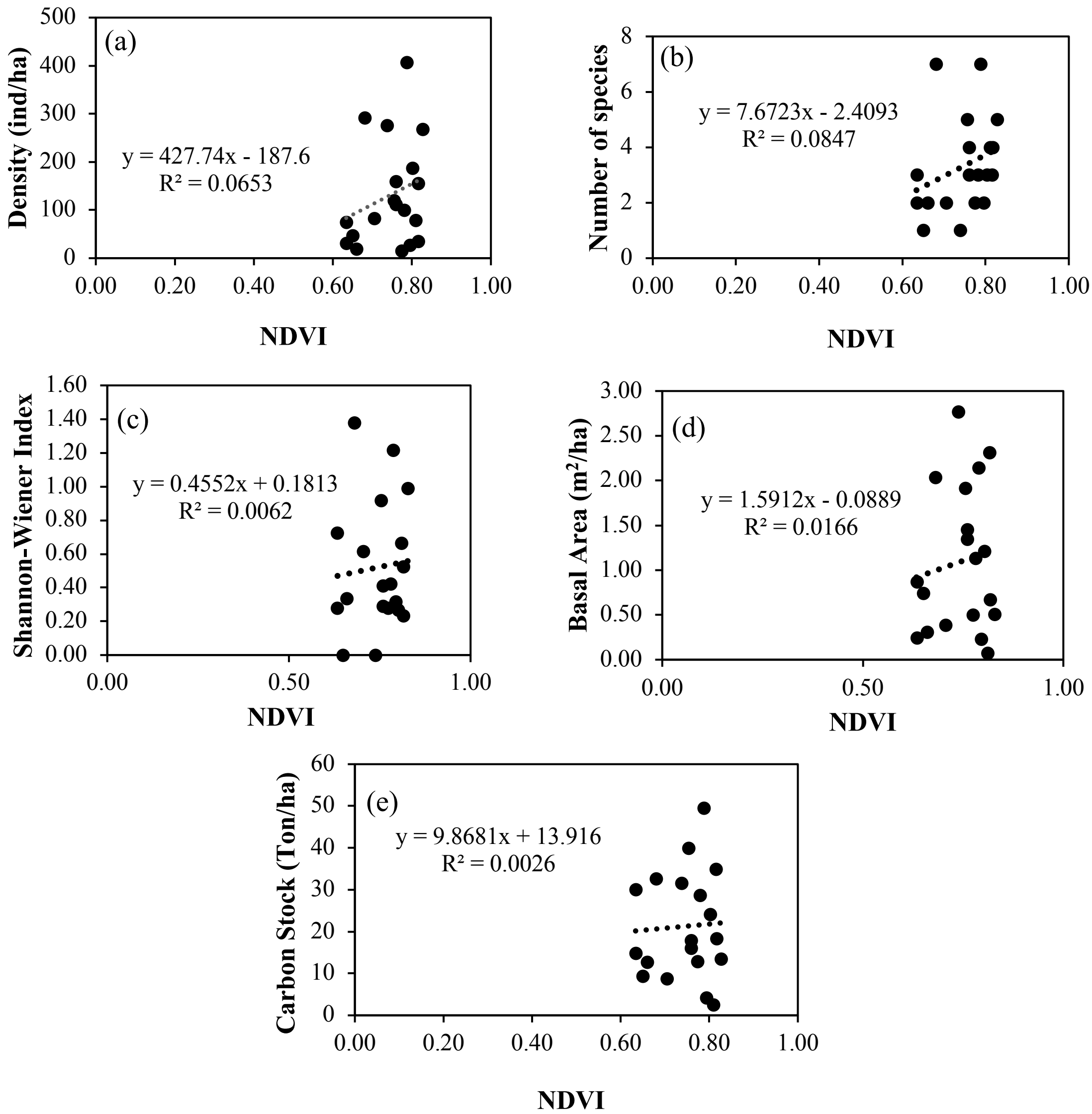

Fig. 8. Relationship between NDVI values and other observed variables. (a) NDVI with tree density (b) NDVI with the number of species (c) NDVI with Shannon-wiener Index (d) NDVI with basal area (e) NDVI with carbon stock.

The coefficient of determination (R^2) values are relatively low, indicating a modest explanatory power of the independent variables. Specifically, the R^2 values between NDVI and carbon stocks, tree density, basal area, number of species, and the Shannon-Wiener index are 0.3%, 6.5%, 1.6%, 8.5%, and 0.6%, respectively. A small R^2 value suggests that these variables have limited capacity to account for the variations in the NDVI (Natoen et al. 2018).

4. Conclusions

The community forests of Situ Daun Village are generally in an improving condition in terms of vegetation cover as indicated by changes in land cover over 10 years (2013–2023), showing a significant increase in land cover, especially in the high-density class from 1.34 ha (2013) to 10.82 ha (2023). This study found 178 plant species across 40 families, with Fabaceae and Myrtaceae being the most dominant. Pine (*Pinus merkusii*) dominates in the tree growth stage for all density levels, followed by clove (*Syzygium aromaticum*). The high-density class has the highest diversity index for the tree growth level of 1.74 but is still in the moderate category. The vegetation structure in the Situ Daun Village community forest forms an inverted J curve at medium and high-density class, indicating natural regeneration and the sustainability of healthy forest areas. The total carbon stock was 83.08 tons carbon/ha, with an average for the 3 vegetation densities of 27.69 tons C/ha. Future research is recommended to use satellite imagery with higher resolution or multitemporal data to increase accuracy in analyzing changes in vegetation density with NDVI or other indices. Studies on stand structure and composition dynamics, including environmental and human factors that influence vegetation growth, can yield more detailed insights for land rehabilitation strategies. Forest and land carbon stock measurements can add primary data, such as soil carbon content and greenhouse gas emissions, to provide a comprehensive picture of carbon mitigation potential in the study area.

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