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Comparison of allometric model performance for estimating aboveground biomass from the rehabilitation of *Casuarina equisetifolia* coastal forest

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ABSTRACT

Coastal forest rehabilitation increasingly relies on *Casuarina equisetifolia* because of its capacity to establish under challenging coastal conditions and contribute to biomass accumulation. However, different allometric equations may produce substantially different biomass estimates, and comparative evidence for rehabilitated coastal forests in Indonesia remains limited. This study evaluated the relative agreement of three candidate allometric equations with the Dudley and Fownes species-specific equation used as a reference for *C. equisetifolia* in a rehabilitated coastal forest in Kulon Progo, Indonesia. Field measurements of diameter at breast height and tree height were obtained from 20 sampling points, and aboveground biomass was estimated using the four equations. Agreement was assessed using standard deviation, coefficient of variation, mean absolute error (MAE), root mean square error (RMSE), mean bias error (MBE), and Pearson correlation coefficient. Among all statistical tests performed, the EWM results ranked Ketterings first (0.66), followed by Chave (0.57) and Brown (0.26). The principal limitation is the absence of independent or destructive biomass measurements; therefore, the findings demonstrate relative agreement with the reference model rather than absolute model accuracy. Practically, the results provide a transparent framework for comparative screening of allometric equations when independent biomass validation is unavailable. The study contributes comparative evidence for rehabilitated coastal *C. equisetifolia* in Indonesia and identifies Ketterings et al. as the equation showing the strongest agreement with the selected reference under the tested conditions. Independent biomass validation across additional sites and tree-size classes is needed to determine whether this agreement reflects greater absolute accuracy.

Keywords: coastal forest rehabilitation, *Casuarina equisetifolia*, aboveground biomass, allometric method.

INTRODUCTION

Coastal forest rehabilitation is increasingly recognized as a nature-based approach for restoring degraded coastal ecosystems and supporting ecosystem functions, including biomass accumulation and carbon storage. (Paxton et al., 2024). *Casuarina equisetifolia* is a fast-growing pioneer tree species that is widely used in tropical coastal rehabilitation because of its ability to establish under relatively harsh environmental conditions, including sandy soils, salinity, and seasonal water limitation (Zhang et al., 2023), Its establishment can contribute to vegetation development, soil stabilization, and the recovery of ecosystem functions in disturbed coastal environments. Because aboveground biomass (AGB) is an important component of forest carbon stocks, reliable biomass estimation is relevant for evaluating vegetation development, forest management, and carbon-related assessments in rehabilitated coastal forests (F. Wang et al., 2013; Xue et al., 2016).

Aboveground biomass is commonly estimated using allometric equations, which provide a practical and non-destructive alternative to destructive biomass harvesting. These equations relate measurable tree attributes, such as diameter at breast height (DBH), tree height, and wood density, to biomass (Krause et al., 2023; Stovall et al., 2023). Numerous allometric models have been developed for tropical forests, ranging from species-specific equations to equations intended for broader geographic or ecological domains (Dutta et al., 2022). However, equations developed under different forest types, climatic conditions, geographic regions, and tree structural characteristics may produce different biomass estimates when applied to rehabilitated coastal forests dominated by *C. equisetifolia* (Wang et al., 2023). Consequently, selecting an equation for a particular application requires consideration of both its predictor variables and the ecological and geographic context in which it was developed (Picard et al., 2024).

Previous studies of *C. equisetifolia* have frequently applied individual species-specific or general allometric equations for biomass estimation (Farma et al, 2025; Vallejo and Tano, 2023). However, comparative assessments of alternative equations for *C. equisetifolia*, particularly in rehabilitated coastal forests, remain limited. Differences among equations can introduce substantial variation in estimated AGB and consequently affect biomass and carbon-stock assessments (Mulatu et al., 2024). Comparative evaluation is therefore useful for identifying how consistently alternative equations reproduce estimates from a selected reference equation under a common set of field measurements.

For *C. equisetifolia*, comparative evidence concerning the agreement between species-specific and more general allometric equations remains limited, particularly for rehabilitated coastal forests in Indonesia. The present study therefore compares three general or broader-domain allometric equations proposed by Chave et al., Brown et al., and Ketterings et al. with the species-specific equation of Dudley and Fownes for estimating AGB of *C. equisetifolia* in a rehabilitated coastal forest in Kulon Progo, Indonesia. The Dudley and Fownes equation was selected as the reference model because it was developed using biomass data for *C. equisetifolia* and therefore provides a species-specific basis for comparison. Importantly, its use as a reference does not imply that it represents the true biomass of the trees sampled in the present study. The candidate equations represent different calibration contexts and predictor requirements. The Chave et al. equation is a widely used pantropical model incorporating DBH, tree height, and wood density (Chave et al., 2014). The Brown et al. equation provides a broader tropical-forest comparison based primarily on DBH (Walker et al., 2016). The Ketterings et al. equation was developed from tropical tree data collected in Indonesia and incorporates DBH and wood density (Ketterings et al., 2001). These differences provide a basis for examining whether models developed at broader geographic scales or using different predictor variables show different levels of agreement with a species-specific reference equation when applied to rehabilitated coastal *C. equisetifolia*.

Accordingly, this study aimed to (1) quantify AGB estimates obtained from the Dudley and Fownes, Chave et al., Brown et al., and Ketterings et al. equations; (2) compare the agreement of the three candidate equations with the Dudley and Fownes reference estimates using multiple statistical indicators; and (3) synthesize these indicators using the entropy weight method (EWM) and examine the stability of the resulting ranking through sensitivity analysis. The statistical indicators were used to characterize different aspects of agreement, including dispersion, relative variability, absolute error, root mean square error, bias, and correlation.

We hypothesized that the candidate equations would differ in their degree of agreement with the species-specific reference estimates because of differences in their predictor variables and original calibration contexts. In particular, because the Ketterings et al. equation was developed using tropical vegetation data from Indonesia, we expected it to show relatively close agreement with the Dudley and Fownes reference estimates in the study area. However, this hypothesis concerns relative agreement with the reference model, not absolute biomass accuracy.

The intended outcome of the study is therefore a transparent comparative assessment of alternative allometric equations under conditions where independent biomass validation is unavailable. The resulting ranking should be interpreted as an assessment of relative agreement with the selected reference equation and ranking stability under the tested weighting scenarios, rather than as evidence that any candidate equation provides the most accurate estimate of actual biomass. Independent field measurements, preferably including destructive biomass sampling or a separate validation dataset, would be required to establish absolute model accuracy.

MATERIALS AND METHODS

Study area

The study was conducted in a coastal forest rehabilitation area established under the 2019 forest and land rehabilitation (RHL) program south of Yogyakarta International Airport (YIA), in Kulon Progo Regency, Special Region of Yogyakarta, Indonesia. The study site forms part of the YIA greenbelt rehabilitation area and covers approximately 30 hectares, with coordinates at 7°53′55″ S, 110°02′03″ E to 7°54′44″ S, 110°04′03″ E (Figure 1). The rehabilitation area extends along the southern side of the YIA runway between Congot Beach and Glagah Beach.

Data collection and processing

A systematic sampling design was used to establish 20 sampling points across the approximately 30-ha rehabilitation area. The sampling points were generated using a predefined systematic grid in ArcGIS to provide relatively uniform spatial coverage of the study area and to capture spatial variation in vegetation structure (Marvin and Asner, 2016). Each sampling unit consisted of a 5 × 5 m plot. Field measurements included diameter at breast height (DBH) and tree height for *Casuarina equisetifolia* individuals within the sampling plots. These measurements were used as inputs for the allometric equations according to the predictor variables required by each model. No destructive biomass sampling was conducted, and no independently measured plot-level AGB data were available for model validation.

The Dudley and Fownes equation was therefore used as a reference model for comparative purposes, rather than as a ground-truth or independently validated estimate of actual biomass. AGB estimates from the Chave et al., Brown et al., and Ketterings et al. equations were compared with the Dudley and Fownes reference estimates using the statistical indicators described below. The model showing the greatest overall agreement with the reference estimates was identified through the EWM-based comparative ranking. This ranking

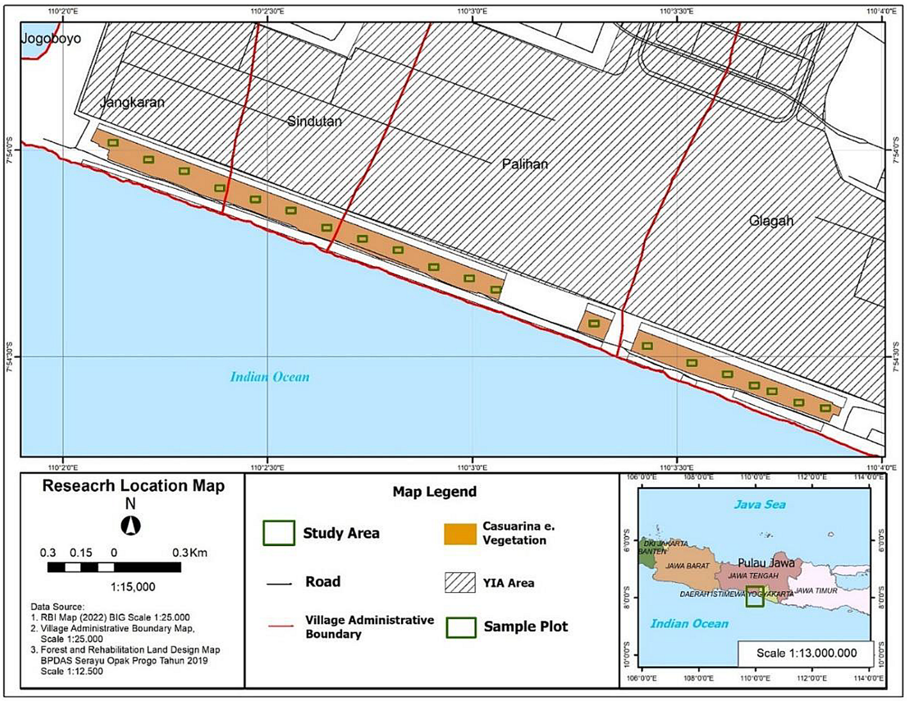

Figure 1. Sampling points and spatial distribution of vegetation within the research area

was interpreted as relative agreement with the reference model and not as evidence of absolute biomass accuracy. One sampling point contained no vegetation and therefore did not yield tree-level measurements. The treatment of this sampling point in the statistical analysis is described explicitly in the corresponding data-analysis procedures. Figure 2 presents the overall workflow of the study.

Dudley et al. allometric model

The Dudley et al. model is an allometric empirical relationship that relates tree dimensions to biomass obtained by destructive sampling. This relationship may be used to estimate biomass in a non-destructive manner. The regression analysis relating biomass to DBH for *C. equisetifolia* trees yielded an allometric equation representative of species growth. Biomass is related to the DBH by an allometric equation, which is derived from field measurements to estimate biomass (Dudley, 1992).

For the analyses, we chose the Dudley and Fownes model as the reference model, as it is a local (species-specific) allometric model developed for *C. equisetifolia*. The Dudley and Fownes model was based on empirical data for the same species, thus better characterizing its morphological features, crown architecture, and biomass allocation patterns in *C. equisetifolia*.

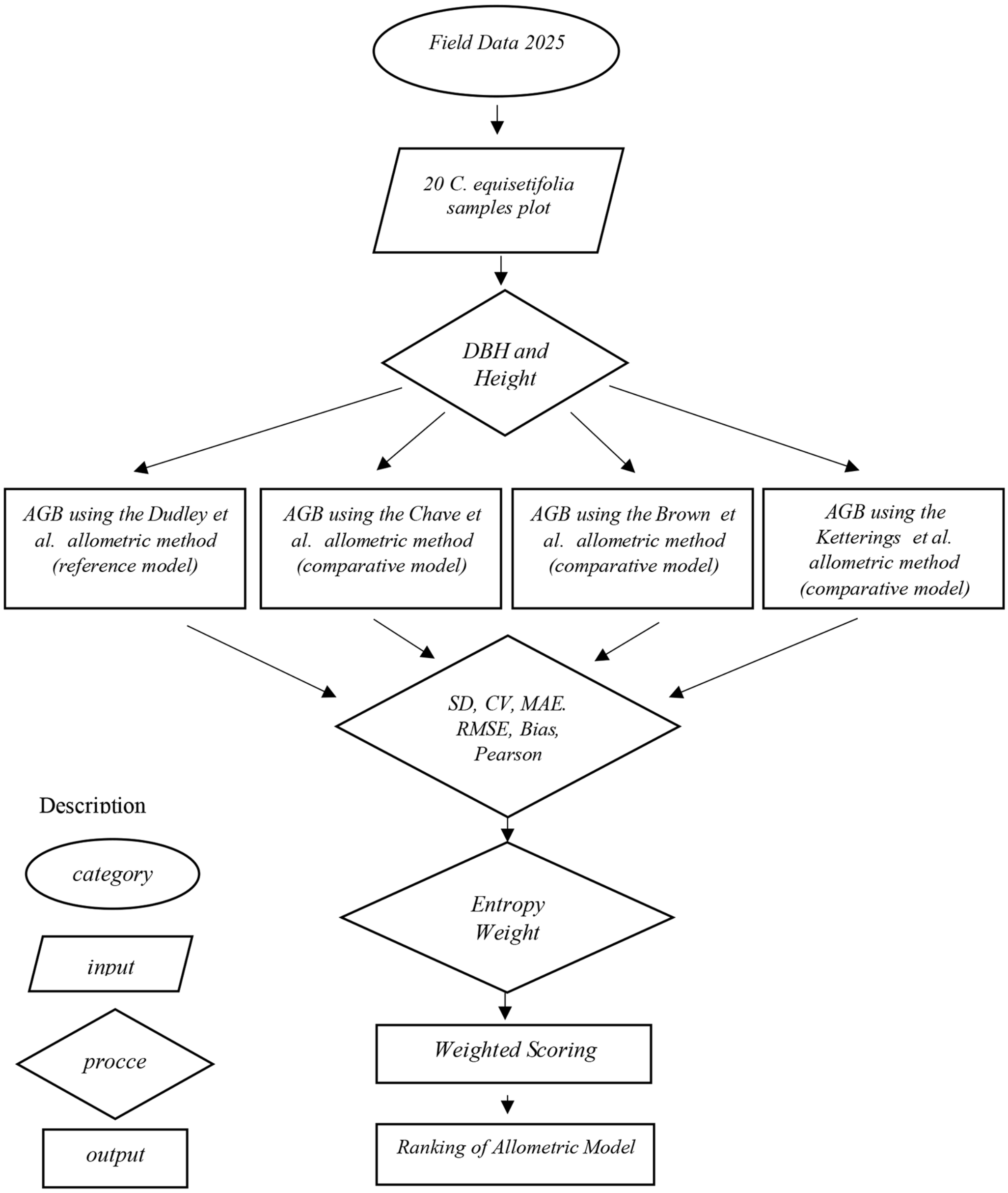

Figure 2. Flowchart of the research metodology applied in this study

Chave et al. allometric model

Chave et al. allometric model is used to estimate above-ground biomass (AGB) and serves as a general reference model (not specific to any particular species). This model utilizes the pantropical equation developed by Chave et al. to estimate the AGB of individual trees based on diameter at breast height (DBH), tree height (H), and wood density (ρ) (Chave et al., 2014). Among pantropical allometric equations, the Chave model is one of the most commonly used and well-known for estimating aboveground biomass in tropical forests from measurements of tree diameter. Therefore, this model was chosen for comparison against the species-specific model of Dudley and Fownes for *C. equisetifolia* to evaluate the ability of a generic pantropical model to capture the biomass characteristics of rehabilitated *C. equisetifolia* within its natural coastal biomass. Therefore, this model was chosen for comparison against the species-specific model of Dudley et al. for *C. equisetifolia* to evaluate the ability of a generic pantropical model to capture the biomass characteristics of rehabilitated *C. equisetifolia* within its natural coastal biomass.

Brown et al. allometric model

Brown et al. allometric model exploits the empirical relationship between above-ground biomass and DBH that was obtained for tropical trees through destructive sampling. Brown's allometric model exploits the empirical relationship between above-ground biomass and DBH that was obtained for tropical trees through destructive sampling. Using the DBH measured for each tree, biomass is computed by Brown's allometric equation, allowing for an indirect estimation of the biomass of trees without destroying them.

Brown's (1989) model was selected for comparative purposes because it was specifically designed for dry tropical forests that share environmental characteristics with the study site. These conditions reflect the ecological context that formed the basis for Brown's (1989) equation (Walker et al., 2016). In this way, it can be used as a general tropical comparative model for estimating biomass relative to the more species-specific equation provided by Dudley and Fownes. This comparison of the two models can thus test the applicability of the dry tropical forest model for estimating the above-ground biomass of *C. equisetifolia* growing in the rehabilitated coastal ecosystem.

Ketterings et al. allometric model

The Ketterings et al. (2001)) equation was developed from destructive biomass measurements of tropical trees in Jambi, Indonesia, and estimates aboveground biomass from DBH and wood density. The equation is expressed in Table 1. The equation was included as a broader Indonesian tropical-forest model rather than as a species-specific equation for *C. equisetifolia*. Its inclusion allowed comparison of a model developed from Indonesian tropical-tree data with the species-specific Dudley and Fownes reference equation.

Allometric model equations

According to the variables required by each model, four allometric models were used to estimate AGB of *C. equisetifolia* Table 1. As a result, they differed in the predictor variable requirements: some equations required only the DBH, while others required the tree height and/or wood density in addition to the DBH. Therefore, each model was calculated using only the variables required by its original formulation, as opposed to forcing the same set of input variables through all models.

For the 20 sample trees, DBH was measured in the field and used in accordance with the specifications of each model. Tree height was also measured and incorporated into the Chave et al. model, which requires both diameter and height

Table 1. Allometric model equation

No	Allometric Model	Predictors (20 samples)	Equation	Source
1	Dudley at al.	Diameter (cm)	$ln(AGB) = -2.177 + 2.523 ln(DBH)$ or $AGB = 0.1134 \times DBH^{2.523}$	(Dudley, 1992)
2	Chave et al.	Diameter (cm), height (m), wood density (g cm^{-3})	$AGB = 0.0673 \times (\rho \times DBH^2 \times H)^{0.976}$	(Walker et al., 2016)
3	Brown et al.	Diameter (cm)	$AGB = 34.4703 - 8.0671 \times DBH + 0.6589 \times DBH^2$	(Walker et al., 2016)
4	Ketterings et al.	Diameter (cm), wood density (g cm^{-3})	$AGB = 0.11 \times \rho \times DBH^{2.62}$	(Ketterings et al., 2001)

data. A wood density of 0.83 g cm^{-3} was assumed for all sample trees, based on IPCC 2006 data for Asia on *C. equisetifolia* wood density. This wood density value was only used in the models where wood density was one of the predictor variables, i.e., the Chave et al. and Ketterings et al. models. AGB estimates derived from these calculations were then used to compare the performances of the four allometric models.

Comparison method for allometric models using the entropy weight method (EWM)

In this study, the allometric models were compared using statistical indicators of mean, standard deviation (SD), coefficient of variation (CV), mean absolute error (MAE), root mean square error (RMSE), mean bias error (MBE), and Pearson correlation coefficient (r) with respect to the reference model. The SD formula equation as:

$$SD = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}} \quad (1)$$

where: *SD* is sample standard deviation, x_i is value of the i-th data point, $\bar{x}$ is sample mean, n is sample size, and the CV formula equation as:

$$CV = \sqrt{\frac{SD}{\bar{x}}} \times 100\% \quad (2)$$

where: *CV* is coefficient of variation (%), *SD* is sample standard deviation, $\bar{x}$ is sample mean and the MAE formula equation as:

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|AGB_{com} - AGB_{ref}\right| \quad (3)$$

where: *MAE* is mean absolut error, AGB_{com} is biomass estimation comparative model, AGB_{ref} is biomass estimation reference model, n is sample size, and the RMSE formula equation as:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(AGB_{com} - AGB_{ref})^2} \quad (4)$$

where: *RMSE* is root mean square error, AGB_{com} is biomass estimation comparative model, AGB_{ref} is biomass estimation reference model, n is sample size, and the mean bias formula equation as:

$$MBE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(AGB_{com} - AGB_{ref})} \quad (5)$$

where: *MBE* is mean bias error, AGB_{com} is biomass estimation comparative model, AGB_{ref} is biomass estimation reference model, n is sample size, and the pearson correlation coefficient (r) formula equation as:

$$r = \frac{\sum(AGB_{com} - \overline{AGB}_{com})(AGB_{ref} - \overline{AGB}_{ref})}{\sqrt{\sum(AGB_{com} - \overline{AGB}_{com})^2 \sum(AGB_{ref} - \overline{AGB}_{ref})^2}} \quad (6)$$

where: *r* is pearson correlation coefficient, AGB_{com} is biomass estimation comparative model, AGB_{ref} is biomass estimation reference model, $\overline{AGB}_{com}$ is mean biomass estimation comparative model and $\overline{AGB}_{ref}$ is mean biomass estimation reference model.

The SD, CV, MAE, and RMSE were then estimated, and we calculated the 95% Confidence Interval (CI) to quantify the uncertainty associated with the estimate.. A confidence interval offers a range of values likely to contain the population mean at a certain confidence level and, thus, describes the precision of an estimate. In this case, the 95% confidence interval represented the uncertainty in the evaluation results. The confidence interval was calculated using the t-distribution according to the following equation as:

$$CI_{95\%} = \bar{X} \pm t_{0.975,n-1}\frac{SD}{\sqrt{n}} \quad (7)$$

where: $\bar{X}$ sample mean AGB, *SD* is the standar deviation, *n* is the sample size and *t* is the critical value of the t-distribution with n-1 degrees of freedom. For n = 20, the critical value is $t_{0,975,19}$ = 2.093 (NIST/SEMATECH, 2012).

We then compared the performances of all allometric models using a weighted score approach based on the Entropy Weight Method (EWM), an Multi-Criteria Decision Analysis MCDA method that objectively determines weights for each indicator according to data variability without any subjective judgment on the part of the researcher (Zhu et al., 2020).

For each indicator, the three candidate models were treated as the evaluation alternatives. Benefit criteria were transformed so that higher normalized values indicated better agreement with the reference model, whereas cost criteria were transformed so that lower values indicated better agreement. The Normalization equation (*N*) for indicator *j* was calculated as:

For benefit criteria (where higher values are better), an example is the Pearson correlation

$$N_{ij} = \frac{X_{ij} - \min(X_j)}{\max(X_j) - \min(X_j)} \quad (8)$$

For cost criteria (where lower value is better), for example CV, MAE, RMSE, MBE

$$N_{ij} = \frac{\max(X_j) - X_{ij}}{\max(X_j) - \min(X_j)} (8) \quad (9)$$

where: X represent the AGB value for each indicator.

For each indicator j, the normalized values N_{ij} were converted into proportions:

$$P_{ij} = \frac{N}{\sum_i N_{ij}} \quad (10)$$

The entropy of indicator j was calculated as:

$$E_{ij} = -\frac{1}{\ln(n)} \sum_i P_{ij} \ln(P_{ij}) \quad (11)$$

where: $n = 3$ is the number of candidate models. When $p_{ij} = 0$, the term $p_{ij} \backslash ln(p_{ij})$ was set to zero.

The diversification coefficient was calculated as:

$$D_{ij} = 1 - E_{ij} \quad (12)$$

and the entropy weight as:

$$EW_j = \frac{D_j}{\sum_j D_j} \quad (13)$$

The final composite score for each model was calculated as the weighted sum of the normalized indicator value with formula in the equation as:

$$R_{AGB} = N_{SD}EW_{SD} + N_{CV}EW_{CV} + N_{MAE}EW_{MAE} + N_{RMSE}EW_{RMSE} + + N_{MBE}EW_{MBE} + N_r EW_r \quad (14)$$

A sensitivity analysis was conducted to examine whether the model ranking changed under alternative relative weights assigned to error-based criteria and Pearson correlation. The error-based criteria (MAE, RMSE, and absolute MBE) were assigned a combined weight ranging from 80% to 20%, while Pearson correlation was assigned the complementary weight ranging from 20% to 80%. The seven scenarios were evaluated in 10-percentage-point increments. Within each scenario, the combined error weight was equally distributed among MAE, RMSE, and absolute MBE, and the resulting composite scores were calculated using the normalized indicator values. The sensitivity analysis was interpreted as an assessment of ranking stability across the predefined weighting scenarios rather than as an exhaustive analysis of all possible weighting schemes. For each weighting scenario, a composite performance score was calculated as:

$$S_i = \sum_{j=1}^{n} w_j N_{ij} \quad (15)$$

where: w_j represent the weight assigned to metric j and N_{ij} is the normalized performance of model i.

The stability of model ranking was calculated as the proportion of weighting under which a model maintained its ranking.

RESULTS AND DISCUSSION

Comparison of biomass estimates derived from different allometric models

AGB estimates for *Casuarina equisetifolia* were calculated using the Dudley and Fownes, Chave et al., Brown et al., and Ketterings et al. allometric equations. The Dudley and Fownes equation was used as the reference model for comparative purposes because it was developed for *C. equisetifolia*. No destructive biomass measurements were available for the sampled trees; therefore, the results presented here represent differences and agreement among model-based estimates rather than independent estimates of actual biomass.

The four models showed similar spatial patterns in estimated AGB across the sampling points, although the magnitude of the estimates differed among equations (Table 2; Figure 3). The Ketterings et al. model generally produced estimates close to the Dudley and Fownes reference estimates, whereas the Brown et al. model generally produced lower estimates. The Chave et al. estimates were intermediate for most sampling points. These results indicate that the choice of allometric equation affected the magnitude of estimated AGB while retaining a broadly similar spatial pattern across the sampled trees.

Comparative agreement of allometric models with the reference estimates

The statistical comparison showed clear differences among the three candidate models

Table 2. Sampling point coordinates and AGB estimates

Plot samples coordinat		DBH (cm)	Height (m)	AGB by Dudley et al. (kg)	AGB by Chave et al. (kg)	AGB by Brown et al. (kg)	AGB by Ketterings et al. (kg)
Lat. (⁰)	Long. (⁰)						
-7.899.971	110.035.377	7.56	5.5	18.67	15.36	11.14	18.29
-7.900.391	110.036.827	22.29	8	285.69	182.79	182.03	310.83
-7.900.847	110.038.277	11.46	8.93	53.33	55.54	28.56	54.39
-7.901.528	110.039.727	19.11	8.9	193.75	150.20	120.93	207.67
-7.901.984	110.041.177	28.03	9.5	509.29	338.11	326.03	566.56
-7.901.244	110.042.627	16.88	12	141.67	157.81	86.04	150.03
-7.903.121	110.044.077	9.24	9.8	30.97	39.95	16.19	30.94
-7.903.577	110.045.527	No vegetation					
-7.904.032	110.046.978	12.74	5.40	69.66	41.80	38.64	71.78
-7.904.714	110.048.428	15.29	9.7	110.38	105.70	65.16	115.78
-7.905.169	110.049.878	12.42	8.9	65.33	64.77	35.92	67.15
-7.905.624	110.050.965	15.29	6.2	110.38	68.29	65.16	115.78
-7.906.699	110.054.954	13.69	8.3	83.51	73.17	47.52	86.67
-7.907.899	110.057.129	12.74	9.5	69.66	72.54	38.64	71.78
-7.908.582	110.058.941	13.54	5	81.22	43.67	46.04	84.20
-7.909.037	110.060.392	14.49	9.05	96.38	88.95	55.92	100.57
-7.909.492	110.061.479	10.27	6.85	40.44	34.61	21.12	40.81
-7.909.719	110.062.205	9.39	7.15	32.26	30.30	16.82	32.27
-7.910.174	110.063.292	15.61	10	116.30	113.39	69.10	122.23
-7.910.403	110.006.438	9.02	5.90	29.15	23.22	15.31	29.05

Table 3. Statistical evaluation of each allometric model

Model	Mean	SD	CV (%)	MAE	RMSE	MBE	Pearson
Dudley et al (ref. model)	106.90	115.27	107.83	0	0	0	1
Chave et al	85.01	77.22	90.84	24.91	48.15	-21.89	0.97
Brown et al	64.31	74.67	116.11	42.59	58.18	-42.59	0.99
Ketterings et al	113.84	128.38	112.77	6.99	14.69	6.94	0.99

in their agreement with the Dudley and Fownes reference estimates Table 3. The Chave et al. model produced a mean AGB of 85.01 kg, compared with 106.90 kg for the reference model. Its MAE was 24.91 kg and RMSE was 48.15 kg, while the MBE was −21.89 kg, indicating an overall tendency toward lower estimates than the reference model.

The Brown et al. model produced the lowest mean AGB (64.31 kg) and the largest negative bias (−42.59 kg). Its MAE and RMSE were 42.59 and 58.18 kg, respectively. Despite these differences in magnitude, the Brown et al. estimates showed a strong linear association with the reference estimates (Pearson's r = 0.99).

The Ketterings et al. model produced a mean AGB of 113.84 kg, with an MAE of 6.99 kg and RMSE of 14.69 kg. Its MBE was 6.94 kg, indicating a small overall tendency toward higher estimates than the reference model. Pearson's r was 0.99, indicating a very strong linear association with the reference estimates.

Among the three candidate models, the Ketterings et al. model therefore showed the smallest MAE and RMSE and a small mean bias relative to the Dudley and Fownes reference estimates. However, these results indicate closer agreement with the reference model and should not be interpreted as evidence of greater absolute accuracy because independent biomass observations were not available.

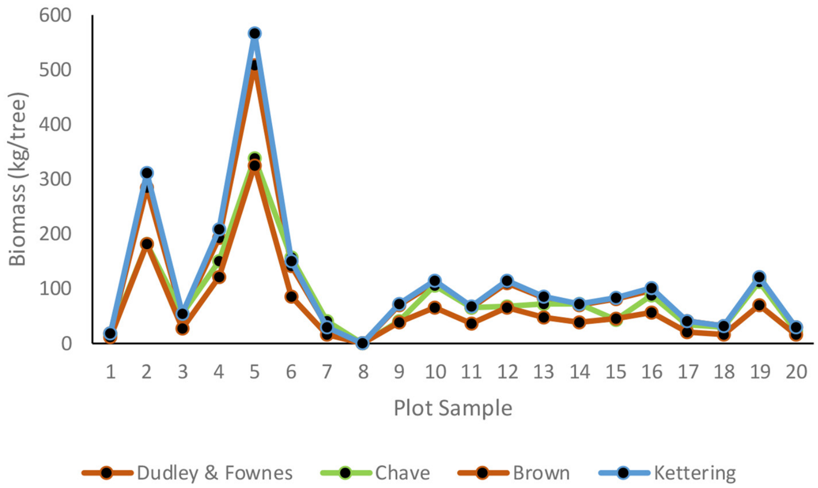

Figure 3. AGB estimates obtained from the four allometric models across the sampling points

Table 4. EWM based statistical weight for the allometric models

Indicator	Allometric model	Proportion (P)	LN(P)	PxLN(P)	Total(PxLN(P))	Entropy value	Diversification	Entropy weight
SD	Chave et al.	0.49	-0.71	-0.35	-0.69	0.63	0.37	0.13
	Brown et al.	0.51	-0.68	-0.34				
	Ketterings et al.	0	0	0				
CV	Chave et al.	0.88	-0.12	-0.11	-0.36	0.33	0.67	0.24
	Brown et al.	0	0	0				
	Ketterings et al.	0.12	-2.15	-0.26				
MAE	Chave et al.	0.33	-1.10	-0.37	-0.63	0.58	0.42	0.15
	Brown et al.	0	0	0				
	Ketterings et al.	0.12	-0.40	-0.27				
RMSE	Chave et al.	0.19	-1.67	-0.31	-0.48	0.44	0.56	0.20
	Brown et al.	0	0	0				
	Ketterings et al.	0.81	-0.21	-0.174				
Bias	Chave et al.	0.37	-1.00	-0.37	-0.65	0.60	0.40	0.14
	Brown et al.	0	0	0				
	Ketterings et al.	0.63	-0.46	-0.29				
Pearson	Chave et al.	0	0	0	-0.69	0.63	0.37	0.13
	Brown et al.	0.50	-0.70	-0.35				
	Ketterings et al.	0.50	-0.69	-0.35				
Total						3.21	2.80	1

Entropy weighting of evaluation indicators

The entropy weighting procedure assigned different weights to the six evaluation indicators (Table 4). CV received the highest weight (0.24), followed by RMSE (0.20), MAE (0.15), MBE (0.14), SD (0.13), and Pearson's correlation coefficient (0.13). These weights reflect the relative variation of the three candidate models across the selected indicators and therefore describe the contribution of each indicator within the EWM framework.

The higher weights assigned to CV and RMSE indicate that these indicators contributed more strongly to differentiation among the candidate models under the applied entropy-weighting procedure. The resulting weights should not be interpreted as evidence that these indicators are intrinsically more important for biomass-model validation. Rather, they reflect the information structure of the three-model dataset used in this study.

Table 5. Ranking of allometric models

Allometric model	Score	Ranking
Ketterings et al.	0.66	1
Chave et al.	0.57	2
Brown et al.	0.26	3

EWM-based ranking of the allometric models

The EWM composite scores ranked the Ketterings et al. model first (0.66), followed by the Chave et al. model (0.57) and the Brown et al. model (0.26) (Table 5). The first-place ranking of the Ketterings et al. model was primarily associated with its relatively small MAE, RMSE, and absolute bias, together with a high Pearson correlation coefficient. The Chave et al. model showed intermediate agreement, whereas the Brown et al. model received the lowest composite score because of its larger absolute differences from the reference estimates.

The results demonstrate that a high Pearson correlation alone does not necessarily correspond to close agreement in magnitude. For example, both Brown et al. and Ketterings et al. produced Pearson's r = 0.99, but their MAE and bias values differed substantially. The EWM ranking therefore reflects the combined behavior of the selected indicators rather than correlation alone. Importantly, the Ketterings et al. model should not be described as the most accurate model on the basis of this analysis. Its result indicates that it had the highest overall agreement with the Dudley and Fownes reference estimates among the three candidate models under the specified evaluation framework.

Confidence intervals and sensitivity analysis

The estimated mean AGB and corresponding 95% confidence intervals differed among the four allometric models (Table 6). The Brown et al. model produced the lowest mean AGB (64.31 kg; 95% CI: 29.37–99.26 kg), whereas the Ketterings et al. model produced the highest mean AGB (113.84 kg; 95% CI: 53.76–173.92 kg). The Dudley and Fownes reference model had a mean of 106.90 kg (95% CI: 52.95–160.85 kg), while the Chave et al. model had a mean of 85.01 kg (95% CI: 48.87–121.15 kg).

The confidence intervals describe uncertainty around the estimated mean AGB for the sampled observations. They should not be interpreted as measures of the absolute accuracy of the allometric equations. The overlap between the intervals also indicates that differences among the estimated mean AGB values should be interpreted cautiously given the sample size.

The sensitivity analysis examined whether the ranking changed when the relative weights assigned to error-based criteria and Pearson correlation were varied across seven predefined scenarios (Table 7). The combined weight of MAE, RMSE, and absolute MBE ranged from 80% to 20%, while the weight assigned to Pearson correlation ranged from 20% to 80%.

Across all seven scenarios, the Ketterings et al. model retained the highest composite score and therefore remained ranked first. The Chave et al. model ranked second in the first two scenarios, whereas the Brown et al. model ranked second under the remaining scenarios. Thus, the first-place ranking of the Ketterings et al. model was stable within the predefined weighting scenarios examined in this study, while the relative position of the Chave et al. and Brown et al. models was sensitive to the weighting assigned to error and correlation criteria.

Overall, the findings indicate that the Ketterings et al. equation produced estimates most closely aligned with the Dudley and Fownes reference estimates among the three candidate equations tested. This result is consistent with the relatively small MAE, RMSE, and absolute bias observed for the Ketterings et al. model.

Table 6. Convidence interval of allometric model

Allometric model	Mean	SD	SE	95%CI
Dudley et al.	106.90	115.27	25.77	52.95-160.85
Chave et al.	85.01	77.22	17.27	48.87-121.15
Brown et al.	64.31	74.67	16.70	29.37-99.26
Ketterings et al.	113.84	128.38	28.71	53.76-173.92

Table 7. Sensitivity analysis of model performance rankings

Scenario	Error weight (MAE, RMSE, BIAS)	Pearson weight	Chave	Brown	Ketterings
1	80%	20%	0.35	0.20	1
2	70%	30%	0.31	0.30	1
3	60%	40%	0.26	0.40	1
4	50%	50%	0.22	0.50	1
5	40%	60%	0.17	0.60	1
6	30%	70%	0.13	0.70	1
7	20%	80%	0.10	0.80	1

However, because the reference equation was not independently validated against measured biomass in the present study, the results cannot establish which equation provides the most accurate estimate of actual AGB.

The Ketterings et al. equation was originally developed using tropical tree data from Indonesia and includes wood density as a predictor (Ketterings et al., 2001). These characteristics provide a relevant basis for its inclusion in the comparison, but geographic origin alone does not demonstrate superior applicability to rehabilitated coastal *C. equisetifolia*. The present results provide empirical evidence of closer agreement with the selected reference equation at the study site, while independent biomass measurements would be required to determine whether this agreement reflects greater absolute accuracy.

The Dudley and Fownes equation was retained as the reference because of its species-specific basis for *C. equisetifolia*. Nevertheless, the present analysis does not establish that the Dudley and Fownes equation provides the true biomass values for the sampled trees. Consequently, the EWM ranking should be interpreted as a comparative framework for evaluating agreement among alternative equations rather than as an independent validation of model accuracy.

Future studies should incorporate destructive biomass measurements or an independent validation dataset covering a larger number of trees and, where possible, a broader range of tree sizes and site conditions. Such data would allow direct assessment of prediction errors and provide an independent basis for determining the absolute accuracy and transferability of the alternative allometric equations.

CONCLUSIONS

The study goal was achieved within the defined analytical scope. The three candidate allometric equations differed substantially in their agreement with the Dudley and Fownes reference estimates for *Casuarina equisetifolia*. The Ketterings et al. equation showed the closest overall agreement, with the lowest MAE and RMSE and a relatively small mean bias, and it remained ranked first across all seven predefined sensitivity scenarios. The hypothesis that the candidate models would differ systematically in their agreement with the reference estimates was therefore supported. The expectation that the Ketterings et al. model would show relatively close agreement with the species-specific reference was also supported.

The principal contribution of this study is the comparative evidence obtained for *C. equisetifolia* in a rehabilitated coastal forest in Kulon Progo, Indonesia, where alternative allometric equations were evaluated under the same field observations. The results show that models with similarly high Pearson correlation coefficients can nevertheless differ substantially in their agreement in magnitude, demonstrating the value of combining correlation with error- and bias-based indicators. The EWM-based framework further provided a transparent way to integrate these complementary indicators and assess the stability of the resulting ranking.

The findings extend previous biomass-estimation studies by providing a structured comparison of species-specific and broader-domain equations for rehabilitated coastal *C. equisetifolia*, a context for which comparative evidence remains limited. Importantly, the study does not establish the absolute accuracy of the Ketterings et al. equation or any other candidate model because independent biomass measurements were unavailable.

The Ketterings et al. equation should therefore be regarded as the model showing the greatest agreement with the selected reference under the conditions and criteria examined, rather than as a validated estimate of actual biomass.

The study also identifies a clear direction for future research. Independent destructive biomass measurements and/or an independent validation dataset should be used to test whether the observed agreement with the Dudley and Fownes reference translates into greater absolute accuracy. Expanding validation across different tree sizes, stand conditions, and coastal rehabilitation sites would further clarify the transferability of the tested equations and could support the development or calibration of a site- or species-specific equation for rehabilitated *C. equisetifolia* forests in Indonesia.

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