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Carbon Storage Potential and Economic Valuation in the Arboretum of Forest Area with Special Purpose (KHDTK) Aek Nauli, Indonesia

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ABSTRACT

Sustainable forest management is expected to significantly contribute to preventing climate change and supporting the achievement of the Forestry and Other Land Use (FOLU) Net Sink 2030. This study aims to determine the potential for biomass storage and carbon and economic valuation in the Arboretum of Forest Area with Special Purpose (KHDTK) Aek Nauli, North Sumatra, Indonesia. This study used systematic sampling with random start as an inventory method. The estimation of above-ground carbon uptake used general allometric equations and benefit transfer methods for the economic value of carbon. This study found 62 species of woody plants with 5 species classified as endangered according to the International Union for Conservation of Nature (IUCN) Red List of Threatened Species, namely *Agathis dammara*, *Dryobalanops aromatica*, *Tectona grandis*, *Pinus merkusii* and *Saurauia bracteosa*. There are 734 individuals of woody plants, including 84% in the tree phase and 16% in the pole phase, with dominant species in both phases, namely *Pinus merkusii* and *Schima wallichii*. Potential biomass and carbon stocks in the pole phase were 4.76 tons/ha and 2.24 tons/ha, respectively, while in the tree phase were 338.69 tons/ha and 159.19 tons/ha. The total estimated carbon sequestration reached 592.42 tons.CO_2e/ha. Carbon stocks' total potential economic value is IDR 2,578,832,243 (USD 164,100). Therefore, the Arboretum of KHDTK Aek Nauli is considered to have the potential to support the achievement of the FOLU Net Sink 2030 target. It is expected that the potential economic value of carbon can be converted into real value and optimized through a carbon trading scheme to offset greenhouse gas emissions and support the sustainable management of KHDTK Aek Nauli.

1. Introduction

Greenhouse gas (GHG) concentrations that exceed the threshold cause a greenhouse effect that increases global temperature. Carbon dioxide (CO_2) is one major GHG factor that causes the onset of global temperature increase. The CO_2 gas is closely related to anthropogenic activities. According to the Intergovernmental Panel on Climate Change (IPCC), five sectors are the main contributors to CO_2 emissions, namely energy use, industry and product use, PKPL (agriculture, forestry, and land use), and waste (Pedersen et al. 2021). Efforts to reduce GHG concentrations in the atmosphere are to reduce the release of CO_2 into the air (Triatmojo and Pamoengkas 2024).

Forests play a role in absorbing greenhouse gases because they can store carbon dioxide in the form of biomass and carbon (Ige 2018). One of the Indonesian government programs to reduce GHG is Forestry and Other Land Use (FOLU) Net Sink 2030, which aims to achieve a net sink of 140 million tons of CO_2 in the forestry and land sector by 2030. Increasing biomass and forest carbon stocks, as well as preventing deforestation and land degradation, are mitigation actions in the FOLU Net Sink 2030 (KLHK 2022).

Achieving the FOLU Net Sink 2030 target requires a lot of resources and action, especially at the site level. This includes increasing carbon stocks with biodiversity in mind. Maintaining and increasing carbon stocks is key to mitigating the impacts of climate change (Hilmi et al. 2021). Forest Area with Special Purpose (KHDTK) supports the FOLU Net Sink program. Based on the FOLU Net Sink Work Plan in the Conservation Sector for 2022, KHDTK plays a role in preventing deforestation and land degradation and environmental services, including maintaining carbon stocks.

KHDTK Aek Nauli is a forest area rich in natural potential, natural attractions and fauna biodiversity. Within the KHDTK Aek Nauli, there is a 50 ha arboretum that consists of plant blocks. The arboretum, composed of various species of trees, is important in absorbing greenhouse gases, especially atmospheric carbon dioxide (Akhabue et al. 2021). In supporting the FOLU Net Sink 2030 Program, studying the potential and economic valuation of carbon stored in stands within the Arboretum of KHDTK Aek Nauli is necessary. Based on the great potential of the Arboretum of KHDTK Aek Nauli in sequestering carbon and the absence of research that specifically examines the location, this research will focus on the economic valuation of carbon in the Arboretum of KHDTK Aek Nauli and the pole and tree phases because these phases can make a greater contribution to carbon sequestration. The results of this study are expected to provide information on the potential and economic valuation of carbon stands in the Arboretum of KHDTK Aek Nauli, as well as insights into its role in carbon storage, which supports climate change mitigation efforts.

2. Materials and Methods

2.1. Study Area

The study was conducted at the Arboretum of KHDTK Aek Nauli, managed by the Environmental and Forestry Instrument Standards Implementation Center (BPSILHK) Aek Nauli. Administratively, the arboretum is located in Sibaganding Village, Girsang Sipanganbolon District, Simalungun Regency, North Sumatra Province, with geographical coordinates of 4° 89' North latitude and 43° 25' East longitude (**Fig. 1**). Geographically, the arboretum is bordered with PT Toba Pulp Lestari in the North and East and KHDTK Aek Nauli in the South and East.

The Arboretum of KHDTK Aek Nauli is located in a high elevation area, which is between 1,164 – 1,218 masl, with topographic shapes and land contours mostly flat, some parts sloping even steep, forming shallow valleys, and has a land slope between 3–65%. The soil type in the Arboretum of KHDTK Aek Nauli is dominated by yellowish-brown Podzolic soil. Rainfall in the Aek Nauli area is included in type A, and the annual rainfall ranges from 2,199–2,452 mm (Kholibrina and Susilowati 2018).

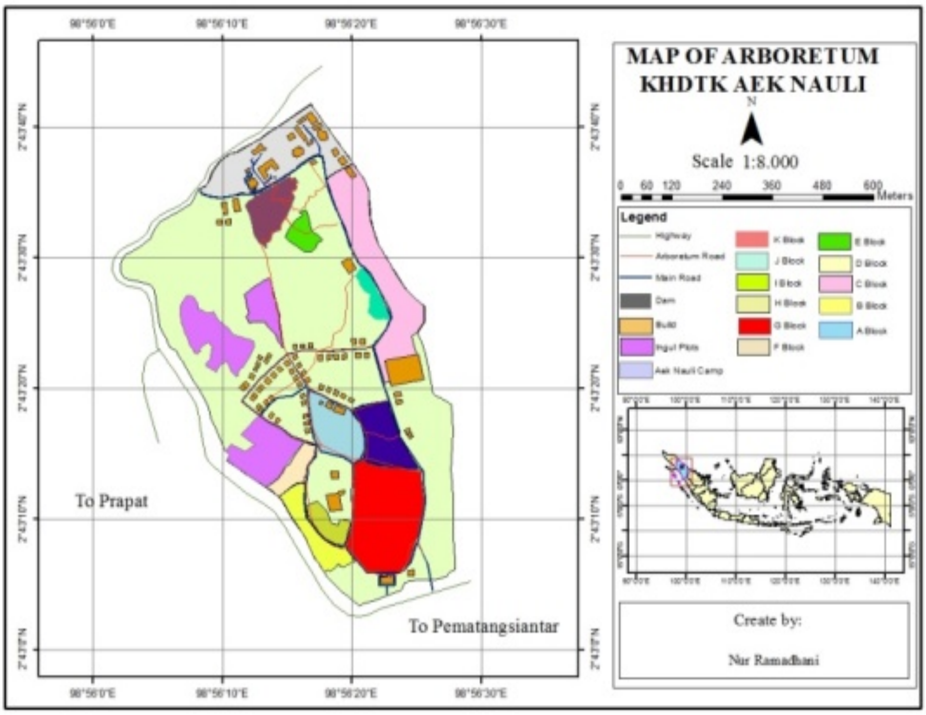

Fig. 1. Map of the study area in the KHDTK Aek Nauli.

2.2. Tools and Material

The equipment used in this study was a map of the research location, global positioning (GPS) tracker, diameter tape (phi band), compass, meter, rope, tally sheet, and camera for documentation. The object of research was the stands with diameter of more than 10 cm.

2.3. Sampling

The sampling method in sample plot making is based on the systematic sampling method with a random start with a sampling intensity of 5% of the total area of the Arboretum of KHDTK Aek Nauli. In a forest group with an area of 1,000 ha or more, the sampling intensity is 2%, while if it is less than 1,000 ha, the sampling intensity is 5%–10% (Fahmi and Saepuloh 2023). Based on the above provisions, a sampling intensity of 5% is used because the area of the Arboretum of KHDTK Aek Nauli is 50 ha.

2.4. Research Approach

The method used in carbon stock estimation is non-destructive. The non-destructive method in forest carbon is a method of calculating biomass without damaging trees.

2.5. Plot Establishment

Data was collected using square plots with 63 sample plots with an area of 20 m × 20 m for tree-level stands and 10 m × 10 m for pole-level stands. 80% of the total carbon stored in forests is in tree biomass (Sun and Liu 2020). Therefore, measurements at this phase provide a more accurate estimate of carbon stocks.

2.6. Data Collection

Data collected included tree species and diameter at breast height (DBH). Stand data were collected at the pole phase (diameter 10–19 cm) and tree phase (diameter of more than 20 cm) for measurement of the DBH of the individual tree measuring tape was used. DBH trees that are fairly straight or learning were measured parallel to their trunk. For a tree that is forked at or below 130 cm, DBH was measured just below the fork, but if the fork is close to the ground, it was considered as two trees (Alimbon and Manseguaio 2021)

2.7. Data Analysis

2.7.1. Biomass estimation

The allometric equation used in this study to estimate above-ground tree biomass is as follows (Wiryono et al. 2016). The allometric formula is as follows:

$$W = 0.11 \times p \times D^{2.62} \quad (1)$$

where W is biomass (kg/tree), p is the density of wood (g/cm^3), and D is the diameter at breast height (cm).

A model was chosen due to the similarity of the site to secondary forests and the analysis results that incorporated the relationship between tree diameter and height, as well as average tree wood density, resulting in a better estimate of carbon stocks.

2.7.2. Carbon storage estimation

Estimation of carbon stocks from stand biomass is calculated using the following formula (Nanda et al. 2023; Sari et al. 2022):

$$C = B \times 0.47 \quad (2)$$

where C is total carbon stock (tons.C/ha), B is biomass (tons/ha) and 0.47 = percentage value of carbon content. Furthermore, the calculation of carbon dioxide is converted by the time of the CO_2 with 3.67.

3. Results and Discussion

KHDTK Aek Nauli is a forest area rich in natural potential, natural attractions and fauna biodiversity. KHDTK Aek Nauli has an arboretum area consisting of neatly arranged plant blocks built as many as 12 types of blocks. Poles and trees dominate the Arboretum of KHDTK Aek Nauli, and vegetation is mostly from native species, as are the results of planting at the site (Kholibrina and Susilowati 2018). Some of the native species of the area that are currently maintained are pine species and local types of upland forests. Medicinal-type high trees, native trees, endemic plants and local forest trees dominate the Arboretum of KHDTK Aek Nauli.

3.1. Potential Vegetation of the Arboretum of KHDTK Aek Nauli

From the results of research conducted in the Arboretum of KHDTK Aek Nauli, there are a total of 734 individuals with 62 different species, and the two dominant species are *Pinus merkusii* 30.65% (225 individuals) dan *Schima wallichii* 6.54% (48 individuals) (**Table 1**).

Table 1. Stands composition of the Arboretum of KHDTK Aek Nauli

No.	Species	Family	Number of individuals	Percentage (%)	IUCN status
1	*Agathis dammara*	Araucariaceae	1	0.14	VU
2	*Acacia mangium*	Fabaceae	1	0.14	LC
3	*Alnus nephalensis*	Beturaceae	4	0.54	N/A
4	*Persea americana*	Lauraceae	8	1.09	LC
5	*Adinandra dumosa*	Theaceae	18	2.45	LC
6	*Mangifera foetida*	Anacardiaceae	1	0.14	LC
7	*Casuarina sumatrana*	Casuarinaceae	21	2.86	LC
8	*Durio zibenthus*	Malvaceae	1	0.14	N/A
9	*Eucalyptus alba*	Myrtaceae	2	0.27	LC
10	*Cratoxylon arborescens*	Guttiferaceae	4	0.54	N/A
11	*Exbucklandia populnea*	Hammelidaceae	25	3.41	LC
12	*Trema orientalis*	Ulmaceae	1	0.14	LC
13	*Syzygium aqueum*	Myrtaceae	12	1.63	LC
14	*Szygium malaccense*	Myrtaceae	1	0.14	N/A
15	*Tectona grandis*	Verbenaceae	19	2.59	EN
16	*Caliandra calothyrsus*	Fabaceae	26	3.54	N/A
17	*Dryobalanops aromatica*	Dipterocarpaceae	1	0.14	VU
18	*Cinnamomum burmanii*	Lauraceae	6	0.82	LC
19	*Styrax* sp.	Styraceae	21	2.86	N/A
20	*Aleurites moluccanus*	Euphorbiaceae	11	1.50	N/A
21	*Scodocarpus bornensis*	Olacaceae	5	0.68	N/A
22	*Symplocos fasciculata*	Symplocaceae	4	0.54	LC
23	*Macademia integrifolia*	Proteaceae	3	0.41	N/A
24	*Macaranga sumatrana*	Euphorbiaceae	2	0.27	NT
25	*Switenia macrophylla King*	Meliaceae	7	0.95	N/A
26	*Mangifera indica*	Anacardiaceae	2	0.27	DD
27	*Garcinia mangostana L.*	Guttiferceae	1	0.14	N/A
28	*Palaquium obovatum*	Sapotaceae	3	0.41	LC
29	*Litsea* spp.	Lauraceae	36	4.90	N/A
30	*Litsea odorifera*	Lauraceae	2	0.27	N/A
31	*Acer laurinum*	Aceraceae	9	1.23	LC
32	*Cinnamomum subavenium*	Lauraceae	10	1.36	LC
33	*Gnetum gnemon*	Gnetaceae	15	2.04	LC
34	*Shorea leprosula*	Dipterocarpaceae	1	0.14	NT
35	*Melia azedarach*	Meliaceae	39	5.31	LC
36	*Pterocymbium tinctorium*	Stercualiaceae	1	0.14	LC
37	*Artocarpus heterophyllus*	Moraceae	8	1.09	N/A
38	*Quercus sumatrana*	Fagaceae	24	3.27	NT
39	*Pinus merkusii*	Pinaceae	6	0.82	VU
40	*Sauraula bracteosa*	Actinidaceae	225	30.65	VU
41	*Alstonia scholaris*	Apocynaceae	1	0.14	LC
42	*Schima wallichii*	Theaceae	6	0.82	LC
43	*Altingia excelsa*	Hammelidaceae	48	6.54	LC
44	*Dracontomelon dao*	Anacardiaceae	8	1.09	LC
45	*Adenanthera paronina*	Fabaceae	1	0.14	LC
46	*Alstonia angustifolia Wall*	Apocynaceae	2	0.27	LC
47	*Rhoudolia tesymanii*	Acanthaceae	8	1.09	LC
48	*Dacrydium elatum*	Podocarpaceae	1	0.14	LC
49	*Glochidion arborescens*	Euphorbiaceae	4	0.54	N/A
50	*Bischofia javanica*	Euphorbiaceae	2	0.27	LC
51	*Piper aduncum*	Piperaceae	10	1.36	LC
52	*Schefflera longifolia*	Araliaceae	1	0.14	LC
53	*Macaranga peltata*	Euphorbiaceae	2	0.27	N/A
54	*Glochidion superbum*	Euphorbiaceae	1	0.14	N/A
55	*Gynotroches axillaris Blume*	Rhizophoraceae	4	0.54	N/A
56	*Artocapus incisa*	Moraceae	2	0.27	N/A
57	*Peronema canescens Jack*	Verbenaceae	11	1.50	LC
58	*Toona sureni*	Meliaceae	23	3.13	LC
59	*Fragraea fragarans*	Loganiaceae	3	0.41	N/A
60	*Symplocos spicata*	Symplocaceae	4	0.54	N/A
61	*Artocarpus odoratissmus*	Moraceae	1	0.14	NT
62	*Engelhardia wallichiana*	Juglandaceae	4	0.54	LC
	Total		**734**	**100**	

Notes: DD = Data Deficient, EN = Endangered, LC = Least concern, NT = Near Threatened, VU = Vulnerable, N/A = unidentified.

Pinus merkusii and *Schima wallichii* are the dominant species and highly adaptable to highland conditions. *Agathis dammara*, *Acacia* sp., *Mangifera foetida*, and *Durio zibenthus* are the least found species. There are also five plant species with endangered status according to the IUCN Red List namely *Agathis dammara, Dryobalanops aromatica, Tectona grandis, Pinus merkusii*, and *Sauraula bracteosa*. According to Ristiara et al. (2017), dominant species can master where they grow and develop according to their environmental conditions, which are entirely or mostly at the top level of all species in a vegetation community. The Arboretum of KHDTK Aek Nauli has an average value of the Shannon-Wiener diversity index (H') of 3.06, indicating high species diversity. The species of stands composing the Arboretum of KHDTK Aek Nauli vary, and the number of each type varies. Species diversity can indicate a community's ability to balance its components from various disturbances that arise (Roswell et al. 2021). Biodiversity including species diversity, is an indicator of community stability, meaning that the community can maintain its stability despite disturbances to the constituent components of the community. The higher the species diversity in a habitat or the greater the populations that make up the community, the more stable the community. Biodiversity like that found in this area provides many ecological and economic benefits. Species diversity is a part of stand structure complexity. Tree diameter and height diversity are typically defined as stand structural diversity (Ali 2019). However, high biodiversity also makes the area vulnerable to disturbances, such as deforestation and poaching. Therefore, the management of this area should be done by considering ecological, social and economic aspects in an integrated manner.

3.2. Diameter Distribution of the Arboretum of KHDTK Aek Nauli

The diameter distribution of trees is a structural characteristic used to describe virgin forests. The distribution of stand diameters within a stand is the basis for determining the ecological and economic value of the stand, stand structure and stability, and appropriate management practices (Güner et al. 2023). Stand diameter distribution is the frequency of tree diameters at breast height (DBH) within a forest stand. It is a key factor in determining the structure and value of a forest stand, as well as the management practices that should be employed (Chen et al. 2019). The stand diameter distribution is a simple potential factor for describing tree characteristics in forest stands. The diameter distribution and number of individuals are presented in **Fig. 2**.

Fig. 2 shows that the Arboretum of KHDTK Aek Nauli has a variety of diameter classes in the pole and tree phases, and the entire diameter distribution of stands in the Arboretum of KHDTK Aek Nauli is categorized into 11 diameter classes (**Fig. 2c**). The distribution of tree diameter is an important parameter in describing stand properties. Tree diameter strongly correlates with volume and other tree characteristics (Güner et al. 2023). Diameter plays an important role in the natural regeneration process, affecting seed dispersal, competition and stand structure, all of which contribute to the success of forest regeneration. Natural regeneration promotes the ecological sustainability of natural forests as it involves 'close to nature' silvicultural forestry practices. Natural regeneration facilitates the establishment and growth of native species, enhancing the stability, resilience and diversity of forest ecosystems (Hammond et al. 2021). As shown in **Fig. 2b**, the diameter distribution in the tree phase is shaped like an inverted J curve. The health of a tree population can be seen by its ability to produce new generations and have a stable distribution that allows for continuous regeneration. If regeneration is continuous, then the distribution of species groups will show an inverted J-shape curve, representing healthy regeneration (Gebeyehu et al. 2019). The shape of the inverted J-curve is generally considered an important characteristic of old-growth forests in a state of equilibrium (Bauhus et al. 2017).

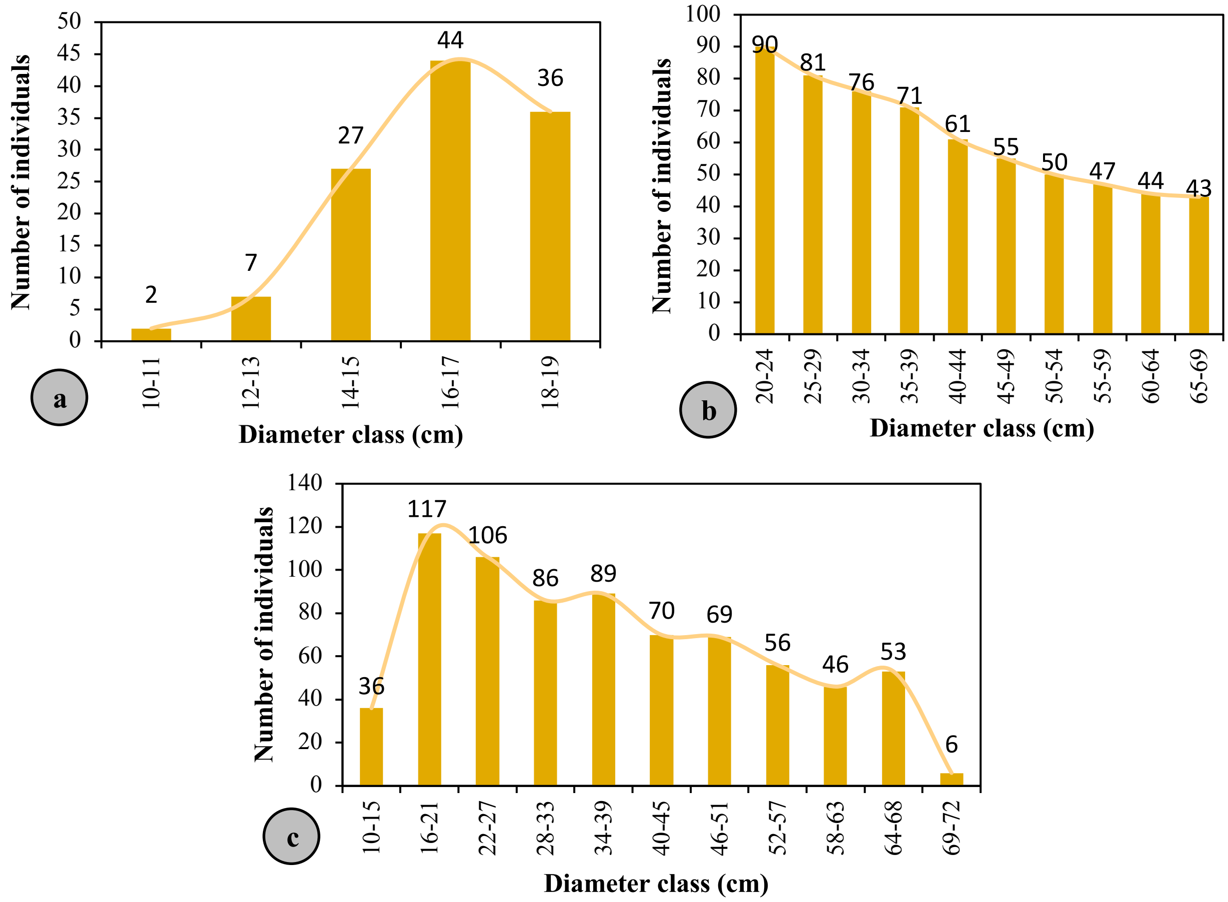

Fig. 2. Diameter distribution of the Arboretum of KHDTK Aek Nauli: (a) pole phase, (b) tree phase, (c) stands.

Forest stands can considerably differ between the trees' size structure and size growth, even with similar mean tree dimensions (mean diameter, mean volume) or cumulative hectare-related characteristics (standing stock, biomass). Especially in mixed-species stands, any differences in size structure can strongly determine stand productivity via differences in resource acquisition, resource-use efficiency, and respiratory losses (Pretzsch and Schutze 2016).

3.3. Biomass and Carbon Storage Estimation of the Arboretum of KHDTK Aek Nauli

Above-ground biomass is the total amount of above-ground living material in a tree and is often described as a biomass density, with units of mass per unit area (Araza et al. 2022). A part of the total biomass of the stand is the amount of carbon stored by the stand (carbon stock). In this study, above-ground biomass was obtained from tree trunks. Tree trunks have a large biomass value and are a key component in forest carbon storage. Darmawan et al. (2022) explained that each tree species can sequester carbon, increasing the amount of biomass in the trunk. The results of calculating biomass and stand carbon from each species in the Arboretum of KHDTK Aek Nauli are shown in **Table 2.**

Table 2. Stands biomass from each species in the Arboretum of KHDTK Aek Nauli

No.	Species	Number of individuals	Biomass (tons)	Biomass (tons/ha)	Carbon (tons/ha)
1	*Agathis dammara*	1	0.07	0.03	0.01
2	*Acacia mangium*	1	4.6	1.82	0.86
3	*Alnus nephalensis*	4	6.35	2.52	1.18
4	*Persea americana*	8	3.19	1.26	0.59
5	*Adinandra dumosa*	18	9.43	3.74	1.76
6	*Mangifera foetida*	1	0.39	0.15	0.07
7	*Casuarina sumatrana*	21	59.49	23.61	11.10
8	*Durio zibenthus*	4	1.71	0.68	0.32
9	*Eucalyptus alba*	1	0.48	0.19	0.09
10	*Cratoxylon arborescens*	2	4.38	1.74	0.82
11	*Exbucklandia populnea*	25	35.46	14.07	6.61
12	*Trema orientalis*	1	0.37	0.15	0.07
13	*Syzygium aqueum*	24	15.5	6.15	2.89
14	*Szygium malaccense*	12	0.21	0.08	0.04
15	*Tectona grandis*	1	19.92	7.91	3.72
16	*Caliandra calothyrsus*	19	3.83	1.52	0.71
17	*Dryobalanops aromatica*	26	1.94	0.77	0.36
18	*Cinnamomum burmanii*	1	2.08	0.83	0.39
19	*Styrax* sp.	5	9.91	3.93	1.85
20	*Aleurites moluccanus*	6	12.97	5.15	2.42
21	*Scodocarpus bornensis*	21	2.04	0.81	0.38
22	*Symplocos fasciculata*	11	0.52	0.21	0.10
23	*Macademia integrifolia*	4	2.8	1.11	0.52
24	*Macaranga sumatrana*	3	0.24	0.09	0.04
25	*Switenia macrophylla*	2	12.96	5.14	2.42
26	*Mangifera indica*	7	2.04	0.81	0.38
27	*Garcinia mangostana*	2	0.64	0.25	0.12
28	*Palaquium obovatum*	1	3.52	1.40	0.66
29	*Litsea* spp.	3	22.89	9.08	4.27
30	*Litsea odorifera*	36	6.68	2.65	1.25
31	*Acer laurinum*	2	3.51	1.39	0.66
32	*Cinnamomum subavenium*	9	8.71	3.46	1.62
33	*Gnetum gnemon*	10	3.05	1.21	0.57
34	*Shorea leprosula*	15	31.05	12.32	5.79
35	*Melia azedarach*	1	2.19	0.87	0.41
36	*Pterocymbium tinctorium*	39	5.16	2.05	0.96
37	*Artocarpus heterophyllus*	1	4.48	1.78	0.84
38	*Quercus sumatrana*	8	11.95	4.74	2.23
39	*Pinus merkusii*	6	408.52	162.11	76.19
40	*Sauraula bracteosa*	225	0.15	0.06	0.03
41	*Alstonia scholaris*	1	3.6	1.43	0.67
42	*Schima wallichii*	6	75.18	29.83	14.02
43	*Altingia excelsa*	48	12.8	5.08	2.39
44	*Dracontomelon dao*	8	4.2	1.67	0.78
45	*Adenanthera paronina*	1	0.18	0.07	0.03
46	*Alstonia angustifolia*	2	7.22	2.86	1.35
47	*Rhoudolia tesymanii*	8	6.91	2.74	1.29
48	*Dacrydium elatum*	1	0.23	0.09	0.04
49	*Glochidion arborescens*	4	3.13	1.24	0.58
50	*Bischofia javanica*	2	0.49	0.20	0.09
51	*Piper aduncum*	10	1.23	0.49	0.23
52	*Schefflera longifolia*	1	0.15	0.06	0.03
53	*Macaranga peltata*	2	0.31	0.12	0.06
54	*Glochidion superbum*	1	0.49	0.20	0.09
55	*Gynotroches axillaris*	4	4.99	1.98	0.93
56	*Artocapus incisa*	2	1	0.40	0.19
57	*Peronema canescens*	11	3.93	1.56	0.73
58	*Toona sureni*	23	3.77	1.49	0.70
59	*Fragraea fragarans*	3	1.41	0.56	0.26
60	*Symplocos spicata*	4	3.8	1.51	0.71
61	*Artocarpus odoratissmus*	1	0.13	0.05	0.02
62	*Engelhardia wallichiana*	4	4.97	1.97	0.93
	Total	**734**	**865.50**	**343.45**	**161.42**

Table 2 shows the potential biomass and carbon of the Arboretum of KHDTK Aek Nauli. The largest is *Pinus merkusii* at 162.11 tons/ha and 76.19 tons/ha, and the smallest is *Agathis dammara* at 0.03 tons/ha and 0.01 tons/ha, respectively. The different types of trees will have different abilities to absorb CO_2 in the air (Muslih et al. 2022). The number of trees in a forest area directly affects total biomass and carbon storage. The more trees there are, the greater the potential total biomass can be produced. Each tree stores a certain amount of carbon, depending on species and size. Biomass is also influenced by diameter. A larger DBH means a larger trunk and branch surface, resulting in higher tree biomass (Adhikari et al. 2021). Biomass differences are influenced by vegetation density, diameter size diversity, and specific gravity distribution of the vegetation. Land use consisting of trees with species that have high wood density values will produce higher biomass compared to land with species that have low wood density values (Joshi et al. 2024). Plant species have different biomass production rates based on efficiency (Ige 2018). Several factors, including differences in tree species, tree height and environmental factors, influence biomass differences. Meanwhile, carbon stocks are strongly influenced by biomass; therefore, anything that increases or decreases in biomass potential will also affect carbon storage.

Table 2 shows that the biomass and carbon stocks in the Arboretum of KHDTK Aek Nauli are 343.45 tons/ha and 161.42 tons/ha, respectively. Carbon storage in the KHDTK Bengkulu University is lower. Research results in the KHDTK Bengkulu University are 22.97 tons/ha and 10.55 tons/ha (Andreas et al. 2023). Furthermore, biomass and carbon can also be seen from the diameter class. Carbon storage in the Arboretum of KHDTK Aek Nauli based on diameter class is shown in **Fig. 3**.

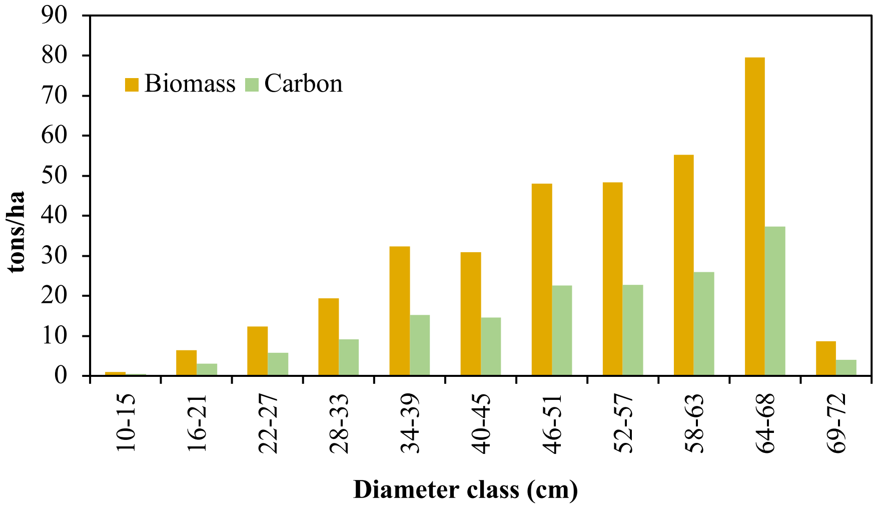

Fig. 3. Biomass and carbon storage potential of the Arboretum of KHDTK Aek Nauli.

The biomass value is directly proportional to the value of carbon storage (**Fig. 3**). Trees with large diameters can store more carbon because the main contribution of biomass is in the trunk (Ristiara et al. 2017). Carbon content varies due to differences in biomass between species. As biomass content increases, the value of carbon content increases, indicating that carbon content is directly proportional to biomass content. Biomass and carbon stock value differences in each diameter class are caused by the plot's number of stands and DBH (Heriyanto et al. 2023). The larger the diameter, the greater the biomass storage resulting from CO_2 conversion and increased CO_2 absorbed by the plants. (Ledheng et al. 2022). The more vegetation there is in an area, the higher its ability to anchor CO_2 from the air and stored energy in the area and vice versa (Marnaek et al. 2024). The high value of carbon in KHDTK Aek Nauli shows that this area has great potential in climate change mitigation efforts. Forests in this area act as an effective carbon sink, thus contributing to maintaining the global climate balance.

3.4. Carbon Economic Valuation in the Arboretum of KHDTK Aek Nauli

The economic value of a forest with a carbon stock can be estimated using shadow prices, and the carbon price used is based on benefit transfer. Benefit transfer is a nonmarket valuation tool widely used in various decision contexts. Its primary role is deriving reliable estimates of value from prior research when new, original research is not feasible, given time and resource constraints (Rosenberger and Loomis 2017). Estimating the economic value of carbon means calculating the carbon potential obtained using the agreed carbon price. This study uses a carbon selling price of USD 5.54/ton of carbon with the price adjustment using the benefit transfer method, which is then converted into IDR (Pradhana 2022). Based on the USD to Rupiah exchange rate on 29 February 2024 (IDR 15,715), the carbon price per ton after being converted to Rupiah is IDR 87,061. The results of the economic value calculation of carbon in the Arboretum of KHDTK Aek Nauli are presented in **Table 3.**

Table 3. Carbon economic value of the Arboretum of KHDTK Aek Nauli

No.	Species	Carbon (tons.C/ha)	Carbon (tons.CO_2e/ha)	Carbon economic value	
				USD	IDR
1	*Agathis dammara*	0.01	0.05	14.12	221,889
2	*Acacia mangium*	0.86	3.15	871.65	13,698,032
3	*Alnus nephalensis*	1.18	4.35	1,203.69	18,916,023
4	*Persea americana*	0.59	2.18	603.95	9,491,138
5	*Adinandra dumosa*	1.76	6.46	1,788.82	28,111,320
6	*Mangifera foetida*	0.07	0.27	73.57	1,156,147
7	*Casuarina sumatrana*	11.10	40.72	11,279.93	177,264,178
8	*Durio zibenthus*	0.32	1.17	324.96	5,106,677
9	*Eucalyptus alba*	0.09	0.33	91.48	1,437,560
10	*Cratoxylon arborescens*	0.82	2.99	829.60	13,037,207
11	*Exbucklandia populnea*	6.61	24.27	6,723.04	105,652,545
12	*Trema orientalis*	0.07	0.25	70.34	1,105,428
13	*Syzygium aqueum*	2.89	10.61	2,939.14	46,188,579
14	*Szygium malaccense*	0.04	0.14	40.16	631,099
15	*Tectona grandis*	3.72	13.64	3,777.67	59,366,114
16	*Caliandra calothyrsus*	0.71	2.62	726.80	11,421,696
17	*Dryobalanops aromatica*	0.36	1.33	367.08	5,768,661
18	*Cinnamomum burmanii*	0.39	1.42	394.32	6,196,676
19	*Styrax* sp.	1.85	6.78	1,878.57	29,521,760
20	*Aleurites moluccanus*	2.42	8.88	2,459.05	38,643,941
21	*Scodocarpus bornensis*	0.38	1.40	386.65	6,076,252
22	*Symplocos fasciculata*	0.10	0.36	98.59	1,549,366
23	*Macademia integrifolia*	0.52	1.92	531.44	8,351,583
24	*Macaranga sumatrana*	0.04	0.16	45.06	708,122
25	*Switenia macrophylla*	2.42	8.87	2,456.37	38,601,782
26	*Mangifera indica*	0.38	1.40	387.53	6,090,098
27	*Garcinia mangostana*	0.12	0.44	121.81	1,914,169
28	*Palaquium obovatum*	0.66	2.41	667.16	10,484,426
29	*Litsea* spp.	4.27	15.67	4,339.99	68,202,991
30	*Litsea odorifera*	1.25	4.57	1,266.50	19,903,106
31	*Acer laurinum*	0.66	2.40	665.91	10,464,705
32	*Cinnamomum subavenium*	1.62	5.96	1,651.04	25,946,122
33	*Gnetum gnemon*	0.57	2.09	577.80	9,080,064
34	*Shorea leprosula*	5.79	21.25	5,886.87	92,512,232
35	*Melia azedarach*	0.41	1.50	415.26	6,525,745
36	*Pterocymbium tinctorium*	0.96	3.53	978.20	15,372,374
37	*Artocarpus heterophyllus*	0.84	3.07	849.44	13,348,972
38	*Quercus sumatrana*	2.23	8.18	2,266.64	35,620,237

No.	Species	Carbon (tons.C/ha)	Carbon (tons.CO_2e/ha)	Carbon economic value	
				USD	IDR
39	*Pinus merkusii*	76.19	279.62	77,455.77	1,217,217,411
40	*Sauraula bracteosa*	0.03	0.10	28.76	451,968
41	*Alstonia scholaris*	0.67	2.46	681.76	10,713,907
42	*Schima wallichii*	14.02	51.46	14,253.50	223,993,827
43	*Altingia excelsa*	2.39	8.76	2,426.24	38,128,357
44	*Dracontomelon dao*	0.78	2.87	795.86	12,506,899
45	*Adenanthera paronina*	0.03	0.12	34.15	536,600
46	*Alstonia angustifolia*	1.35	4.94	1,368.11	21,499,813
47	*Rhoudolia tesymanii*	1.29	4.73	1,310.17	20,589,389
48	*Dacrydium elatum*	0.04	0.16	43.83	688,861
49	*Glochidion arborescens*	0.58	2.14	592.93	9,317,880
50	*Bischofia javanica*	0.09	0.34	93.50	1,469,381
51	*Piper aduncum*	0.23	0.84	233.74	3,673,156
52	*Schefflera longifolia*	0.03	0.10	28.18	442,872
53	*Macaranga peltata*	0.06	0.22	59.68	937,814
54	*Glochidion superbum*	0.09	0.34	93.79	1,473,910
55	*Gynotroches axillaris*	0.93	3.42	946.76	14,878,351
56	*Artocapus incisa*	0.19	0.68	189.25	2,974,025
57	*Peronema canescens*	0.73	2.69	745.09	11,709,144
58	*Toona sureni*	0.70	2.58	714.07	11,221,550
59	*Fragraea fragarans*	0.26	0.96	266.56	4,188,962
60	*Symplocos spicata*	0.71	2.60	720.52	11,323,024
61	*Artocarpus odoratissmus*	0.02	0.09	24.71	388,363
62	*Engelhardia wallichiana*	0.93	3.40	942.90	14,817,731
	Total	**161.42**	**592.42**	**164,100.05**	**2,578,832,243**

Table 3 shows the carbon economic value of the Arboretum of KHDTK Aek Nauli with a carbon sequestration of 592.42 tons.CO_2e /ha is IDR 2,578,832,24 or USD 164,100. The economic carbon value in the Arboretum of KHDTK Aek Nauli stand is greater than other studies, such as in the research of Borsari et al. (2016) with a carbon economic value of stands in the Winona State University Arboretum of USD 20,148 with a total carbon stock of 88.38 tons.CO_2e. The difference in the economic value of standing carbon is influenced by carbon stocks, forest area, and carbon prices used.

Carbon economic valuation is important in climate change mitigation and can be used as the basis for payment mechanisms for environmental services through the REDD+ scheme. The REDD+ scheme provides financial incentives that support area managers in climate change mitigation efforts and sustainable forest management (Ojea et al. 2016). Through the REDD+ scheme, the Environmental and Forestry Instrument Standardization Agency (BSILHK) Bogor received funding for climate change mitigation efforts. It was registered in the National Registry System (SRN) during the 2018–2020. The results of the carbon economic assessment have a role in supporting the achievement of the FOLU Net Sink 2030 program by recording its contribution to the National Registry System (SRN). Still, the assessment results cannot be converted into real value because the area is managed by a government agency, not a business actor for the carbon trading scheme.

4. Conclusions

The potential biomass and carbon stocks contained in the stands in the Arboretum of KHDTK Aek Nauli for the pole phase are 4.76 tons/ha and 2.24 tons/ha, respectively, while for the tree phase are 338.69 tons/ha and 159.19 tons/ha respectively. The total estimated carbon sequestration is 592.42 tons.CO_2e/ha and the total economic value of the carbon stock potential of the Arboretum of KHDTK Aek Nauli based on carbon unit price per ton is USD 164,100 (carbon selling price of 5.54 USD/ton and rupiah to the dollar exchange rate of IDR 15,715). The Arboretum of KHDTK Aek Nauli is important in preserving the environment, especially concerning carbon sequestration. Its large carbon storage potential shows that this arboretum provides significant environmental service benefits for the KHDTK Aek Nauli area. Therefore, forest management in this arboretum should be carried out sustainably to maintain and enhance carbon stocks, and this effort is in line with Indonesia's commitment to reduce greenhouse gas emissions by 2030.

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