Vol. 14(2): 211-225, May 2026

DOI: https://doi.org/10.23960/jsl.v14i2.1391

P-ISSN: 2339-0913
E-ISSN: 2549-5747

Jurnal Sylva Lestari

Journal homepage: https://sylvalestari.fp.unila.ac.id

Full Length Research Article

The Role of Sibolangit Nature Tourism Park in Climate Change Mitigation: Aboveground Biomass, Carbon Stock, and CO_2 Equivalent

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ARTICLE HISTORY:

Received: 7 December 2025
Peer review completed: 24 January 2026
Received in revised form: 22 February 2026
Accepted: 24 March 2026

KEYWORDS:

Allometric equation
Conservation area
Global warming
Sibolangit Nature Tourism Park
Tropical forest

ABSTRACT

Carbon dioxide (CO_2) is the main greenhouse gas, and its atmospheric concentration continues to increase. Globally, in 2019, the average CO_2 at Earth's surface reached 409.8 ppm. Information on carbon storage remains a strategic issue for sustainable forest management and climate change mitigation. Sibolangit Nature Tourism Park is a 24.85 ha conservation area with high biodiversity and a range of potential environmental services. This study aims to quantify the aboveground biomass, carbon stock, and CO_2-equivalent emissions in the Sibolangit Nature Tourism Park. The study used 5% intensity sampling, resulting in 31 plots selected using simple random sampling. The plot size was 400 m^2 (trees), 100 m^2 (poles), 25 m^2 (saplings), and 4 m^2 (seedlings). The vegetation species, height and diameter at breast height were recorded to measure the biomass of trees, poles, and saplings. The aboveground biomass of vegetation was estimated using a non-destructive method with Chave's allometric equation, while the biomass of seedlings was calculated using a destructive method according to SNI 7724-2019. The carbon stock was measured by multiplying the biomass by 0.47. The carbon stock value was then converted to CO_2-equivalent using a conversion factor of 3.67. The results showed that Sibolangit Nature Tourism Park had an aboveground biomass of 525.73 t/ha, a carbon stock of 247.09 t C/ha, and a total carbon stock of 6140.30 t C, equivalent to 906.84 t CO_2/ha. The study site had potential as an atmospheric CO_2 absorber, indicating its primary role in climate change mitigation and in the FoLU Net Sink 2030 program.

1. Introduction

The increase in greenhouse gases (GHG) in the atmosphere causes an imbalance in the earth's energy budget. This phenomenon leads to rising global temperatures and triggers climate change. Various disasters, such as irregular changes in seasons, drought, difficulty accessing clean water, climate instability, decreased agricultural productivity (Hossain et al. 2020; Sudarma and As-syakur 2018), floods, food crises, rising sea levels, and increased health risks, are negative impacts of climate change. Carbon dioxide (CO_2) is the primary GHG whose atmospheric concentration continues to increase. Globally, the average CO_2 at the earth's surface reached 409.8 ppm in 2019 (Dunn et al. 2020).

Information on carbon storage remains a strategic issue for sustainable forest management and is part of climate change adaptation and mitigation efforts. Changes in land cover and forestry account for more than 17% of total global GHG emissions. On the other hand, forests play a crucial role in mitigating climate change, especially by providing environmental services for carbon sequestration, commonly known as carbon sinks.

About 48% of the total carbon stocks of terrestrial ecosystems is stored in forest ecosystems (IPCC 2001). During photosynthesis, vegetation absorbs CO_2 from the atmosphere, converts it into organic carbon in the form of carbohydrates, flows it throughout the network, and stores it in biomass such as stems, branches, roots, leaves, tubers, etc. It is known as the sequestration process (C-sequestration), the process of storing carbon within plant tissue. It confirms that climate change mitigation efforts must involve land-use change and forestry. Since forests naturally function as the most efficient carbon sink on earth, they can become a source of GHG emissions if not managed properly (Basyuni et al. 2015; Eddy et al. 2021). The Indonesian government has committed to mitigating global warming and climate change, including through the $REDD^+$ scheme, which promotes sustainable forest management and increases forest carbon stocks.

Trees, the main component of forests, can absorb large amounts of carbon (Lorenz and Lal 2010). Conservation areas in Indonesia are reported to store at least 625 gigatons of CO_2 (DitPJLKH 2015). Previous research has calculated the potential for carbon storage in several conservation areas in Indonesia, for instance: Bromo Tengger Semeru National Park has carbon stores of 193.49 t CO_2/ha in primary forest, 267.42 t CO_2/ha in secondary forest and 90.07 t CO_2/ha in plantation forest (Noor'an et al. 2015), Ruteng Nature Tourism Park in RKW region I Golo Lusang 2,226.19 t CO_2/ha (Dey et al. 2019), and Lake Buyan-Lake Tamblingan Nature Tourism Park 2,038.95 t CO_2/ha (Maku et al. 2020).

It is undeniable that, in addition to biodiversity, the diversity of forest stand structures also contributes significantly to ecosystem services. In this regard, the diversity of forest stand structures is considered an essential factor driving ecosystem services such as habitat provision, resilience to disturbances, and drought (Dieler et al. 2017; Grote et al. 2016; Hilmers et al. 2018; Nikinmaa et al. 2020). Furthermore, stand structure also plays a crucial role in forest carbon storage. Forest structure, influenced by tree diameter at breast height (DBH) and height, serves as a key indicator for estimating the extent of carbon stored within a forest (Huang et al. 2025) through carbon sequestration (Austin et al. 2020). This highlights the importance of analyzing stand structure as supporting data for carbon stock estimation.

Sibolangit Nature Tourism Park is a conservation area covering 24.85 ha and was established in 1980 through the Decree of the Indonesian Minister of Agriculture Number 636/Kpts/Um/1980. The area has high biodiversity and is suitable as a natural laboratory to develop environmental and conservation education (BBKSDA-North Sumatra 2016). Like other conservation areas, Sibolangit Nature Tourism Park also provides various environmental services, including natural tourism potential (Ginting et al. 2013), water management, oxygen supply, and carbon sequestration and storage. According to Indonesian Government Regulation Number 28 of 2011, one of the uses of the Nature Tourism Park is carbon storage and sequestration.

Biomass is a key indicator in assessing an ecosystem. Accurate forest biomass estimation is crucial for determining carbon stocks, evaluating ecosystem services, and formulating mitigation strategies to address the impacts of climate change (Ali et al. 2015; Herold et al. 2019; Rodríguez-

Veiga et al. 2017). Therefore, analysis of biomass and carbon sequestration in Sibolangit Nature Tourism Park is necessary to provide baseline data for sustainable forest management planning, maintain ecosystem integrity, and support Sibolangit Nature Tourism Park's role in climate change mitigation.

2. Materials and Methods

2.1. Study Area

The research was conducted at Sibolangit Nature Tourism Park in Sibolangit District, Deli Serdang Regency, North Sumatra Province (**Fig. 1**). It is located in 98°36'36" E–98°36'56" E and 3°17'50" N–3°18'39" N. Sibolangit Nature Tourism Park has undulating topography, and its slope factor is 5%–10% approximately. The elevation of this location is 558 meters above sea level. According to the Schmidt and Ferguson classification, it has a B-type climate with annual rainfall of 2500–3000 mm, humidity of 60%–80%, and temperatures ranging from 25°C to 35.6°C.

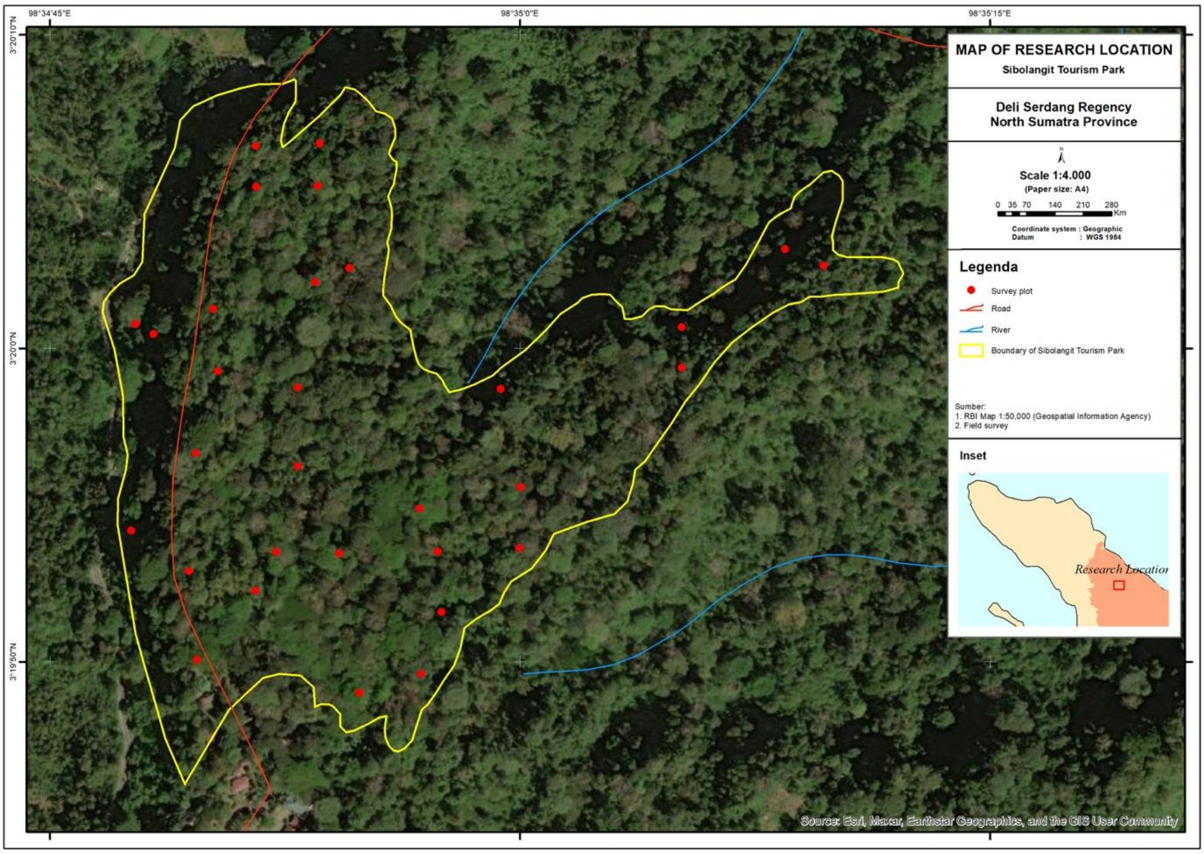

Fig. 1. Research location and sampling plot distribution.

2.2. Sampling and Data Collection

The study used 5% intensity sampling, resulting in 31 plots across 24.85 ha of the Sibolangit Nature Tourism Park, using a simple random sampling method. The total area of the sampling plot was 1.24 ha. It was appropriate for the minimum sampling area in a tropical rain forest (Sunyata 2024). The plot size was 400 m^2 (trees), 100 m^2 (poles), 25 m^2 (saplings), and 4 m^2 (seedlings) (Mueller-Dombois and Ellenberg 1974; SNI 7724-2019). The vegetation species, height, and DBH (±1.3 m) were recorded to estimate the biomass of trees, poles, and saplings. Growth stages are categorized based on height and DBH. Individuals less than 1.5 m tall are categorized as seedlings, and young trees greater than 1.5 m tall and with a DBH of less than 10 cm are categorized as saplings. Individuals with a DBH between 10 and 20 cm are categorized as poles, and mature trees are those with a DBH greater than 20 cm (SNI 7724-2019; Susilowati et al. 2021; Susilowati et al. 2025; Widianingsih and Santhyami 2025). For seedlings, destructive sampling was applied; all seedlings within the 4 m^2 sub-plots were harvested (cut without roots). The total wet weight was measured in the field, and representative samples were sent to the laboratory for determination of the dry weight (Irawan and Purwanto 2020; SNI 7724-2019).

2.3. Estimation of Biomass, Carbon Stock, and CO_2 Equivalent

The aboveground biomass of trees, poles, and saplings was estimated using a non-destructive method. The biomass was calculated using the following allometric equation (Chave et al. 2014).

$$AGB_{est} = 0.0673\ (\rho D^2 H)^{0.976} \quad (1)$$

where AGB_{est} is aboveground biomass (kg), ρ is species-specific weight (g/cm^3), D is diameter at breast height (cm), and H is height of vegetation (m).

The seedlings' biomass was measured using Equation 2, as specified in SNI 7724-2019 (Irawan and Purwanto 2020).

$$Seedlings\ biomass = \frac{Sample\ dry\ weight}{Sample\ wet\ weight} \times Total\ wet\ weight \quad (2)$$

The carbon stock was then calculated as the biomass multiplied by 0.47. The formula was presented in Equation 3 as stated in SNI 7724-2019.

$$C = B \text{ x } \%\ C\ organic \quad (3)$$

where C is the carbon content of biomass (kg), B is total biomass (kg), and % C organic is the carbon content percentage, which is 0.47, or using the carbon percentage obtained from laboratory analysis.

Carbon stock value was converted to carbon dioxide equivalent (CO_2e). The conversion used the molecular weight ratio of CO_2 to C, yielding a conversion factor of 3.67 (IPCC 2006). The formulas were presented in Equation 4.

$$CO_2e = C \text{ x } 3.67 \quad (4)$$

where CO_2e is carbon dioxide equivalent (ton CO_2/ha) and C is carbon stock (ton C/ha).

3. Results and Discussion

3.1. Aboveground Biomass and Carbon Stock

The results showed a clear difference in the contribution of tree density and aboveground biomass (AGB) across tree life stages (**Table 1**). Saplings had the highest tree density (1581 individuals/ha), followed by poles (376 individuals/ha) and trees (175 individuals/ha). Despite differences in stem density, biomass accumulation showed the opposite pattern. The trees contributed significantly to the biomass in Sibolangit Nature Tourism Park (486.96 t/ha), much higher than poles (30.10 t/ha), saplings (8.63 t/ha), and seedlings (0.05 t/ha). It highlighted that stem size is more strongly affected by biomass than by stem density, consistent with allometry (Chave et al. 2014). A small number of large-diameter trees may preserve biomass equivalent to that of numerous smaller trees. The life stage of a tree is determined by its height and diameter, which serve as growth indicators and are highly correlated with biomass production (Amanuel et al. 2025; Sarjono et al. 2017; Sumida 2015). Biomass refers to the weight of the living material produced by plants (Danarto and Setyorini 2019). In addition, species diversity affects biomass accumulation (Astiani and Ripin 2016; Wirabuana 2021), as our previous study found that mature trees had the highest species diversity (49 species) among life stages (Ulfa et al. 2022).

Based on the data analysis, trees showed high variability, with the standard deviation (SD) exceeding the mean. It indicates a highly heterogeneous spatial distribution of AGB in the study site. The presence of large-diameter trees in a few sampling plots influences the AGB proportion, leading to gradient variance. The dominance of large trees and their importance to biomass accumulation were also reported in Gunung Gede Pangrango National Park (Rozak et al. 2017) and Gunung Kerinci National Park (Sulistyawati et al. 2018). The total AGB potential at the study site was 525.73 t/ha. The value was higher than the biomass accumulation in Ketambe Resort of Gunung Leuser National Park (Nasution and Efendi 2020), in Pesanggrahan Preserve Area (Kundariati et al. 2024) and also in a local forest management of Gunungkidul, Yogyakarta and the secondary tropical forest at South Kalimantan, which both had the wider study area (Suyanto et al. 2022; Tohirin et al. 2021).

Table 1. Number of species, tree density and the average of aboveground biomass, carbon stock, and CO_2 equivalent of each tree life stage at Sibolangit Nature Tourism Park

Tree Growth Stage	Number of Species	Tree Density (ind/ha)	AGB (t/ha)	Carbon Stock (t C/ha)	CO_2 Equivalent (t CO_2/ha)	Total Carbon Stock (t C)
Seedling	19	-	0.05 ± 0.04	0.02 ± 0.02	0.08 ± 0.07	0.57 ± 0.46
Sapling	34	1581	8.63 ± 8.17	4.05 ± 3.84	14.88 ± 14.09	100.76 ± 95.40
Pole	23	376	30.10 ± 19.30	14.15 ± 9.07	51.92 ± 33.30	351.53 ± 225.45
Tree	49	175	486.96 ± 538.97	228.87 ± 253.31	839.96 ± 929.66	5687.44 ± 6294.86
Total			525.73 ± 237.35	247.09 ± 111.56	906.84 ± 409.41	6140.30 ± 2772.18

The study demonstrated that trees in the Sibolangit Nature Tourism Park stored 228.87 t C/ha, equivalent to 839.96 t CO_2/ha, indicating the amount of carbon that plants can absorb and store in biomass. The value is directly derived from AGB estimation. Therefore, the pattern of carbon stock distribution is similar to the AGB. The result showed that trees in the Sibolangit Nature Tourism Park stored 228.87 t C/ha, equivalent to 839.96 t CO_2/ha. This value was much higher than the carbon stored in poles (14.15 t C/ha), saplings (4.05 t C/ha), and seedlings (0.02 t C/ha). The differences were influenced by vegetation diameter and height, which are the primary factors in estimating forest vegetation biomass and carbon stocks. According to Manafe et al. (2016), carbon stocks are associated with tree diameter, with larger trunks indicating higher carbon stocks. Ma et al. (2020) also reported that carbon accumulation in trees within forests is associated with increased trunk carbon concentration, which is influenced by tree size and age. Furthermore, age, which is related to vegetation growth, was strongly correlated with carbon production (Sarjono et al. 2017) and with biomass accumulation, which increases continuously until reaching an optimal peak at a certain age, indicating vegetation over-maturity (Dey et al. 2019).

Sibolangit Nature Tourism Park had approximately 247.09 t C/ha. It was higher than Gunung Leuser National Park-Bukit Lawang area (55.31 t C/ha) (Siregar et al. 2025), Sigogor Mountain Nature Reserve (14.62 t C/ha) (Waskitho and Triwanto 2018), and the lowland and montane rainforest of Gunung Gede Pangrango National Park (55.84 and 97.32 t C/ha, respectively) (Sunyata 2024). On the other hand, the previous studies reported higher forest carbon stock. For instance, at Lake Buyan Nature Tourism Park (577.22 t C/ha) (Maku et al. 2020), at Bukit

Tigapuluh National Park (269.20 t C/ha) (Darmawan et al. 2022), at the ecotourism development concession area of Gunung Gede Pangrango National Park (560.47 t C/ha) (Sawitri et al. 2025), and the lower montane forest at Suan Phueng Nature Education Park (493.74 t C/ha) (Chanlabut and Nahok 2022). Those areas were generally wider than the Sibolangit Nature Tourism Park. The amount of carbon stored varies with the diversity, density, and age of existing plants, soil type, climate and rainfall, topography, and other biophysical conditions, including the silvicultural techniques and forest management applied (Chairul 2016; Hairiah and Rahayu 2007).

Sibolangit Nature Tourism Park stored a total of 6140.30 t C, equivalent to 906.84 t CO_2/ha. Through photosynthesis, CO_2 in the air is absorbed by plants and, with the help of sunlight, is converted into carbohydrates, which are distributed throughout the plant body and stored in leaves, stems, branches, fruits, and flowers (Hairiah and Rahayu 2007). It is undeniable that CO_2 concentration has a beneficial effect on photosynthesis (Bao et al. 2018), thereby significantly reducing atmospheric carbon emissions. Therefore, some concerns should be given to preserve the remaining forests in the study site. Sibolangit Nature Tourism Park has high potential as a storage and absorber of atmospheric CO_2, supporting climate change mitigation and the FoLU Net Sink 2030 program, specifically (Ministry of Environment and Forestry 2022). Therefore, sustainable management is highly required to conserve this tropical forest as a carbon pool.

3.2. Horizontal Stand Structure

Forest vegetation forms a varied stand structure, depending on the growth class achieved. Stand structure is closely related to increases in tree diameter and height, which in turn affect carbon storage within the forest. Research results presented that the Sibolangit Nature Tourism Park forest had a diverse stand structure. The study found that the horizontal stand structure in the Sibolangit Nature Tourism Forest does not reflect stable forest conditions, as it was dominated by certain classes (**Fig. 2**).

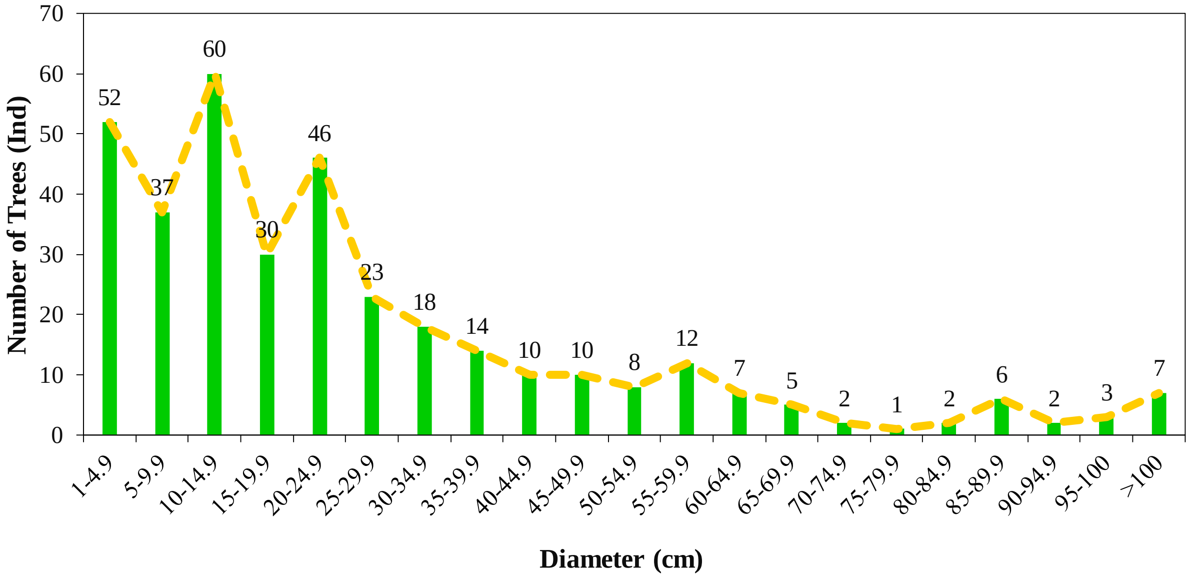

Fig. 2. Horizontal stand structure of tree composition in Sibolangit Nature Tourism Park.

The result showed that the largest number of individuals was in the 10–14.9 cm diameter class (60 trees), followed by the 1–4.9 cm diameter class (52 trees), indicating that the majority of the tree population was in the juvenile-to-small-pole phase. Although the results showed a predominance of juvenile individuals, which is common in natural forests, there were significant disparities in the number of individuals in several juvenile phases, including the 5–9.9 and 15–19.9 cm diameter classes (**Fig. 2**). It is not yet clear how this phenomenon occurs in a relatively well-maintained forest area. However, anthropogenic factors and natural events are suspected to be the primary drivers of the loss of several tree growth stages in the study area. This finding was also reported by Hartoyo et al. (2025), who, in their latest research, found that forests recovering from disturbance exhibited an imperfect inverted J shape.

The accumulation of tree diameter classes in the Sibolangit Nature Tourism Park forest indicates a forest composition that has experienced disturbance. The imperfect inverted J-pattern (**Fig. 2**) showed a dominance of tall individuals in small-diameter classes, followed by a gradual decline as diameter increased, with a significant decrease in numbers across several diameter classes. Although this pattern generally reflects the characteristics of natural forests, a drastic decrease in the number of individuals in a particular diameter class indicates a disturbance that eliminated individuals at a specific growth stage. The imperfect inverted J-pattern also highlighted the presence of relatively large-diameter trees at the study site. There were seven trees with diameters above 100 cm belonging to the species *Pterocarpus indicus*, *Litsea* sp., *Bischovia javanica*, and *Samanea saman*. Sibolangit Nature Tourism Park is composed of both native and exotic species. Certain species have developed into substantial trees with diameters approaching 1 meter, for instance *Dalbergia latifolia*, *Pterocarpus indicus*, and *Samanea saman* (BBKSDA-North Sumatra 2016). A large-diameter tree is a key individual in the forest's ability to store carbon. Therefore, their existence needs to be well-conserved (Chanlabut and Nahok 2022). The loss of large-diameter trees releases significant amounts of carbon and increases atmospheric GHG emissions, triggering global warming.

Overall, the tree composition based on diameter class formed an inverted J-shaped pattern, a pattern commonly found in natural forests, reflecting active regeneration and recruitment of young individuals (Ademoh et al. 2017; Mensah et al. 2018; Rawat et al. 2018). The dominant composition of young trees in the Sibolangit Nature Tourism Park forest indicates the active recruitment at the study site. Conversely, older trees with a diameter class >50 cm showed a significant decline, indicating that natural regeneration has occurred well, although not perfectly. The high proportion of young trees in the Sibolangit Nature Tourism Park forest is expected to play a pioneering role in forming a healthy forest, with a positive impact on the overall forest ecosystem, providing complex habitats and supporting the lives of various biodiversity living within it.

The inverted J-pattern formed by the accumulation of tree diameters at the research site indirectly influences future carbon stocks. This is related to active recruitment and the composition of the vegetation that may form, providing a limited number of trees or vice versa. It cannot be denied that, in addition to ensuring future seedling recruitment, the presence of old trees is highly beneficial as a carbon reserve in the Sibolangit Nature Tourism Park. Therefore, information on the horizontal structure of vegetation is an important indicator of ecosystem balance, including a warning about carbon stocks, especially if the pattern formed does not reflect a healthy forest. Equally important, the survival of young individuals, which are vulnerable to disturbance, is crucial for maintaining a well-formed ecosystem and increasing carbon stocks.

3.3. Vertical Stand Structure

Similar to the Horizontal stand structure, the vertical stand structure also depicts an unbalanced pattern between strata. The research results showed a significant increase in the number of individuals in the young stratum (**Fig. 3**). The spike in the number of trees in stratum C with tree height of 4–20 m indicates an imbalance in the population between old and young trees.

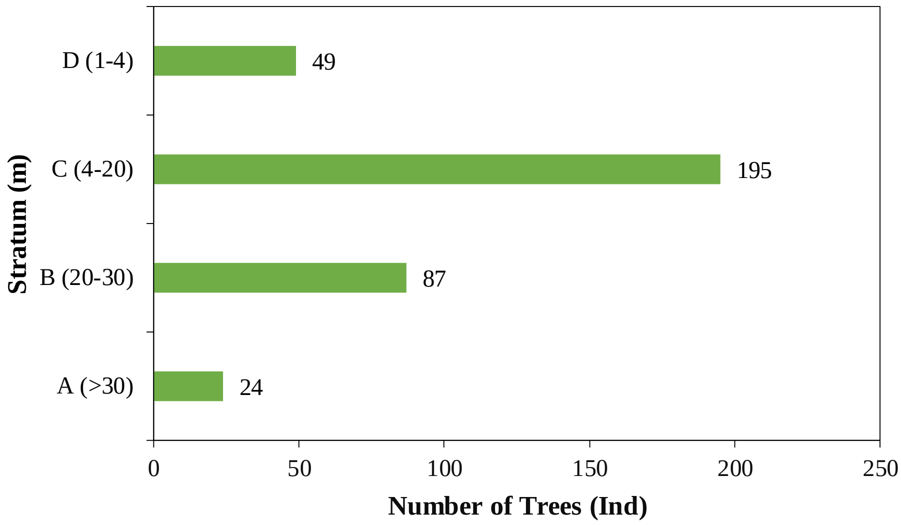

Fig. 3. Vertical stand structure in Sibolangit Nature Tourism Park.

Based on **Fig. 3**, the tree composition in the Sibolangin Nature Tourism Park shows unbalanced stratification, with strong dominance in the middle stratum, namely stratum C (4–20 m), with 195 individuals. It indicates that the majority of the stand is in the secondary growth phase, with a higher proportion of young trees than mature trees. This phenomenon is common in forests undergoing disturbance, whether from anthropogenic pressures or natural dynamics, and is followed by intensive regeneration over time. The high number of individuals in this class indicates active vertical competition and a sufficient light supply at the early growth stage in the past. This imbalance is thought to be caused by an open canopy due to the loss of mature individuals in the past. As a result, the incoming light supports the growth of seedlings and young trees, allowing them to thrive and dominate the study site. According to Willms et al. (2017), increased light intensity often results in dominant vegetation in the middle and lower strata. Furthermore, research by Willson et al. (2020) also found that canopy openness increases light intensity along the gradient due to some disturbances.

In contrast to stratum C, the numbers of stands classified as stratum D and A were the lowest, at 49 and 24 individuals, respectively. The low regeneration in these lower strata indicates regenerative barriers, which several factors, including unfavorable microclimate conditions for germination and intense competition with other vegetation, could cause. This phenomenon is closely related to past disturbances in the area. Although concrete evidence of past disturbances at the study site has not been collected, anthropogenic activities are suspected to be the primary factor in the imbalance in tree composition. Overall, the vertical distribution pattern exhibits a unimodal curve with a distinct peak in the middle strata. This pattern is common in tropical forests undergoing intermediate succession, where the accumulation of individuals in the middle strata is higher than in the lower or upper strata. The structure confirms that the stand has high productivity at an intermediate growth stage, but has not yet achieved ecological stability, characterized by proportional balance between strata and strong understory regeneration.

Tree height is an indicator of stored carbon reserves along with stem diameter. Stem size and tree height are positively correlated with carbon reserves in an ecosystem, with larger plants indicating greater carbon storage. This finding was also expressed by Proulx (2021), who stated that aboveground biomass is influenced by dense vegetation and is determined by plant height. Therefore, vertical structure can serve as a reminder of the importance of balanced tree composition in an ecosystem.

Based on the results, it cannot be denied that the Sibolangit Nature Tourism Park urgently requires attention to the continuity of its ecological processes. Analysis of carbon stocks and stand structure has illustrated the importance of conservation measures to maintain and repair past damage. Older trees with the highest carbon stores are vulnerable to loss. Meanwhile, ongoing regeneration is experiencing imbalances in several tree diameter and height classes. This is of particular concern given the potential for future disparities in the number of individuals, which could impact ecological processes.

3.4. Diameter Class Proportion to the Carbon

Diameter class plays an important role in determining the amount of carbon stored in forests. Furthermore, Wirabuana et al. (2021) confirmed that stand density and species diversity were related to carbon stock production in forests. **Fig. 4** showed that Sibolangit Nature Tourism Park was dominated by vegetation with a diameter class of < 10 cm (54.92%). The larger the tree's diameter, the fewer the number of individuals. Only 7 trees with a diameter > 100 cm were observed (1.17%). The condition describes a forest ecosystem dominated by regeneration, with the succession process ongoing. Forests that are dominated by regeneration or young trees also indicate that the location is a secondary forest. It signifies that the secondary forest differs from the natural primary forest, which is dominated by mature stands (Heriyanto et al. 2023).

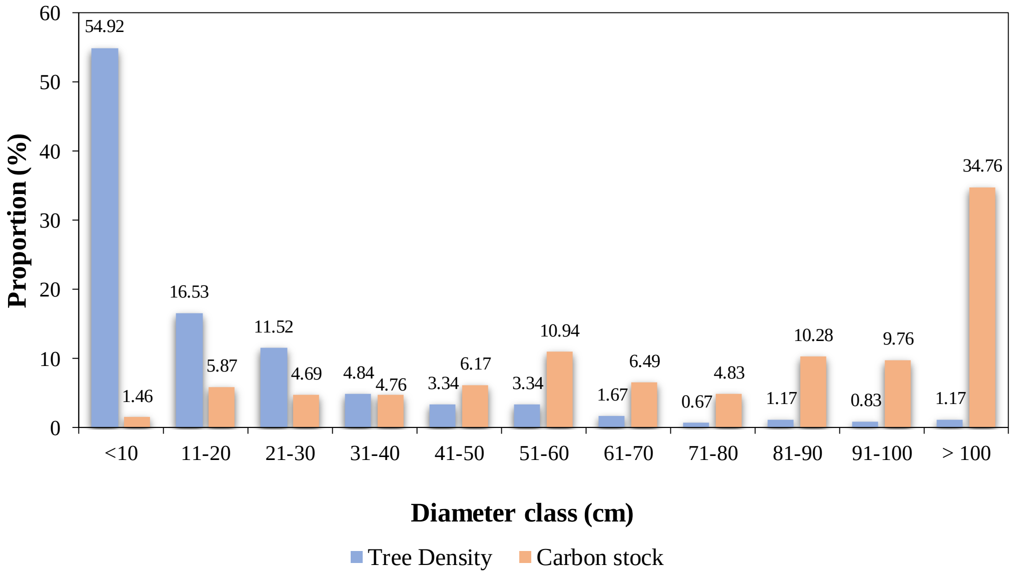

Fig. 4. Proportion of tree density and carbon stock based on DBH class in Sibolangit Nature Tourism Park.

The study results also showed that an increase in diameter class led to higher carbon stock, despite low density. The diameter class range of 81–90 cm, 91–100 cm, and >100 cm accounts for only 3.17% of the tree density. However, the total amount of stored carbon stocks reached 54.80% of the total area addressed, and the larger the diameter, the greater the impact on carbon storage in the forest. It suggested their importance as a carbon sink in the forest. Large trees (diameter >100 cm) made a greater contribution (by 34.76 %) to the increase in carbon stocks at the study site compared to small trees (e.g., diameter <20 cm, which contributed 7.33% of total carbon stock (**Fig. 4**). The presence of large-diameter trees in tropical forests is significant because they store a considerable amount of carbon. Hence, sustainable forest management and conservation strategies should be implemented to ensure their protection.

4. Conclusions

Sibolangit Nature Tourism Park had an aboveground biomass of 525.73 t/ha, a carbon stock of 247.09 t C/ha, and a total carbon stock of 6140.30 t C, equivalent to 906.84 t CO_2/ha. The study site had a high potential as an absorber of atmospheric CO_2, indicating its primary role in climate change mitigation and in the FoLU Net Sink 2030 program. The tree structure was dominant in several growth stages. Conservation strategies and attention to the stability of the Sibolangit Nature Tourism Park ecosystem are urgently needed.

Acknowledgments

The University of Sumatera Utara fully funded this research through the TALENTA research grant, contract number 136/UN5.2.3.1/PPM/SPP-TALENTA USU/2021. We also thank BBKSDA Sumatera Utara, the management of Sibolangit Nature Park (TWA), and students who supported us during the field research.

Author Contributions

M.U.: Conceptualization, Methodology, Data Acquisition, Writing – Review and Editing, Visualization, Supervision, Project Administration, Funding Acquisition, Writing – Original Draft Preparation, Writing – Review and Editing; M.M.H.: Conceptualization, Methodology, Software, Data Acquisition; Y.E.R.: Data Acquisition, Methodology; A.W.S.: Formal Analysis, Investigation, Resources, Validation; P.Y.A.P.W: Formal Analysis, Investigation, Resources, Validation; I.M.G.: Formal Analysis, Investigation, Resources, Validation.

Conflict of Interest

The authors declare no conflict of interest.

Declaration of Generative AI and AI-Assisted Technologies in the Manuscript Preparation

Not applicable.

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