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Regional Case Study

Allometric equation of *Paraserianthes falcataria* (L.) and *Anthocephalus cadamba Miq*. for estimating carbon stocks

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Abstract

Coal mining can increase land degradation and deforestation, so efforts are needed to ensure land use in post-mining areas. Therefore, mining companies must carry out land reclamation to restore the important function of forests by planting *sengon laut* (*Paraserianthes falcataria* (L.)) and burflower tree (*Anthocephalus cadamba* Miq.). In contrast to mining, which produces emissions and carbon that contribute to global warming, land reclamation helps absorb carbon and produce oxygen for living things. Therefore, a study was carried out to estimate the carbon stocks from reclamation activities at PT. Indobara Borneo. A quantitative approach through Stratified Random Sampling was applied in this study. Carbon estimation is carried out using allometric equations. The allometric equation of *Paraserianthes falcataria* (L.) is $Y = 0.028D^{2,695}$, while the allometric equation of *Anthocephalus cadamba* Miq. is $Y = 0.035D^{2,600}$. The total carbon stocks for burflower tree plants are 84.51 tons/ha with a CO2 sink potential of 974.73 tons/Ha, while the total carbon stocks for *sengon laut* plants are 86.18 tons/ha with a CO2 sink potential of 1355.49 tons/ha. The value of CO_2 sink and carbon stock indicates that there are environmental services to restore and improve vegetation.

Keywords: Coal Mining; greenhouse effect; land changes

1. Introduction

Environmental damage resulting from mining activities that intentionally remove vegetation, transform the landscape, and change the soil composition can cause erosion, sedimentation, soil nutrients, and soil compaction, leading to land degradation. Therefore, efforts are required to improve the environmental conditions of the mining area through reclamation and post-mining activities (Herdiansyah et al., 2018). According to Marbà et al. (2018), land conversion causes an increase in accumulated carbon emissions from anthropogenic activities by 32%. Therefore, mining companies must carry out reclamation no later than one month after there are no more mining activities in post-mining land and its surroundings.

Population growth drives environmental change, especially climate change, such as the mining land. Increasing human need impact the process of change and environmental characteristics. This influence occurs continuously at various spatial and temporal levels and can have good or bad effects (Aklile and Beyene, 2014). Spatial interaction between socio-economic activities in an area is one of the factors that can influence land use. As population increases, current land use changes tend to have negative impacts (Liao et al., 2013). Changes in land use are a major cause of greenhouse gas emissions (CO, CH, and NO). The rapid urbanization of local ecological systems and the environment impacts natural carbon stocks (Long et al., 2014).

Carbon is an element absorbed from the atmosphere through photosynthesis and stored in the biomass. Various factors, including climate, topography, land characteristics, age and density of vegetation, species composition, and growing area quality, influence the carbon absorption level in forests. The primary storage for carbon is found in biomass (including the upper part, such as stems, branches, twigs, leaves, flowers, and fruit, as well as the lower part, such as roots), dead organic matter, soil, and stored in wood products which can be emitted for long-term products (Azham, 2015).

Forests can act as both a sink (carbon sink) and a source (carbon emitter) (Sorbu et al., 2021). Accurate information regarding forest carbon stored in forest biomass and necromass is essential for describing the conditions of forest ecosystems for sustainable forest resource management, so that it is economically and ecologically profitable (Idris et al., 2013; Komul and Hitipeuw, 2022). By measuring, it can be seen how much carbon is absorbed from the vegetation (Komul and Hitipeuw, 2022). Trees, understorey, or shrubs can absorb CO2 during photosynthesis and store it as organic material in the biomass (Suryandari et al., 2019).

Sengon laut (*Paraserianthes falcataria* (L.) and burflower tree (*Anthocephalus cadamba* Miq.) were chosen for planting in reclamation areas because they are fast-growing trees and can absorb carbon more quickly than other trees. *Sengon laut* can grow on various soil types ranging from poor to good drainage, marginal soil to fertile soil, dry soil to damp soil, and low salinity soil. Likewise, burflower trees have a high tolerance for various soil types and can be planted on critical land. Both trees can grow under poor soil conditions; however, their ability to absorb carbon differs. In addition to the burflower tree and *sengon laut*, several natural plants are also planted on the reclaimed land, such as white meranti (*Shorea agami* P.S.Ashton), red meranti (*Shorea leprosula* Miq.), *meranti batu* (*Parashorea aptera* Sloot.), and yellow meranti (*Shorea acuminatissima* Symington).

According to research conducted by Ohorella et al. (2022), *sengon laut* can grow in various soil types, including dry, moist, and even soil containing salt and acid, as long as the drainage level is adequate. In photosynthesis, *sengon laut* leaves absorb Nitrogen (N) and Carbon dioxide (CO2) from the air. With these characteristics, photosynthesis proceeds more efficiently to absorb more CO2 than other trees. The highest carbon stocks in the *sengon laut* were found in the stem part, with 67% of the trees (42.52025 kg C/ha from the stem part of 85.0405 kg/ha). Based on the explanation above, this study aimed to estimate the *sengon laut* (*Paraserianthes falcataria* (L.)) and burflower tree (*Anthocephalus cadamba* Miq.) carbon stocks in the post-mining reclamation land of the PT. Indobara Borneo.

Several studies have been conducted at PT Borneo Indobara. Agustina et al. (2023) studied carbon stocks and CO2 absorption in oil palm reclamation areas. Noor et al. (2020) have conducted a carbon stock analysis in the reclamation area in 2019. Koirin and Prasetia (2023) studied the risk analysis of coal haul road upgrades to support sustainable development. Saputra et al. (2022) conducted a study on the analysis of soil formation from overburden cover rock in reclamation areas. Nugroho et al. (2021) studied the effect of understorey diversity on wildlife in coal mine reclamation areas. Based on these previous studies, this research provides the latest information on carbon stocks in reclamation areas specialized in burflower trees and *sengon lauts*.

2. Methods

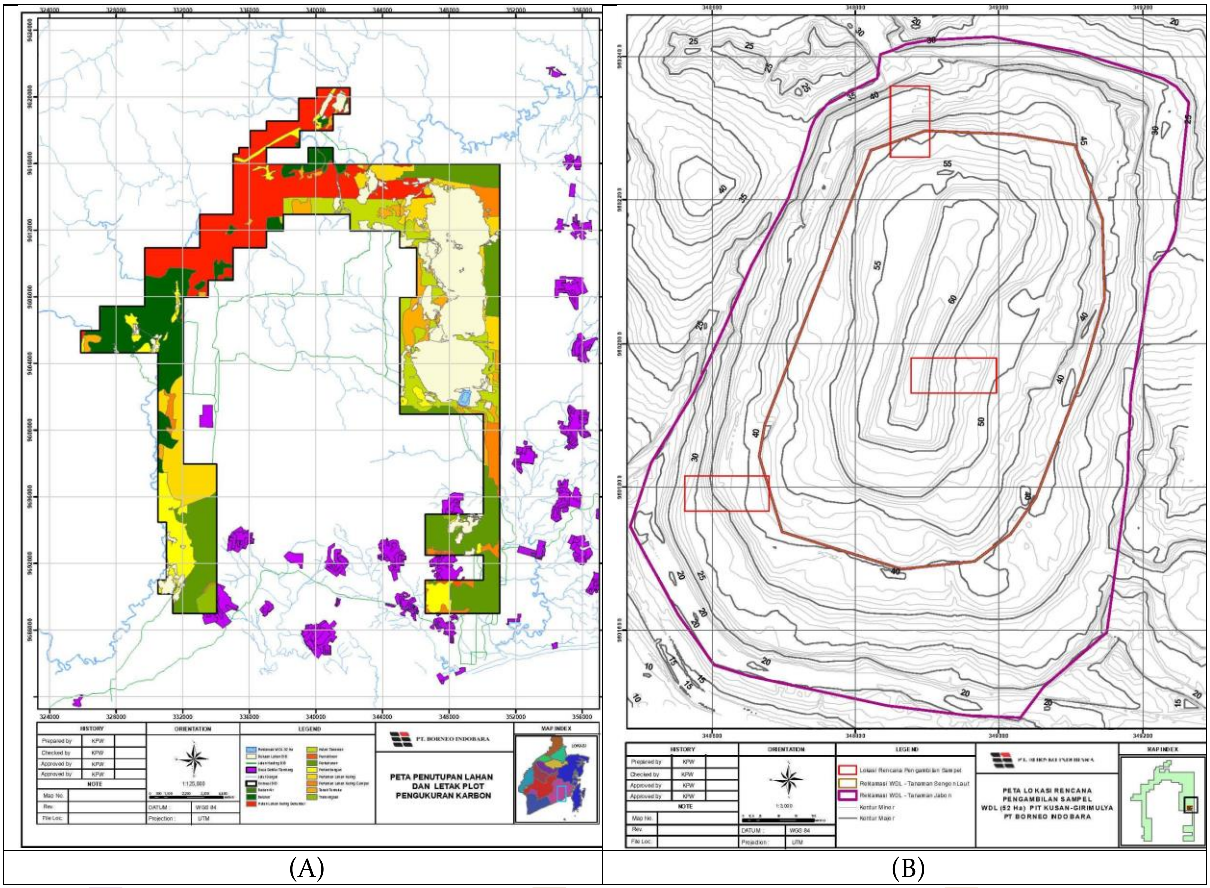
2.1 Study Area

PT. Borneo Indobara is a company operating in the coal mining sector in Tanah Bumbu Regency, South Kalimantan province. Currently, PT. Borneo Indobara mines in two active areas, the West and the East Blocks. PT. Borneo Indobara is working to increase coal production from year to year. Increasing coal production cannot be separated from environmental management as one of PT. Borneo Indobara's commitment to preserving the environment. Administratively, study area is in mining area of Contract

Mining Agreement/ *Perjanjian Kontrak Penambangan Batu Bara* (PKP2B) of PT Borneo Indobara with an area of 24,100 ha in the Satui, Angsana, Sungai Loban, Teluk Kepayang, and Kuranji Subdistricts, Tanah Bumbu Regency, South Kalimantan. Of 24.100 ha, this area is covered with secondary forests, palm oil plantations, reclamation areas (burflower tree, *sengon laut*, and oil palms), acacia plantations, and mining areas. This area has an elevation range of 10 – 180 m. PT. Borneo Indobara is ± 200 km from the Capital of South Kalimantan and ± 100 km from the Capital of Tanah Bumbu Regency.

The study area has an average wet month of 9.8 months and an average dry month of 1.4 months. A Q value of 13.9% was obtained. This data indicates that the study area has climate type A and is categorized as wet/very wet. The average monthly rainfall is 213.9 mm/month, with an average number of rainy days of 19 days/month.

The study was conducted in July – August 2023 in the reclamation and revegetation area of PT Borneo Indobara area (WDL Pit Kusan-Girimulya) (Figure 1), Tanah Bumbu Regency, South Kalimantan. This reclamation area has an area of 52 ha. Burflower tree planting was conducted in 2013, whereas *sengon laut* planting was conducted in 2015.



(A) (B)

Notes: □ : Burflower tree reclamation area, □ : *Sengon laut* reclamation area; □ : Sampling areas

Figure 1. Study area in the WDL Pit Kusan-Girimulya, Tanah Bumbu Regency, PT. Borneo Indobara, South Kalimantan (A) Sampling plot using stratified random sampling (B)

2.2 Procedures

This study used a quantitative approach to create allometric equations using destructive methods in burflower trees and *sengon lauts*. It calculates biomass in each part of trees, biomass potential, and carbon sink in reclamation areas. Stratified random sampling was employed to select samples based on the vegetation planting time (Figure 1). An illustration of a sample plot can be seen in Figure 2.

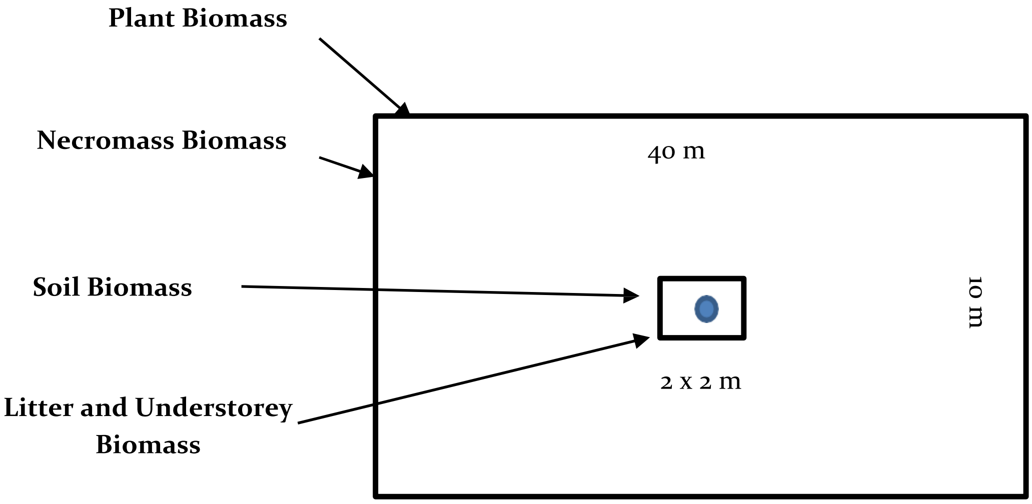


Figure 2. Sample plot using stratified random sampling

2.2.1 Allometric Equations for *Sengon Laut* And Burflower Tree

An allometric equation was developed to calculate carbon stocks. An allometric equation was created to measure carbon stocks appropriate for age, structure, and local edaphic conditions. This equation was intended to minimize the bias of the measurement results. Allometrics were made on seven-year-old burflower trees and *sengon laut*, which were dominant plants in the reclamation area. 15 *Sengon laut* trees and 15 burflower trees were selected based on five classifications of diameter at Breast Height (DBH), such as <10 cm, 10-14 cm, 15-19 cm, 20-24 cm, and 25-30 cm. Besides, sampling was conducted from elevations of 40, 50, and 60 m asl. Parameters of allometric equations, including total tree height (m), free branch height (m), DBH (cm), stem weight (kg), leaf weight (kg), branch weight (kg), and root weight (kg). Those data were used to calculate tree volume (m^3), wood specific gravity (g/cm^3), and water content (%).

Trees were cut using a chainsaw, and the roots, stems, branches, and leaves were cut. Each plant part was separated and weighed to determine wet weight. The roots were removed using mechanical equipment (excavator) and weighed as wet weight. Ovening the roots, stems, branches, and leaves at 105°C for 2 x 24 hours was carried out to obtain dry weight. The data were classified to determine the unit mean, standard deviation, and the minimum and maximum values. Subsequently, several equations (Eqs. (1, 2, 3)) for the root, stem, branch, and leaf values were analyzed to determine the fit parameter, fitting, and validation test values. The formula using following Equations (1), (2), and (3) (Unk et al., 2022):

$$Y = aD^b \tag{1}$$

$$Y = a(D^2H)^b \tag{2}$$

$$Y = aD^bH^c \tag{3}$$

Where Y is the dependent variable; D is the diameter; H is the height; and a,b, and c are constants.

This statistical analysis was carried out to show that each allometric model tested had a good level of accuracy with variations in carbon stock in each part and in total individual trees that could be explained by predictor variables in DBH and tree height.

2.2.2 Tree Biomass Calculation

Biomass was measured in a 10 × 40 m plot (400 m^2) in the north-south direction. Tree DBH (>5 cm) was measured to calculate biomass (Wibowo et al., 2013). The biomass calculation used allometric equations that have been developed destructively. Furthermore, the Biomass Expansion Factor (BEF) equation was used as follows following euation (4), (Wibowo et al., 2013):

$$Bap = v\ x\ BJ\ x\ BEF\ x\ f \qquad (4)$$

Where Bap is the tree's surface biomass (kg); v is the volume of branch-free wood (m^3); BJ is the specific gravity of wood (kg/ m^3); BEF is Biomass Expansion Factor (1.67 default); and f is the tree number factor (0.7 default).

2.2.3 Understorey Biomass Measurement

Understorey includes shrubs with DBH <5 cm, height < 1.5 m, climbing plants, grasses, or weeds. m using 0.5 x 0.5 m quadrants in a 10 m × 40 m plot (Wibowo et al., 2013) of three sample plots by cutting all understory (shrubs, grasses, herbs) contained in the quadrant. The understory biomass was estimated by taking plant parts (involving destruction).

2.2.4 Measurement of Woody and Litter Necromass Biomass

The measured necromass includes two components: woody necromass and non-woody necromass. A woody necromass is a fallen tree, stump, and dead tree (Afriansyah et al., 2019). The non-woody necromass is litter on the forest floor (rough and fine). This necromass classification is recommended by Maas et al. (2020), who state that necromasses need to be categorized according to their shape and size because each necromass component has specific characteristics and is distributed differently in the forest area.

Sampling were made on 10 x 40 m plots where the woody necromass was DBH > 5 cm and 0.5 m in height. Measurements were made on the length and circumference of the woody necromasses. The dry weight formula for necromass is the same as for unbranched trees. Non-woody necromass was measured in the same plots as in the understory biomass plots. Woody necromass used a 0.5 x 0.5 m plot consisting of leaves and stems/branches of dead plants. The length of the stem/branch will not exceed 50 cm. Rough litter sampling was carried out after completing understory biomass sampling. Fine litter sampling was carried out after completing rough litter sampling. The fine litter was sieved through a 2 mm pore hole.

2.2.5 Measurement of Soil Organic Matter

The soil used was undisturbed and in the same plot as the understorey and litter sampling. Soil was taken at a depth of 0-10 cm, 10-20 cm, and 20-30 cm. This sample was used to analyze the Organic C content and bulk density as the basis for determining the carbon content. The formula for determining soil carbon following equation (5) (Murdiyarso et al., 2004):

$$C = BD\ x\ Corg\ x\ soil\ thickness\ x\ area \qquad (5)$$

Where, BD is the bulk density (g/cm^3) and Corg is Organic C (%).

Soil sampling was conducted with several procedures, including (1) the soil surface was cleaned of grass or litter, then flattened; digging the soil to a depth of 5 - 10 cm and flattened with a knife; (3) placing the tube on the soil surface perpendicular to the soil surface, then insert ¾ of the tube into the soil, (4) placing another tube on top of the first tube, then press up to 1 cm into the soil; (5) separating the upper tube from the lower tube; (6) digging the tube with a shovel. The end of the shovel should be deeper than the end of the tube so that the soil from under the tube can be lifted; (7) the soil surface should be the same as the tube surface; both the top and bottom of the tube, and the sides of the tube are closed using plastic; and (8) the tube should be labeled with a description of soil depth, time, and sampling location.

2.2.6 Measurement of Carbon Dioxide (CO2) Gas

All biomass and necromass data per plot were entered into a table that estimated the total carbon stock per sample area following equation (6)

$$\frac{C}{ha} = Cbap + Cbbp + Clitter + Csoil \qquad (6)$$

Where $Cbap$ is the surface biomass; $Cbbp$ is the subsurface biomass; Clitter is litter biomass; and Csoil is the soil biomass. The concentration of carbon in organic matter is typically approximately 46% (Hairiah et al., 2011). Therefore, the estimated total carbon stock per part can be measured by multiplying the total mass weight by the carbon concentration using Equations (7) and (8)(Wibowo et al., 2013).

$$Biomass\ per\ area = \frac{Total\ Biomass}{Area\ (m2)} \tag{7}$$

$$Carbon\ Stock = Biomass\ per\ area\ x\ 0.46 \tag{8}$$

2.2.7 Measurement of Total Carbon Stock Per Area

The carbon stocks are not equal to the mass of carbon dioxide (CO2) stored in the area because CO2 is a carbon atom (C) that has bound two oxygen atoms (O). If the mass of CO2 gas is 3.67 times the mass of C, then the formula is following equation (9).

$$nCO_2 = 3.67\ x\ Total\ Carbon\ Stocks \tag{9}$$

Where 3.67 was obtained from the calculation in equation (10) (Hardjana, 2010):

$$\frac{Atomic\ mass\ of\ C + 2x\ Atomic\ mass\ of\ O}{Atomic\ mass\ of\ C} = \frac{6 + (2\ x\ 8)}{6} = 3.67$$

2.2.8 The Reclamation Area's Ability to Absorb CO2

The calculation of the ability of the reclamation area to absorb CO2 was conducted by dividing the total CO2 by the age of planting following equation (10) (Saputri et al., 2022):

$$Absortive\ capacity\ (per\ year) = \frac{Total\ CO_2}{Plant\ age} \tag{10}$$

3. Result and Discussion

3.1 Allometric Equation of *Sengon laut* and Burflower tree

Carbon storage measurements of the burflower tree and *sengon laut* reclaimed plants are shown in Table 1. The total carbon stock of the *sengon laut* was relatively higher than the burflower tree. However, the distribution of carbon stock in *sengon laut* roots is much lower than in burflower tree roots. The low carbon stock in the burflower tree is caused by the lower biomass accumulation. Interestingly, both species have the highest carbon stock in the stem. Stem is a vital plant organ that translocates water, nutrients, and photosynthetic products.

Table 1. Destructive sampling of carbon storage measurements of burflower tree and *sengon laut*

Species	Unit	D	H	V	WC	R	S	B	L	Total
		(cm)	**(m)**	**(m3)**	**(%)**	**(kg)**	**(kg)**	**(kg)**	**(kg)**	**(kg)**
***Paraserianthes falcataria* (L.)**	Mean	17.4	12.2	0.41	39.70	19.91	59.08	3.74	2.89	85.63
	SD	7.0	4.4	0.35	4.23	16.65	52.91	2.38	2.08	73.75
	Min	7.0	4.0	0.02	31.88	1.32	2.72	0.54	0.37	4.95
	Max	28.0	17.4	0.99	45.34	48.89	148.33	7.65	6.76	211.64
***Anthocephalus cadamba* Miq.**	Mean	17.8	12.9	0.41	48.05	24.86	53.93	3.13	2.85	84.77
	SD	6.9	3.0	0.33	3.63	28.07	47.79	2.80	2.14	79.70
	Min	8.4	8.5	0.05	42.46	3.44	5.34	0.24	0.07	9.25
	Max	27.7	17.6	1.00	54.95	85.95	146.05	10.21	6.06	246.11

Note: D: Diameter; H: Height; V: Volume; WC: Water Content; R: Root; S: Stem; B: Branch; L: Leaf

The relative contribution of trees to carbon storage accumulation as reclamation plants was mainly dominated by stem organs, followed by roots, branches, and leaves (Table 2). Uniquely, the burflower tree roots had a more significant relative contribution than the *sengon laut*. In contrast, the leaves of *sengon laut* had a more significant relative contribution than the burflower tree. Differences in canopy characteristics and leaf morphological patterns are one of the main factors that cause the higher contribution of leaf organs in the burflower tree to its total carbon storage.

Table 2. The relative contribution of tree components to total carbon storage in burflower tree and *sengon laut*

Species	Root (%)		Stem (%)		Branch (%)		Leaf (%)	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Paraserianthes falcataria **(L.)**	25.22	5.09	64.18	7.91	6.15	2.52	4.45	1.62
Anthocephalus cadamba **Miq.**	28.08	6.44	64.45	4.79	3.86	1.01	3.61	1.8

The statistical evaluation shows that each allometric model tested has a good level of accuracy, where more than 70% of the variation in carbon storage in both each organ and the total individual tree can be explained by predictor variables such as diameter and height in Table (3).

Table 3. Statistical evaluation of allometric model development for carbon storage estimation

Organs	Equations	Fit Parameter			Fitting Test			Validation Test		
		a	b	c	R^2	RSE	AIC	MAB	RMSE	NRMSE
Paraserianthes falcataria **(L.)**										
Root	$Y = aD^b$	0.013*	2.467*	-	0.965	0.220	1.051	0.174	0.230	1.155
	$Y = a(D^2H)^b$	35.836*	0.856*	-	0.974	0.189	-3.488	0.159	0.195	0.980
	$Y = aD^bH^c$	0.013*	1.930*	0.614^{ns}	0.973	0.201	-0.848	0.167	0.210	1.055
Stem	$Y = aD^b$	0.009*	2.925*	-	0.982	0.187	-3.913	0.159	0.194	0.328
	$Y = a(D^2H)^b$	111.791*	1.012*	-	0.986	0.167	-7.269	0.147	0.188	0.319
	$Y = aD^bH^c$	0.009*	2.366*	0.640*	0.988	0.157	-8.295	0.154	0.193	0.326
Branch	$Y = aD^b$	0.016*	1.858*	-	0.973	0.146	-11.271	0.139	0.163	4.364
	$Y = a(D^2H)^b$	6.305*	0.639*	-	0.966	0.165	-7.731	0.131	0.182	4.858
	$Y = aD^bH^c$	0.016*	1.749*	0.124^{ns}	0.974	0.151	-9.596	0.151	0.189	5.056
Leaf	$Y = aD^b$	0.008*	2.010*	-	0.985	0.118	-17.778	0.094	0.128	4.418
	$Y = a(D^2H)^b$	4.931*	0.689*	-	0.969	0.167	-7.268	0.142	0.185	6.377
	$Y = aD^bH^c$	0.008*	2.084*	0.084^{ns}	0.985	0.122	-16.008	0.108	0.147	5.067
Total	$Y = aD^b$	0.028*	2.695*	-	0.986	0.153	-9.930	0.123	0.159	0.186
	$Y = a(D^2H)^b$	159.015*	0.932*	-	0.990	0.130	-14.701	0.123	0.148	0.172
	$Y = aD^bH^c$	0.028*	2.201*	0.565*	0.992	0.123	-15.678	0.122	0.145	0.170
Anthocephalus cadamba **Miq.**										
Root	$Y = aD^b$	0.014*	2.465*	-	0.893	0.380	17.395	0.356	0.410	1.650
	$Y = a(D^2H)^b$	40.542*	0.979*	-	0.902	0.365	16.167	0.339	0.394	1.583
	$Y = aD^bH^c$	0.004*	1.992*	0.936^{ns}	0.901	0.381	18.294	0.363	0.417	1.676
Stem	$Y = aD^b$	0.019*	2.648*	-	0.989	0.123	-16.385	0.111	0.132	0.245
	$Y = a(D^2H)^b$	102.756*	1.051*	-	0.995	0.084	-28.003	0.072	0.089	0.165
	$Y = aD^bH^c$	0.007*	2.216*	0.855*	0.995	0.085	-26.709	0.075	0.091	0.170
Branch	$Y = aD^b$	0.001*	2.650*	-	0.957	0.251	4.906	0.216	0.279	8.901
	$Y = a(D^2H)^b$	5.887*	1.040*	-	0.942	0.291	9.340	0.268	0.316	10.094

Organs	Equations	Fit Parameter			Fitting Test			Validation Test		
		a	b	c	R^2	RSE	AIC	MAB	RMSE	NRMSE
	$Y = aD^bH^c$	0.002*	2.969*	0.6321^{ns}	0.960	0.251	5.752	0.223	0.283	9.027
Leaf	$Y = aD^b$	0.001*	3.176*	-	0.890	0.498	25.529	0.390	0.556	19.469
	$Y = a(D^2H)^b$	6.126*	1.244*	-	0.872	0.537	27.784	0.433	0.598	20.957
	$Y = aD^bH^c$	0.001*	3.766*	1.168^{ns}	0.897	0.502	26.537	0.417	0.555	19.439
Total	$Y = aD^b$	0.035*	2.600*	-	0.979	0.168	-7.055	0.155	0.181	0.214
	$Y = a(D^2H)^b$	156.456*	1.031*	-	0.984	0.147	-11.148	0.128	0.157	0.185
	$Y = aD^bH^c$	0.014*	2.214*	0.763^{ns}	0.984	0.153	-9.166	0.134	0.166	0.195

Notes: a, b, c: Fit coefficient; Y: Equation; D: Diameter; H: Height; R^2: R-squared; RSE: Residual Standard Error; AIC: Akaike Information Criteria; MAB: Mean Absolute Bias; RMSE: Root Mean Squared Error; NRMSE: Normalized Root Mean Square Error.

There are three general parameters used to assess whether a model is valid: MAB, RMSE, and NRMSE. The lower the value of the three, the more valid a model will be. However, specifically for the NRMSE, a model is declared valid if it has NRMSE < 20%. Based on the results, there are two best allometric models for carbon stock estimation at the tree level in the reclamation area, where each model has an accuracy level above 90%. *Sengon laut* has an allometric equation $Y = 0.028D^{2,695}$, while burflower tree has an allometric equation $Y = 0.035D^{2,600}$ (Table 4).

Table 4. Allometric equation for 7-year-old tree-level reclamation plants

Scientific Name	Local Name	Equation	Fitting Test			Validation Test		
			R^2	RSE	AIC	MAB	RMSE	NRMSE
Paraserianthes falcataria **(L.)**	*Sengon laut*	$Y= 0.028D^{2,695}$	0.98	0.15	-9.93	0.12	0.15	0.18
Anthocephalus cadamba **Miq.**	Burflower tree	$Y = 0.035D^{2,600}$	0.97	0.16	-7.05	0.15	0.18	0.21

3.2 Tree Biomass Measurement

The burflower tree shows a slightly lower carbon stock than the *sengon laut* (Table 5). Biomass and carbon stock values in the burflower tree areas are slightly different compared to burflower tree in undisturbed areas in other areas as stated by Afriansyah et al. (2019) that the carbon stock of red burflower trees in community forests with old age has a carbon stock of 51.20 tons/ha and white burflower tree of 59.51 tons/ha. Meanwhile, Rozzi et al. (2022) stated that the five-year-old burflower tree in West Sulawesi produced carbon stocks of 31.54 tons/ha (biomass 68.56 tons/ha). In Jombang, the highest carbon stocks of *sengon* are 88.04 tons/ha and 50.16 kg/tree (Febrianti et al., 2023). Restoring trees with marginal soil fertility in reclamation areas (with a stock value of 33.03 tons/ha) is a fairly high land recovery. The value of this carbon stock will continue to increase with increasing age of reclamation plants.

Table 5. Tree-level biomass and carbon stocks

Reclamation areas	Average number of trees per plot	Biomass (kg/400 m²)	Biomass (ton/ha)	Tree-level carbon stocks (=0.46) (ton/ha)
Sengon laut **(*Paraserianthes falcataria*** **(L.))**	26	2,997.63	71.8	33.03

Burflower tree (*Anthocephalus cadamba* Miq.)	25	2,898.93	74.9	34.45

The value of biomass and carbon stocks in the *sengon laut* area is indeed still lower in value when compared to *sengon laut* in undisturbed areas in other areas, stating that the carbon stock of *sengon laut* in community forests with old age has a carbon stock of 52.10 ton/ha (Afriansyah et al., 2019). The total carbon stock in tree biomass is directly proportional to tree growth and development. In general, net growth (especially of trees in the growth phase) absorbs more CO2, whereas mature forests with little growth only store carbon but cannot absorb extra CO2 (Nursanti and Swari, 2013). In this study, the reclamation area is an area with seven-year-old *sengon laut* (*Paraserianthes falcataria* (L.)) and burflower tree (*Anthocephalus cadamba* Miq.). This area has an average tree height above 10 m and varied in DBH ranging from <10 cm to > 32 cm. Rozzi et al. (2022) state that the biomass in the largest trees is obtained from trees with the largest DBH, so the DBH is also significant. The carbon absorbed by the plant will be stored in woody biomass. Therefore, the greater the DBH, the more biomass is stored, resulting in a greater value. In the previous study of Azizah et al. (2023) on peatlands, the average biomass of sago palm at the tree level in Sungai Tabuk District is 143.56 tons/ha, with the total carbon stored at 67.47 tons/ha. The study shows that increasing the biomass production of trees increases the carbon stock. The relationships between plant carbon stock values and biomass, density, and percent canopy cover are assumed to be influenced by DBH values and the number of individual trees (Lestariningsih et al., 2018). This study suggests that the greater the plant biomass, the greater the amount of carbon stored, regardless of plant species.

3.3 Carbon Stock in Understorey Biomass

As shown in Table 6, the average plant biomass in the burflower tree reclamation area was higher than that in the *Sengon Laut* reclamation area. Understoreys in each land cover type have different densities. Canopy density will affect the growth of understorey in the area. The denser the tree canopy in an area, the lower the understorey biomass due to the lack of sunlight reaching the forest floor. This causes growth of the understory to be suppressed. Understory plants also conduct photosynthesis by absorbing carbon (CO2) from the air and producing O2, which is released into the air (Syaufina and Ikhsan, 2013). Therefore, understoreys also play an essential role in maintaining the environment, especially in absorbing CO2 and storing it in plant tissue (Suryandari et al., 2019).

Table 6. Biomass and carbon stock of understorey

Reclamation areas	Average Biomass of Understorey (g/0.25 m^2)	Average Biomass of Understorey (ton/ha)	Average understorey carbon stock (ton/ha) (=0.46)
***Sengon laut* (*Paraserianthes falcataria* (L.))**	62.40	2.50	1.15
Burflower tree (*Anthocephalus cadamba* Miq.)	81.18	3.25	1.49

3.4 Carbon Stocks in Necromass Biomass

The results show that the necromass biomass of the burflower tree is lower than the *sengon laut* tree, but the average necromass carbon stock of the burflower tree is higher than *sengon laut* (Table 7). Light intensity, humidity, temperature, and soil type can affect the litter decomposition rate, thus affecting necromass biomass (Sorbu et al., 2021). In Manokwari, the high biomass of necromass (litter) and dead wood in secondary forests is thought to be due to logging, so logging residues such as litter, twigs, branches, and stumps, dead wood are stockpiled and accumulated as necromass (Sorbu et al., 2021). That study shows that human activities can affect the number of necromasses on land.

Table 7. Biomass and carbon stocks in woody and litter necromass

Reclamation areas	Average biomass of litter necromasses (ton/ha)	Average biomass of woody necromasses (ton/ha)	Biomass necromass (leaf and wood necromass) (ton/ha)	Average necromass carbon stock (ton/ha) (=0.46)
Burflower tree (*Anthocephalus cadamba* Miq.)	3.45	0.04	3.50	1.61
***Sengon laut* (*Paraserianthes falcataria* (L.))**	3.17	0.74	3.91	1.80

3.5 Carbon Stock in Soil Organic Matter

The carbon content stored in organic matter, both burflower tree and *sengon laut* areas produced similar values (Table 8). C-organic content tended to fluctuate per soil layer (per 10 cm). Carbon stock in the soil is an indicator of soil fertility. Carbon is the most significant component in organic matter. High levels of carbon in the soil will improve soil properties, both physically, chemically, and biologically.

Table 8. C-Organic content at a depth of 0 - 30 cm in reclamation areas

Reclamation areas	Soil depth (cm)	C-Organic content		C Content per layer (ton/ha)	C content (ton/ha) (0 – 30 cm)
		%	C/ton of soil		
Burflower tree (*Anthocephalus cadamba* Miq.)	0 - 10	1.43	0.0143	17.446	48.38
	10 – 20	1.27	0.0127	16.891	
	20 - 30	1.04	0.0104	14.04	
***Sengon laut* (*Paraserianthes falcataria* (L.))**	0 - 10	1.52	0.0152	17.784	48.78
	10 – 20	1.12	0.0112	14.112	
	20 - 30	1.26	0.0126	16.884	

3.6 Estimation of Total Carbon Stock on PT Borneo Indobara's Reclamation Land

Estimating total carbon stocks in an area is the sum of covered ground plant and soil carbon stocks. Carbon stocks of cover ground plants are measured from the sum of carbon stocks stored in the tree biomass, understorey, and necromasses. Meanwhile, carbon is stored in soil, and organic matter content is measured based on soil depth. Based on Table 9, the C stock of the *sengon laut* area is slightly higher than the burflower tree area. As cover ground plants, tree biomass has the highest carbon stock compared to the understory and necromass, but the carbon stock in the soil is higher than that of tree biomass. In mangrove forests, Hidayati et al. (2023) stated that sediment has the highest carbon value compared to aboveground plants, below-surface plants, and dead wood.

Table 9. Estimated total carbon stock

Reclamation areas	Total C stocks in plants (=0.46) (ton/ha)				Total C stock in the soil (0 – 30 cm) (ton/ha)	Total C Stock
	Tree (ton/ha)	Understorey (ton/ha)	Necromass (ton/ha)	Total C in plants (ton/ha)		

Burflower tree (*Anthocephalus cadamba* Miq.)	33.03	1.49	1.61	36.13	48.377	84.51
***Sengon laut* (*Paraserianthes falcataria* (L.))**	34.45	1.15	1.8	37.4	48.78	86.18

3.7 Estimation of CO2 Sink on PT Borneo Indobara Land

The total CO2 sink by plants is measured by multiplying the estimated total carbon value by the conversion factor of the C atoms in CO2 compounds. The formula used to measure carbon sink is the total carbon content multiplied by the conversion value of C atoms in the CO2 compound of 3.67. The CO2 sink is used for photosynthesis. The plants sequester carbon dioxide (CO2) from the atmosphere and then photosynthesize to produce oxygen (O2) released into the air and carbohydrates stored in plant tissues. The older the plant, the more developed the plant size, such as the number of leaves, stem/branch dimensions, and root dimensions. The sink of CO2 from the air will also increase (Anggraini and Arifin, 2021), followed by an increase in the release of O2 into the air. The carbon stocks and sink can reference how much the forests provide ecological benefits (Afriansyah et al., 2019).

The influence of vegetation on reducing emissions in nature is due to the ability of vegetation to absorb emissions that are physiologically capable in plant tissue. The emission absorption ability of each plant is different, depending on three things, including 1) climate, tropical forests absorb more carbon than temperate forests; 2) tree dimensions, the greater the DBH, the greater the ability of the tree to store and sink carbon; and 3) growth rate and life span of the tree. The amount of estimated CO2 sink in reclamation areas is presented in Table 10. The value of CO_2 sink indicates that there are environmental services to restore and improve vegetation.

Table 10. CO_2 Sink Potential in The Reclamation Areas

Reclamation areas	Total C stock (ton/ha)	Area (ha)	Carbon stock (ton)	CO_2 sink potential (ton)	Average potential sink per year (ton/tahun)	Average Plant Age
Burflower tree (*Anthocephalus cadamba* Miq.)	84.51	22	1859.15	6823.10	974.73	Seven years old
***Sengon laut* (*Paraserianthes falcataria* (L.))**	86.18	30	2585.40	9488.42	1355.49	Seven years old

The value of carbon stock and sink shows that there are environmental services to restore and improve vegetation and restore the ecological functions of forests in the reclamation areas of PT Borneo Indobara. Further research is needed to determine the economic valuation of carbon stocks to reveal other ecosystem services in the coal mining reclamation land of PT Borneo Indobara.

4. Conclusions

Two allometric models were created for carbon stock estimation at the tree level in the reclamation area, where each model has an accuracy level above 90%. *Sengon laut* has an allometric equation Y = 0.028D2,695, while burflower tree has an allometric equation Y = 0.035D2,600. With a CO2 sink potential of 974.73 tons/ha, the burflower tree area has a total carbon stock of 84.51 tons/ha, whereas the *sengon laut* has a total carbon stock of 86.18 tons/ha and a CO2 sink potential of 1355.49 tons/ha. The value of the carbon sink and carbon stock indicates that there are environmental services available for enhancing and restoring vegetation.

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