JPPIPA 12(5) (2026)

Jurnal Penelitian Pendidikan IPA

http://jppipa.unram.ac.id/index.php/jppipa/index

Allometric Biomass Equation Model of *Sonneratia alba* in Tanah Merah Mangrove Forest, Kupang, East Nusa Tenggara, Indonesia

Meilyn Renny Pathibang[1*], Yudhistira A. N. R. Ora[1], Aah Ahmad Almuqu[1], Tristania Silvana Lalus[1], Sutan Sahala Muda Marpaung[1]

[1] Forestry Field Program, Politeknik Pertanian Negeri Kupang. Prof. Herman Johanes, Lasiana, Kupang, East Nusa Tenggara, Indonesia.

Received: February 27, 2026
Revised: April 10, 2026
Accepted: May 25, 2026
Published: May 31, 2026

Corresponding Author:
Meilyn Renny Pathibang
meilynoldy@gmail.com

DOI: 10.29303/jppipa.v12i5.15100

Open Access

© 2026 The Authors. This article is distributed under a (CC-BY License)

Abstract: Mangrove forest biomass is an important parameter for carbon stock estimation and the sustainable management of coastal ecosystems. However, specific allometric equations for *Sonneratia alba* in mangrove forest ecosystems under semi arid environmental conditions characterized by relatively low rainfall, high salinity, and distinct muddy substrate characteristics remain limited. This study aims to develop a specific allometric equation model to estimate the biomass of *Sonneratia alba* in the Tanah Merah Mangrove Forest, East Nusa Tenggara. The method used to estimate biomass is destructive sampling and regression analysis. A total of fourteen sample trees representing seven diameter classes were harvested and measured for diameter at breast height (DBH), tree height, and biomass components. The collected data were analyzed to produce the best allometric equations relating tree dimensions to biomass. The results showed that the best equation for stem biomass was B = 0.036D^(2.503), branch biomass was B = 1.269e^(0.154D), leaf biomass was B = 0.000022D^(2.124)H^(2.621), and total biomass was B = 5.607e^(0.142D)). The estimated carbon stock potential of *Sonneratia alba* in the Tanah Merah Mangrove Forest was 8.64 tons ha^{-1}. These findings provide an important scientific basis for improving biomass and carbon stock estimation accuracy and support evidence-based mangrove conservation and management, particularly in coastal ecosystems of East Nusa Tenggara.

Keywords: Allometric; Biomass; Carbon stock; Mangrove Forest; *Sonneratia alba*

Introduction

Deforestation remains one of the major global environmental issues contributing to climate change. Between 2001 and 2020, tropical forests experienced a loss of approximately 1.48 million km², an area exceeding the combined land area of France, Spain, and Germany (Singh, 2020). Forest degradation and land-use change contribute substantially to greenhouse gas emissions and reduce ecosystem resilience to environmental disturbances. In coastal ecosystems, mangrove degradation has been associated with increased vulnerability to strong winds, tidal surges, and coastal erosion (Sadono et al., 2020).

Mangrove forests are among the most productive coastal ecosystems and play an essential role in maintaining environmental stability. They provide habitat for various aquatic and terrestrial organisms, protect shorelines from abrasion and seawater intrusion, and support the livelihoods of coastal communities through fisheries and other ecosystem services (Poedjirahajoe et al., 2019; Richards et al., 2016; Susilo et al., 2017). Indonesia possesses approximately 4.5 million hectares of mangrove forests, representing around 23% of the global mangrove area, making it the country with the largest mangrove extent worldwide (Dinilhuda et al., 2020; Njana, 2017). However, mangrove ecosystems in Indonesia continue to experience rapid degradation due

How to Cite:
Pathibang, M. R., Ora, Y. A. N. R., Almuqu, A. A., Lalus, T. S., & Marpaung, S. S. M. (2026). Allometric Biomass Equation Model of Sonneratia alba in Tanah Merah Mangrove Forest, Kupang, East Nusa Tenggara, Indonesia. *Jurnal Penelitian Pendidikan IPA*, *12*(5), 906–915. https://doi.org/10.29303/jppipa.v12i5.15100

to logging, infrastructure development, land conversion for aquaculture, sand mining, and environmental pollution (Yuliana et al., 2019). Mangrove ecosystems have a significant role in climate change mitigation due to their high capacity for carbon sequestration and storage in both vegetation biomass and soil (Matatula et al., 2021). Biomass estimation is therefore essential for quantifying carbon stocks and understanding the ecological contribution of mangrove forests. Previous studies reported that mangrove carbon stocks range from 3.4 to 218.2 Mg ha^{-1} depending on stand age and site characteristics (Pathibang et al., 2023). Since biomass is strongly related to tree growth characteristics, accurate estimation methods are required to improve carbon stock assessments.

The Tanah Merah Mangrove Forest in Kupang, East Nusa Tenggara, is one of the mangrove ecosystems characterized by relatively high species diversity, including *Sonneratia alba*, *Rhizophora stylosa*, *Rhizophora mucronata*, *Sonneratia caseolaris*, *Lumnitzera racemosa*, *Rhizophora apiculata*, *Avicennia marina*, and *Aegialitis annulata* (Sadono et al., 2020). Among these species, *Sonneratia alba* is one of the dominant mangrove species in the area and contributes substantially to ecosystem structure and function. Nevertheless, information regarding biomass and carbon stock potential of *S. alba* in this region remains limited.

Although allometric equations are widely used to estimate biomass and carbon stocks, species- and site-specific models for *Sonneratia alba* in eastern Indonesia remain limited. Differences in ecological conditions, including semi-arid climate characteristics, relatively low rainfall, high salinity, and specific muddy substrates, may influence tree growth patterns and lead to significant estimation bias when non-site-specific models are applied. Therefore, this study aimed to develop a site-specific allometric equation model for *Sonneratia alba* in the Tanah Merah Mangrove Forest, Kupang, East Nusa Tenggara, using destructive sampling and regression analysis to improve biomass and carbon stock estimation accuracy and support sustainable mangrove management.

Method

This study examined a 30-hectare mangrove forest in Tanah Merah, Kupang (Figure 1). Laboratory analysis was conducted at the Forest Planning Laboratory of the Forestry Department of the Kupang State Agricultural Polytechnic. Data variables were processed using Excel and SPSS software. Meanwhile, the independent and dependent variables were created into allometric equations.

Figure 1. Map of research area in mangrove forest in Tanah Merah village

Research Data and Variables

The data collected in this study are primary and secondary data. The data variables used in the study: 1) The independent variable is the stem diameter at a height of 1.3 m above ground level, commonly called dbh (diameter at breast height), and tree height, 2) The dependent variable is biomass. To facilitate measurement and analysis, this data was processed using Excel and SPSS software. Allometric equations were created for the independent and dependent variables.

Research Implementation Procedures

The method used in the inventory was systematic sampling. Cluster placement and distribution were carried out systematically, adapting to the location and distribution of permanent clusters in previous research (Matatula et al., 2021). The method used to determine the model tree for developing the allometric model was purposive sampling. This method was chosen based on the representativeness of each diameter class and in accordance with the model tree criteria.

The sampling intensity was determined based on the researcher's consideration of the population representativeness. The sampling intensity used was 7.5%, higher than the sampling intensity stipulated in Forestry Ministerial Regulation No.P.67/MENHUT-II/2006 concerning Forest Inventory Criteria and Standards, which stipulates a minimum sampling intensity of 1% at the conservation forest management unit level, including mangrove forests. The cluster design and inventory measurement plot are shown in Figure 2.

The diameter class is determined after conducting an inventory by determining the minimum and maximum diameters (Koh et al., 2018). The calculation results show that there are 7 diameter classes with a class interval of 2.18. A sample of one tree was taken from each diameter class for biomass and carbon measurements.

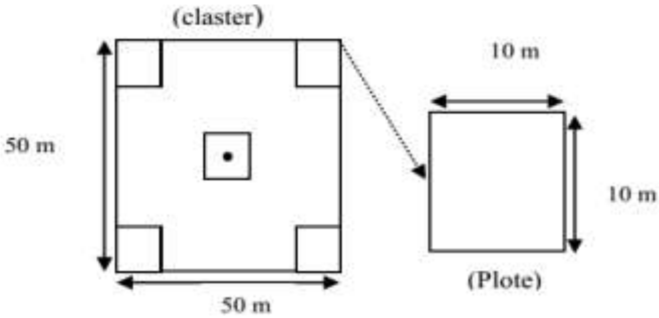

Figure 2. Cluster design and inventory measurement plot

Model Tree Selection

Model trees were selected based on their representative tree diameters at the research site. The criteria for selecting model trees were straight trunks and freedom from pests and diseases. Model trees were divided into two groups: those used for model development and those used for model validation (Matatula et al., 2021). Fourteen trees were harvested, eight for model development, and six for model validation (Figure 3).

Figure 3. Model tree distribution map

Tree Biomass Measurement

Biomass measurements were conducted by felling trees at each predetermined diameter class and selecting sample trees for biomass content research. Each tree was divided into three sections: the trunk, branches, and twigs, as well as leaves. The trunk was divided into three sections: the base, middle, and tip. The branches and twigs were divided into three sections: the base, middle, and tip. The leaves were divided into three sections: the base, middle, and tip of the crown.

Allometric Equation Model

The regression equation models used to estimate the biomass of *Sonneratia. alba* are as follows:

1. Linear/straight-line model: $B = a + bD$
2. Power/geometric model: $B = aD^b$
3. Exponential model: $B = ae^{bD}$
4. Logarithmic model: $B = \log a + b\log D$
5. Multiple linear model: $B = a + bD + cH$
6. Multiple power model: $B = aD^bH^c$
7. Quadratic model: $B = a + bD + cD^2$

Model Development Stage

The best model selected during the model development and validation stage. This stage involves comparing the coefficient of determination (R^2) and the standard error of the estimate (SEE). The statistical test equation is as follows:

$$R^2 = 1 - \frac{\sum_{n-1}^{n}(yi-\hat{y}i)^2}{\sum_{n-1}^{n}(yi-\hat{y}i)^2} \quad (1)$$

$$SEE = \sqrt{\frac{\sum(yi-\hat{y}i)^2}{n-k}} \quad (2)$$

Model Validation Stage

Model validation performed to verify and re-confirm whether the estimation model meets the established criteria. Several values are used in the model validation stage, namely: root mean square deviation (RMSE), mean deviation (SR), aggregate deviation (SA), and bias value (e). The RMSE value describes the accuracy of the estimation, the SR value is the average sum of the absolute values of the differences between the actual biomass and the estimated biomass, proportional to the estimated biomass (Koh at al., 2018).

Result and Discussion

The parameters measured in the inventory of Sonneratia alba species in the Tanah Merah Kupang Mangrove Forest were diameter at breast height (dbh) and tree height. Based on the inventory results, the number of *Sonneratia alba* trees in all observation groups was 65 trees with a minimum diameter of 11.46 cm and a maximum diameter of 26.78 cm. Based on the inventory results, 7 diameter classes were created with a class interval of 2.18 (Table 1).

Table 1. Class Interval

Diameter Class	Interval Class	Number of Trees
1	11.46 - 13.64	2
2	13.65 - 15.83	2
3	15.84 - 18.02	2
4	18.03 - 20.21	2
5	20.22 - 22.40	2
6	22.41 - 24.59	2
7	24.60 - 26.78	2
	Σ	14

The determination of model trees in developing allometric models uses a purposive sampling method. Ecologically, the structure of natural forest stands is generally uneven, therefore, the representation of each diameter class and the suitability of model tree criteria are of particular concern. Uniformity in the number of trees in each class is the result of purposive sampling. This method was chosen to secure a balanced sample at each diameter class level for specific analysis needs.

A total of 14 trees were felled to serve as measurement samples: 8 for model development and 6 for model validation. Model trees were selected based on their representative tree diameters at the research site. Biomass measurements were conducted using a destructive sampling method. Each felled tree was then divided into three sections: the trunk, branches and twigs, and leaves. 250 gram sample was taken from each section for laboratory analysis. Biomass was calculated by directly weighing oven-dried samples until they reached a constant weight (Table 2). The total dry weight of each tree section was calculated using the equation (Taillardat et al., 2018).

Table 2. Biomass Calculation Data

Validation Tree	Dbh (cm)	Height (m)	Stem Biomass (Kg)	Brqnch Biomass (Kg)	Leaf Biomass (Kg)	Total (Kg)
1b	12.10	7	18.09	17.31	0.86	36,26
2b	15.61	5	37.44	4.42	0.21	42.07
3a	17.52	10	48.54	23.25	3.89	75.68
4a	19.75	6.5	64.03	29.58	4.09	97.70
5b	20.38	7	59.54	24.42	4.09	88.05
6b	23.89	9	107.21	14.37	2.90	124.48
7a	25.80	7,5	153.52	158.27	4.80	316.59
7b	26.43	10	107,91	108.99	8,37	225.26
1a	11.78	9	61.10	16.31	2.37	79.78
2a	14.01	6	22.88	7.74	0.73	31.35
3b	16.24	7.5	48.83	42.95	3.28	95.07
4b	19.43	10	69.27	34.48	25.85	129.60
5a	21.97	8.5	126.23	14.27	2.11	142.60
6a	23.89	7	58.87	84.83	4.81	148.51
Total			983.46	581.19	68.36	1.633
Average			70.25	41.51	4.88	116.64

Biomass Allometric Equation Model

The allometric equation model for estimating biomass based on the relationship between the dependent variable, namely, biomass, and the independent variable, namely, tree diameter and height. The equations used to determine the *Sonneratia alba* biomass estimation model are the linear model: B = a + b D, the power model: B = a D b, the exponential model: B = a e B D, the logarithmic model: B = Log a + b log D, the multiple linear model: B = a + b D + c H, the multiple power model: B = a D b H c, the quadratic model: B = a + b D + c D 2. In linear models, multiple linear models and Quadratic models, regression is carried out directly on the original data, while in power models, logarithmic models, exponential models, and multiple power models, regression is carried out by first simplifying the logarithm, which means that the power model, logarithmic model, exponential model, and multiple power model must be changed using natural logarithms before conducting regression analysis (Analuddin et al., 2020). The biomass estimation equation model aims to estimate tree biomass from a stand that has high accuracy (Sumadi et al., 2010). To get the best model that has high accuracy, there are several components used in compiling the best model, namely, the estimation model, model validation, and the best selection based on scoring.

Model Development

The relationship between tree diameter and height is a very important component to consider in developing an estimation model to see the representation of both variables in developing a biomass estimation model that is jointly or the representation of one variable replaces another variable (Bachmid et al., 2018). The results of data analysis at the stage of developing a biomass estimation model for the *Sonneratia alba* species in the Tanah Merah Kupang Mangrove Forest can be seen in Tables 3. 4. 5 and 6. Table 3 shows that all seven models developed had high R^2 (>80%). The R^2 values of the biomass estimation models obtained in this study were higher than those of several tree biomass estimation models found in Salsabilli et al. (2021). The highest R^2 value was found in the multiple power model, and the lowest SEE value was found in the power model. The scoring system for the R^2 value was based on the highest R^2 value, and the SEE value was determined by the lowest value. Therefore, the best models in the stem biomass estimation model development stage were the power model and the multiple power model.

Table 4 shows the highest R^2 value in the quadratic model with a value of 70.5% and the lowest SEE value in the exponential model with a value of 0.869. The scoring system for the R^2 value is seen from the highest R^2 value and the SEE seen from the lowest value. Therefore, the best model in the development stage of the branch biomass estimation model is the quadratic model. Table 5 shows the highest R^2 in the multiple power model with a value of 73.8% and the lowest SEE value in the multiple power model with a value of 0.717. The scoring system for the R^2 value seen from the highest R^2 value and SEE seen from the lowest value. Therefore, the best model in the leaf biomass model development stage is the multiple power model. Table 6 shows the R^2 values of the power model, exponential model, multiple power model, and quadratic model > 80%, while the linear model, logarithmic model, and multiple linear models have values < 80%. Judging from the standard error of the estimation, the power model, exponential model, and multiple power model have lower values than the linear model, logarithmic model, multiple linear model, and quadratic model, which indicates that the power model, exponential model, and multiple power model are more accurate than the linear model, logarithmic model, multiple linear model, and quadratic model. The scoring system for the R^2 value is seen from the highest R^2 value and SEE seen from the lowest value. Therefore, the best models in the total biomass estimation model development stage are the power model, exponential model, and multiple power model.

Table 3. Results of Data Analysis for the Allometric Equation Model Preparation Stage of Stem Biomass

Regression Equation	Model Equation	R^2	SEE
Linear	B = - 86.994 + 8.083D	87%	17.397
Power	B = 0.036D^2.503	96.8%	0.131
Exponential	B = 4.884e^(0.127D)	93.1%	0.193
Logarithmic	B = - 369.973 + 344.246 LogD	81.7%	20.651
Multiple Linier	B = - 80.562 + 7.343D + 0.356H	91.6%	15.362
Multiple Power	B = 0.042D^(2.569)H^(0.162)	97%	0.138
Quadratic	B = 12.544 - 3.190D+0.293D^2	88.9%	17.629

Table 4. Results of Data Analysis for the Allometric Equation Model Development Stage of Branch Biomass

Regression Equation	Model Equation	R^2	SEE
Linear	B = - 105.656 +7.667D	51.3%	41.632
Power	B = 0.006D^2.817	44.4%	0.910
Exponential	B = 1.269e^(0.154D)	49.3%	0.869
Logarithmic	B = -347.520 + 305.980 LogD	42.3%	45.321
Multiple Linier	B = -100.851 + 7.818D - 1.008H	51.4%	45.565
Multiple Power	B = 0.002D^(2.274)H^(1.322)	50.4%	0.941
Quadratic	B = 287.956-36.906D+1.157D^2	70.5%	35.502

Table 5. Results of Data Analysis for the Allometric Equation Model Development Stage of Leaf Biomass

Equation	Model Equation	R^2	SEE
Linear	B = -3.881+0.377D	59.9%	1.719
Power	B = 0.00018D^3.201	52.4%	0.881
Exponential	B = 0.104e^0.159D	47.9%	0.922
Logarithmic	B = -17.964+16.740 LogD	61.1%	1.692
Multiple Linier	B = -6.582+0.292D+0.567H	72.8%	1.549
Multiple Power	B = 0.000022*D*^ (2.124) H^(2.621)	73.8%	0.717
Quadratic	B = 7.985-0.967D+0.035D^2	68.3%	1.674

Table 6. Results of Data Analysis for the Allometric Equation Model Development Stage of Total Biomass

Regression Equation	Model Equation	R^2	SEE
Linear	B = -207.052+16.488D	73.2%	54.299
Power	B = 0.049D^2.622	88%	0.279
Exponential	B = 5.607e^0.142D	91.6%	0.233
Logarithmic	B = -735.441+666.953 LogD	65%	62.088
Multiple Linier	B = -189.442+16.349D-1.487H	73.5%	59.217
Multiple Power	B = 0.033D^(2.518) H^0.253	88.5%	0.299
Quadratic	B = 308.467 41.060D+1.485D^2	83.6%	46.538

Model Validation

Model validation performed to assess and ensure the estimation model meets the established criteria. Several values are used to determine model validation, namely the mean deviation (SR), aggregate deviation (SA), RMSE, and bias (e). The results of the model validation data analysis can be seen in Tables 7, 8, 9, and 10.

The results of the data analysis of the validation stage of the allometric equation model of stem biomass (Table 7) show that the SA values generated from the seven models ranged from -0.203% to -0.120%, the SR values ranged from 0.018% to 0.028%, the bias (e) ranged from -0.028% to -0.018% and the RMSE generated from the seven models ranged from 1.582% to 1.755%. According to Kuswandi (2016), the best model in the validation stage was determined through a scoring system and the model with the lowest score. Based on this statement, the best model in the validation stage of the stem biomass estimation model was the power model. Based on the model validation criteria, the model was selected because it had an SA value of less than 1% and an SR of less than 10% (Sahuri, 2017; Sumadi et al., 2010). For the results of the Data Analysis of the Validation Stage of the Branch Biomass Allometric Equation Model (Table 8) shows that the SA values generated from the seven models ranged from -0.740% to -0.053%, the SR values ranged from 0.008% to 0.071%, the bias (e) ranged from -0.071% to -0.008% and the RMSE generated from the seven models ranged from 1.486% to 1.905%. According to Syahiib et al. (2024), the best model in the validation stage was determined through a scoring system and the model with the lowest score. Based on this statement, the best model in the validation stage of the branch biomass estimation model was the exponential model. Based on the model validation criteria, the model was selected because it had an SA value of less than 1% and an SR of less than 10% (Sumadi & Siahaan, 2010; Sahuri, 2017). Scoring of the SA, SR, e and RMSE values shows that the model has the lowest score.

The Validation Stage of the Leaf Biomass Allometric Equation Model (Table 9) shows that the SA values generated from the seven models ranged from -1.951% to -1.054%, the SR values ranged from 0.086% to 0.110%, the bias (e) ranged from -0.110% to -0.086% and the RMSE generated from the seven models ranged from 1.378% to 1.549%. According to Kuswandi (2016), the best model in the validation stage was determined through a scoring system and the model with the lowest score. Based on this statement, the best model in the validation stage of the leaf biomass estimation model was the multiple power model. Based on the model validation criteria, the model was selected because it had an SA value of less than 1% and an SR of less than 10% (Mishra et al., 2012). Scoring of the SA, SR, e and RMSE values shows that the model has the lowest score. Validation of the Total Biomass Allometric Equation Model (Table 10) shows that the SA values generated by the seven models ranged from -0.368% to -0.012%, the SR values ranged from 0.002% to 0.045%, the bias (e) ranged from -0.045% to 0.002%, and the RMSE generated from the seven models ranged from 1.113% to 1.847%. According to Kuswandi (2016), the best model in the validation stage was determined through a scoring system and the model with the lowest score. Based on this statement, the best model in the validation stage for estimating total biomass was the exponential model. Based on model validation criteria, this model was selected because it had an SA value of less than 1% and an SR of less than 10% (Sumadi & Siahaan, 2010; Sahuri, 2017). Scoring of the SA, SR, e and RMSE values shows that the model has the lowest score.

Table 7. Results of Data Analysis of the Validation Stage of the Allometric Equation Model of Stem Biomass

Regression Equation	Model Equation	SA	SR	e	RMSE
Linear	B = -86.99+8.08D	-0.120	0.018	-0.018	1.650
Power	B = 0.036D^(2.503)	-0.186	0.026	-0.026	1.588
Exponential	B = 0.042D^(2.569) H^(-0.1620	-0.181	0.026	-0.026	1.582
Logarithmic	B = -369,973 + 344.246 LogD	-0.138	0.020	-0.020	1.755
Multiple Linier	B = -80.562 + 7.343D + 0.356H	-0.203	0.028	-0.028	1.613
Multiple Power	B = 4.884 e^ (0.127D)	-0.166	0.024	-0.024	1.648
Quadratic	B = 12.54 - 3.19D+0.29D^2	-0.182	0.026	-0.026	1.612

Table 8. Results of Data Analysis of the Validation Stage of the Branch Biomass Allometric Equation Model

Regression Equation	Model Equation	SA	SR	e	RMSE
Linear	B = - 105.656+7.667D	-0.062	0.010	-0.010	1.847
Power	B = 0.006D^(2.817)	-0.439	0.051	-0.051	1.566
Exponential	B = 1.269e^(0.154D)	-0.363	0.044	-0.044	1.486
Logarithmic	B = - 347.52 + 305.98 LogD	-0.053	0.008	-0.008	1.905
Multiple Linier	B = - 100.851 + 7.818D -1.008H	-0.081	0.012	-0.012	1.863
Multiple Power	B = 0.002D^(2.274) H^(1.322)	-0.389	0.047	-0.047	1.764
Quadratic	B = 287.956 -36.906D + 1.157D^2	-0.740	0.071	-0.071	1.831

Table 9. Results of Data Analysis of the Validation Stage of the Allometric Equation Model of Leaf Biomass

Regression Equation	Model Equation	SA	SR	e	RMSE
Linear	B = - 3.881 + 0.377D	-1.280	0.094	-0.094	1.477
Power	B = 0.00018D^(3.201)	-1.951	0.110	-0.110	1.543
Exponential	B = 0.104e^(0.159D)	-1.930	0.110	-0.110	1.549
Logarithmic	B = -17.964+16.740 LogD	-1.343	0.096	-0.096	1.470
Multiple Linier	B = -6.582 + 0.292D + 0.567H	-1.054	0.086	-0.086	1.388
Multiple Power	B = 0.000022D^(2.124) H^(2.621)	-1.463	0.099	-0.099	1.378
Quadratic	B = 7.985 - 0.967D+ 0.035D^2	-1.581	0.102	-0.102	1.539

Table 10. Results of Data Analysis of the Validation Stage of the Total Biomass Allometric Equation Model

Regression Equation	Model Equation	SA	SR	e	RMSE
Linear	B = -207.052 + 16.488D	-0.305	0.039	-0.039	1.847
Power	B = 0.049D^2.6	0.012	0.002	0.002	1.309
Exponential	B = 5.607e^(0.142	-0.231	0.031	-0.031	1.299
Logarithmic	B = -735.441 +666.953 Log	-0.145	0.021	-0.021	1.804
Multiple Linier	B = -189.442+16.349D -1.48	-0.147	0.021	-0.021	1.730
Multiple Power	B = 0.033D^(2.518) H^(0.2	-0.185	0.026	-0.026	1.113
Quadratic	B = 308,467-41.060D + 1.485D	-0.368	0.045	-0.045	1.689

Best Model Selection

The selection of the best model needs to be done based on a scoring system for each statistical criterion because a certain model can have a higher score on one criterion but lower on another statistical criterion. Because the best estimator models produced at the model development and model validation stages are different, the best model must be determined based on the calculation of the combined ranking of the model development and model validation stages (Siagian, 2011; et al., 2016). The combined ranking of the data model development and validation stages is seen in Tables 11, 12, 13 and 14.

Based on the results of Table 11, the best model for estimating the stem biomass of the Sonneratia alba species in the Tanah Merah Kupang Mangrove Forest is the power model (B), with an R^2 value of 96.8%, SEE = 0.131, SA = -0.186, SR = 0.026, e = -0.026 and RMSE = 1.588. Table 12 shows the best model for estimating the branch biomass of S. alba species in the Tanah Merah Kupang Mangrove Forest, namely the quadratic model (B = 287.956-36.906D + 1.157D^2), with a value of R^2 = 70.5%, SEE = 35.502, SA = -0.740, SR = 0.071, e = -0.071 and RMSE = 1.831. Table 13 shows the best model for estimating the leaf biomass of S. alba species in the Tanah Merah Kupang Mangrove Forest, namely the multiple power model (B = 0.000022D^(2.124) H^(2.621)), with R^2 value = 73.8%, SEE = 0.717, SA = -1.463, SR = 0.099, e = -0.099.031 and RMSE = 1.378, while Table 14 the best model for estimating the total biomass of the Sonneratia alba species in the Tanah Merah Kupang Mangrove Forest is the exponential model. (B), with R^2 value = 91.6%, SEE = 0.233, SA = -0.231, SR = 0.031, e = -0.031 and RMSE = 1.299.

Table 11. Combined Ranking of Stem Biomass Allometric Equation Model Assessment

Regression Equation	Model Equation	Equation Value Ranking						Σ	Rank Combine
		R^2	SEE	SA	SR	e	RMSE		
Linear	B = -86.99+8.08D	6	5	7	1	7	6	32	6
Power	B = 0.036D^(2.503)	2	1	2	6	2	2	15	1
Exponential	B = 0.042D^(2.569) H^(-0.1620	3	3	4	4	4	1	19	2
Logarithmic	B = -369,973 + 344.246 LogD	7	7	6	2	6	7	35	7
Multiple Linier	B = -80.562 + 7.343D + 0.356H	4	4	1	7	1	4	21	3
Multiple Power	B = 4.884 e^ (0.127D)	1	2	5	3	5	5	21	3
Quadratic	B = 12.54 - 3.19D +0.29D^2	5	6	3	5	3	3	25	5

Table 12. Combined Ranking of Branch Biomass Allometric

Regression Equation	Model Equation	Equation Value Ranking						Σ	Rank combine
		R^2	SEE	SA	SR	e	RMSE		
Linear	B = - 105.656+7.667D	3	5	6	2	6	5	27	5
Power	B = 0.006D^(2.817)	6	2	2	6	2	2	20	3
Exponential	B = 1.269e^(0.154D)	5	1	4	4	4	1	19	2
Logarithmic	B = - 347.52 + 305.98 LogD	7	6	7	1	7	7	35	7
Multiple Linier	B = - 100.851 + 7.818D -1.008H	2	7	5	3	5	6	28	6
Multiple Power	B = 0.002D^(2.274) H^(1.322)	4	3	3	5	3	3	21	4

Regression Equation	Model Equation	Equation Value Ranking R^2	SEE	SA	SR	e	RMSE	Σ	Rank combine
Quadratic	B = 287.956 -36.906D + 1.157D^2	1	4	1	7	1	4	18	1

Table 13. Combined Ranking of Leaf Biomass Allometric Equation Model Assessment

Regression Equation	Model Equation	Equation Value Ranking						Σ	Rank combine
		R^2	SEE	SA	SR	e	RMSE		
Linear	B = - 3.881 + 0.377D	5	7	6	2	6	4	30	7
Power	B = 0.00018D^(3.201)	6	2	1	7	1	5	22	2
Exponential	B = 0.104e^(0.159D)	7	3	2	6	2	6	26	4
Logarithmic	B = -17.964+16.740 LogD	4	6	5	3	5	3	26	4
Multiple Linier	B = -6.582 + 0.292D + 0.567H	2	4	7	1	7	2	23	3
Multiple Power	B = 0.000022D^(2.124) H^(2.621)	1	1	4	4	4	1	15	1
Quadratic	B = 7.985 - 0.967D+ 0.035D^2	3	5	3	5	3	7	26	4

Table 14. Combined Ranking of Total Biomass Allometric Equation Model Assessment

Regression Equation	Model Equation	Equation Value Ranking						Σ	Rank combine
		R^2	SEE	SA	SR	e	RMSE		
Linear	B = -207.052 + 16.488D	6	5	2	6	2	7	28	5
Power	B = 0.049D^2.622	3	2	7	1	7	3	23	4
Exponential	B = 5.607e^(0.142D)	1	1	3	5	3	2	15	1
Logarithmic	B = -735.441 + 666.953 LogD	7	7	6	2	6	6	34	7
Multiple Linier	B = -189.442+16.349D -1.487H	5	6	5	3	5	5	29	6
Multiple Power	B = 0.033D^(2.518) H^(0.253)	2	3	4	4	4	1	18	2
Quadratic	B = 308,467-41.060D +1.485D^2	4	4	1	7	1	4	21	3

Biomass Based on the Best Model

The best allometric equation model for total biomass was the Exponential model: B, and therefore, this model was used to calculate the biomass of *Sonneratia alba* in the Tanah Merah Mangrove Forest in Kupang. The results of the *Sonneratia alba* biomass calculation using the best model can be seen in Table 15. The biomass calculated based on the best model was 18.38 tons ha^{-1}.

Table 15. Biomass Based on the Best Model in the Tanah Merah Mangrove Forest

Cluster	Number of Trees	Average Biomass (tons ha^{-1})
2004 Front	3	2.53
2004 Middle	17	19.66
2004 Rear	9	21.31
2006 Front	1	0.79
2006 Middle	12	12.52
2006 Rear	12	76.76
2008 Front	4	1.99
2008 Middle	0	0
2008 Rear	7	29.86
Σ	65	165.42
Average (ton/ha)		18.38

Carbon Stock Potential Based on the Best Model

The estimation of carbon stocks from biomass based on the IPCC (2006) uses the following formula:

$$C = 0.47 \times B. \quad (3)$$

Where:
C: Aboveground carbon content (tons/ha)
B: Biomass (ton/ha)

The results of the carbon calculations for Sonneratia alba can be seen in Table 16. The calculation results show that the potential carbon reserves of the Sonneratia alba species in the Tanah Merah Kupang Mangrove Forest are 8.64 tons ha-1.

Table 16. Carbon Stock Potential Based on the Best Model in the Tanah Merah Mangrove Forest

Cluster	Number of Trees	Average Carbon (ton ha^{-1})
2004 Front	3	1.19
2004 Middle	17	9.24
2004 Rear	9	10.01
2006 Front	1	0.37
2006 Middle	12	5.88
2006 Rear	12	36.08
2008 Front	4	0.94
2008 Middle	0	0
2008 Rear	7	14.03
Σ	65	77.75
Average (ton ha-1)		8.64

Conclusion

The best allometric models that were developed to estimate the biomass of the Sonneratia alba species were: Stem biomass 0.036D^(2.503) Branch biomass 287.956-3.906D + 1.157D^2, Leaf biomass

0.000022D ^(2.124)H^(2.621) Total biomass 5,607e^(0.142D). The carbon reserve potential of the Sonneratia alba species in the Tanah Merah Kupang Mangrove Forest calculated based on the best model is 8.64 tons ha^{-1}.

Acknowledgments
We would like to thank the Kupang State Agricultural Polytechnic for providing us with the opportunity to conduct this research. We would also like to thank the NTT Natural Resources Conservation Center, the Kupang Regency Government, and the Tanah Merah Village Government for granting us permission to conduct research in the mangrove forest.

Author Contributions
MP.: resources, conceptualization, methodology, investigation, data curation, formal analysis, writing – original draft preparation, writing—review and editing; YO.: data curation, formal analysis, writing – original draft preparation, writing—review and editing,. AA: formal analysis, writing – original draft preparation, writing—review and editing TSL: resources, conceptualization, methodology, investigation, data curation, formal analysis, SM: writing – original draft preparation, writing—review and editing.

Funding
Research and articles are funded by the Kupang State Agricultural Polytechnic through pure PNBP funding.

Conflicts of Interest
The data generated and analyzed during this research are not publicly available but can be obtained from the authors upon reasonable request. Conflicts of Interest: The authors declare no conflict of interest.

References

Analuddin, K., La Ode, K., La Ode, M. Y. H., Andi, S., Idin, S., La, S., Rahim, S., La Ode, A. F., & Kazuo, N. (2020). Aboveground biomass, productivity and carbon sequestration in Rhizophora stylosa mangrove forest of Southeast Sulawesi, Indonesia. *Biodiversitas Journal of Biological Diversity*, *21*(4). https://doi.org/10.13057/biodiv/d210407

Bachmid, F., Sondak, C., & Kusen, J. (2018). Estimasi penyerapan karbon hutan mangrove Bahowo Kelurahan Tongkaina Kecamatan Bunaken. *Jurnal Pesisir Dan Laut Tropis*, *6*(1), 8. https://doi.org/10.35800/jplt.6.1.2018.19463

Dinilhuda, A., Akbar, A. A., Jumiati, & Herawaty, H. (2020). Potentials of mangrove ecosystem as storage of carbon for global warming mitigation. *Biodiversitas Journal of Biological Diversity*, *21*(11), 5353–5362. https://doi.org/10.13057/biodiv/d211141

Koh, H. ., Teh, S. ., Kh'ng, X., & Raja Barizan, R. (2018). Mangrove Forests : Protection Against. *Journal of Tropical Forest Science*, *30*(5), 446–460. Retrieved from https://www.jstor.org/stable/26514436

Kuswandi, R. (2016). Model penduga volume pohon kelompok jenis komersial pada wilayah Kabupaten Sarmi, Papua. *Wasian*, *3*(2), 91–96. Retrieved from https://pub.kehutanan.unismuh.ac.id/index.php/wasian/article/view/54/49

Matatula, J., Afandi, A. Y., & Wirabuana, P. (2021). Short Communication: A comparison of stand structure, species diversity and aboveground biomass between natural and planted mangroves in Sikka, East Nusa Tenggara, Indonesia. *Biodiversitas Journal of Biological Diversity*, *22*(3). https://doi.org/10.13057/biodiv/d220303

Mishra, S., & Mishra, D. R. (2012). Normalized difference chlorophyll index: A novel model for remote estimation of chlorophyll-a concentration in turbid productive waters. *Remote Sensing of Environment*, *117*, 394–406. https://doi.org/10.1016/j.rse.2011.10.016

Njana, M. A. (2017). Indirect methods of tree biomass estimation and their uncertainties. *Southern Forests: A Journal of Forest Science*, *79*(1), 41–49. https://doi.org/10.2989/20702620.2016.1233753

Pathibang, M. R., Tanea, D. M., & Matatula, J. (2023). Identifikasi Dan Penyebaran Jenis Mangrove Di Bagian Timur Pulau Menipo Taman Wisata Alam Pulau Menipo. *Partner*, *28*(1), 131. https://doi.org/10.35726/jp.v28i1.6945

Poedjirahajoe, E., & Matatula, J. (2019). The physiochemical condition of mangrove ecosystems in the coastal district of Sulamo, Kupang, East Nusa Tenggara, Indonesia. *Jurnal Manajemen Hutan Tropika*, *23*(5), 173–184. https://doi.org/10.7226/jtfm.25.3.173

Richards, D. R., & Friess, D. A. (2016). Rates and drivers of mangrove deforestation in Southeast Asia, 2000–2012. *Proceedings of the National Academy of Sciences*, *113*(2), 344–349. https://doi.org/10.1073/pnas.1510272113

Sadono, R., Soeprijadi, D., Susanti, A., Matatula, J., Eko Pujiono, Idris, F., & Wirabuana, P. Y. P. (2020). Local indigenous strategy to rehabilitate and conserve mangrove ecosystem in the southeastern Gulf of Kupang, East Nusa Tenggara, Indonesia. *Biodiversitas Journal of Biological Diversity*, *21*(3), 1250–1257. https://doi.org/10.13057/biodiv/d210353

Sahuri, S. (2017). Model Pendugaan Volume Pohon Karet Saat Peremajaan di Sembawa, Sumatera Selatan. *Jurnal Penelitian Hutan Tanaman*, *14*(2), 139–153. https://doi.org/10.59465/jpht.v14i2.848

Salsabilli, C. P. S., Widiastuti, R., Endang, L., & Wahyuningsih, S. (2021). Carbon Stock Estimation Due to Changes in Mangrove Labuhan Maringgai

District, East Lampung Regency. *Proceedings of the International Conference on Sustainable Biomass (ICSB 2019*, *202*, 6–10,. https://doi.org/10.2991/aer.k.210603.002

Siagian, K. (2011). *Tabel Volume Pohon Agathis loranthifolia di Hutan Pendidikan Gunung Walat Kabupaten Sukabumi Provinsi Jawa Barat (Table of Agathis loranthifolia Tree Volume in Gunung Walat Educational Forest, Sukabumi Regency, West Java Province)*. Institut Pertanian Bogor.

Singh, J. K. (2020). Structural characteristics of mangrove forest in different coastal habitats of Gulf of Khambhat arid region of Gujarat, west coast of India. *Heliyon*, *6*(8), e04685. https://doi.org/10.1016/j.heliyon.2020.e04685

Sumadi, A., & Siahaan, H. (2010). Model Penduga Volume Pohon Kayu Bawang (Disoxylum molliscimum Burm F.) Di Provinsi Bengkulu. *Jurnal Penelitian Hutan Tanaman*, *7*(5), 277–231. https://doi.org/10.20886/jpht.2010.7.5.227-231

Susanty, F. H., & Abdurrachman, A. (2016). Analisis Penyusunan Model Pendugaan Volume Pohon 3 Jenis Shorea Di Tarakan, Kalimantan Utara. *Jurnal Penelitian Ekosistem Dipterokarpa*, *2*(1), 29–40. https://doi.org/10.20886/jped.2016.2.1.29-40

Susilo, H., Takahashi, Y., & Yabe, M. (2017). The Opportunity Cost of Labor for Valuing Mangrove Restoration in Mahakam Delta, Indonesia. *Sustainability*, *9*(12), 2169. https://doi.org/10.3390/su9122169

Syahiib, A. N., & Safe'i, R. (2024). The Effect of C-Organic Sediment and Litter Carbon Estimation on Fertility and Site Health in Lampung Mangrove Center. *Jurnal Pengelolaan Sumberdaya Alam Dan Lingkungan (Journal of Natural Resources and Environmental Management)*, *14*(4), 652. https://doi.org/10.29244/jpsl.14.4.652

Taillardat, P., Friess, D. A., & Lupascu, M. (2018). Mangrove blue carbon strategies for climate change mitigation are most effective at the national scale. *Biology Letters*, *14*(10), 20180251. https://doi.org/10.1098/rsbl.2018.0251

Yuliana, E., Hewindati, Y. T., Winata, A., Djatmiko, W. A., & Rahadiati, A. (2019). Diversity and characteristics of mangrove vegetation in Pulau Rimau Protection Forest, Banyuasin District, South Sumatra, Indonesia. *Biodiversitas Journal of Biological Diversity*, *20*(4), 1215–1221. https://doi.org/10.13057/biodiv/d200438