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ALLOMETRIC EQUATIONS FOR ESTIMATING MERCHANTABLE WOOD AND ABOVEGROUND BIOMASS OF COMMUNITY FOREST TREE SPECIES IN JEPARA DISTRICT

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Abstract

Understanding the essential contribution of community forests for industrial development or climate change mitigation principally requires the accurate measurement of merchantable wood and aboveground biomass. However, the quantification of those parameters using the destructive method requires high cost and time consuming. To anticipate these constraints, allometric equations development has a potential contribution to facilitate a more efficient estimation of wood and biomass production without disturbing forest regeneration capacity. Therefore, this study aimed to develop allometric equations for quantifying merchantable wood and aboveground biomass of community forest tree species. The destructive sampling was carried out on 45 trees from three species (15 trees each), namely *Swietenia macrophylla* King, *Falcataria moluccana* (Miq.) Barneby et J.W.Grimes, and *Tectona grandis* L.f. Furthermore, three general allometric equations were examined using some predictor variables, i.e. diameter at breast height (*D*), quadrat diameter at breast height combined with tree height ($D^2 \cdot H$), as well as *D* and *H* separately. The results showed the highest average of merchantable wood and aboveground biomass recorded in *S. macrophylla* (0.41 ±0.10 m^3; 0.33 ±0.07 t), followed by *T. grandis* (0.20 ±0.07 m^3; 0.18 ±0.06 t) and *F. moluccana* (0.16 ±0.05 m^3; 0.06 ±0.02 t). Meanwhile, the relative contribution of foliage biomass to total aboveground biomass gradually declined along with the increasing diameter classes. In contrast, a fluctuating trend was observed in the stem and branch. Also, equation $\ln \overline{Y} = \ln a + b \cdot \ln D$ was best in quantifying the wood and biomass. The addition of *H* as a predictor variable in the equations did not show a meaningful influence to increase accuracy estimation in the species. Based on these results, it was concluded that the development of allometric equations was reliable to facilitate more efficient estimation of merchantable wood and aboveground biomass for community forest tree species with over 95 % accuracy.

Key words: accurate quantification, best equation, climate change mitigation.

Introduction

Sustainable community forest management for industrial development and climate change mitigation principally require accurate quantification of timber production or biomass accumulation as basic consideration in determining yield regulation scheme. This is exceptionally necessary to optimize the important contribution of community forest in stabilizing wood supply for industries and minimizing carbon emissions. However, the measurement of wood as well as biomass production using the destructive method generally requires high cost and time consuming, which is almost impossible to implement for the overall community forest trees (Wirabuana et al. 2020). To solve these problems, the development of allometric equations can become an alternative solution to support more efficient quantification of timber production and biomass accumulation. Besides providing good accuracy, the development of these equations is also capable to rapidly facilitate their estimation without disturbing forest regeneration (Daba and Soromessa 2019). Moreover, they are reliable in quantifying the individual tree characteristics from different observation periods. This is based on the relationship between tree attributes that are highly responsive to the growth periods, such as height and diameter (Kebede and Soromessa 2018). Previous studies also confirmed that the utilization of the equations indicated an excellent accuracy for predicting wood or biomass production in different types of forest, both in monoculture and mixed (Chen et al. 2017, Zhao et al. 2019, Magalhães et al. 2021).

The construction of allometric equations in the community forest is not easy because there are various species with high variation in age distribution and irregular planting designs (Baral et al. 2018). Also, the activity of stand management in this site is not conducted intensively, hence, the variation of stand growth is substantially higher than plantation forest (Wirabuana et al. 2021b). Consequently, it is difficult to obtain the number of samples with a balance distribution for every species. Therefore, the development of allometric equations for specific species is the best solution to minimize the bias estimation of wood and biomass production due to the heterogeneous stand condition (Paul et al. 2013). Furthermore, it was reported that the development of these models provided better accuracy to quantify the individual tree characteristics compared to the use of general allometric equations for mixed species (Paul et al. 2013, Goussanou et al. 2016, Wirabuana et al. 2020). Several works stated that its reliability was also affected by the gradient of site quality (Ngomanda et al. 2014, Nugroho 2014, Zhao et al. 2019). Therefore, the best model for a species can differ from one location to the other.

This study was designed to develop allometric equations for estimating merchantable wood and aboveground biomass of community forest tree species in Jepara. This is a district located in the coastal area of Northern Java with a lot of wood industries that play important roles in the economic sector, like carving, furniture, plywood, and veneer. This means the existence of community forests in the town has a fundamental position for industrial development. Furthermore, the total area of community forest in Jepara is relatively higher than the state by approximately 17,495.53 ha which is equivalent to 50.23 % of the total forest area in this district (BPS 2017). This shows the presence of community forests in the town has a higher contribution to climate change mitigation than the state. Until now, there are no allometric models for estimating merchantable wood and aboveground biomass of community forest tree species in Jepara even though it is highly required to support the effort of sustainable management in the District.

Material and Methods

Study area

The study site was in the community forest in Jepara District, Central Java, Indonesia. The data were obtained from four villages that have a dense cover of community forest, namely Jambu, Sinanggul, Srobyong, and Karanggondang (Fig. 1), with an altitude range of 70–100 m a.s.l. Furthermore, the land configuration was relatively flat with a slope level of 5–10 %, air humidity varied between 72 and 85 %. The daily mean temperature was 29 °C with a minimum of 22 °C and a maximum of 34 °C. This location has an annual rainfall of approximately 2464 mm·year^{-1}. Also, the most rainfall occurs in February with 34 % of the total in a year. Meanwhile, the dry season occurs for almost five months (May to September). The soil type is dominated by alfisol with an acidity level of 5.5–6.0. In general, in this site predominantly are three species, namely *Swietenia macrophylla* King, *Falcataria moluccana* (Miq.) Barneby et J.W.Grimes,

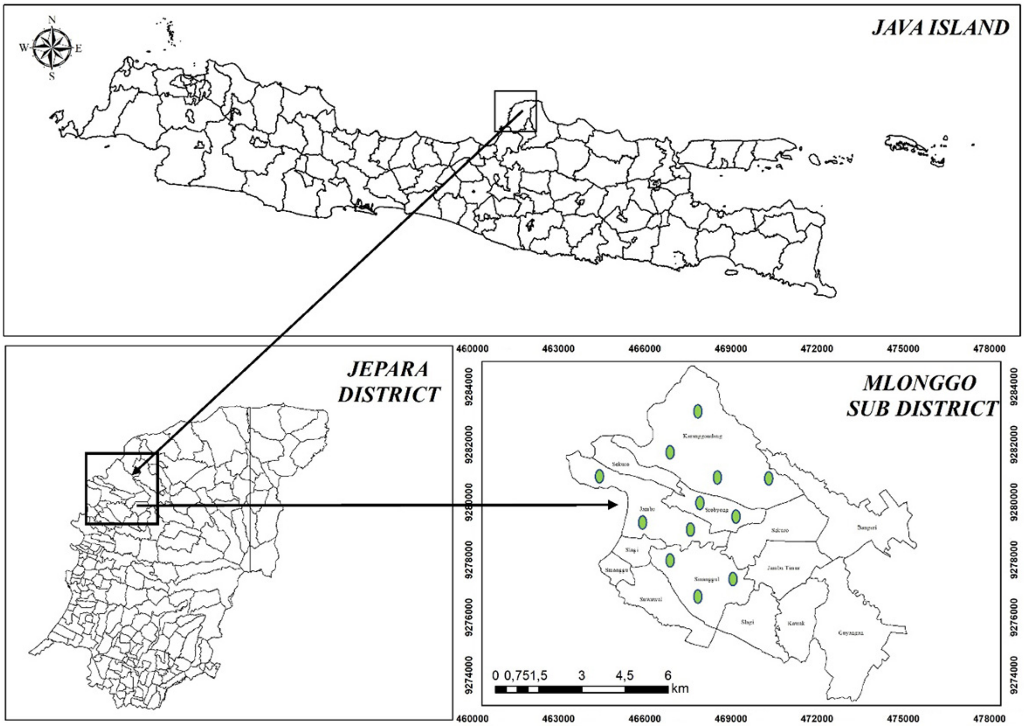

Fig. 1. The study site of community forest around Jepara District.

Note: Green circle indicates a location for destructive sampling to quantify the merchantable wood and aboveground biomass from sample trees.

and *Tectona grandis* L.f. Most stand conditions consisted of mixed species with irregular distribution and high variation in age (BPS 2017).

Data collection

Data collection was conducted step by step in a chronological manner and consisted of three systematic sequence stages, namely tree selection, destructive sampling, and biomass determination. Tree selection stage aimed to obtain several sample trees that represent the growth variation of community forests from four sites. This step was required to derive ideal samples for every species with normal growth performance, not infected by pest or disease, and without defect. Meanwhile, the objective of destructive sampling was to calculate the wood and measure the fresh weight of every tree component before drying the sub-samples in the laboratory. Subsequently, biomass determination was directed to quantify the content in every tree component and the total aboveground for the individual sample. The description of every stage is presented below.

Tree selection

The samples were selected by considering the diameter distribution of every species. This approach was commonly used in several studies to determine the representative sample trees for developing allometric equations, both in monoculture and mixed forest (Altanzagas et al. 2019, Istrefi et al. 2019, Wirabuana et al. 2020, Karyati et al. 2021, Sadono et al. 2021). To facilitate this stage, forest inventory was carried out using the quadrat method with a sampling plot of size 25 m × 25 m (Setiahadi 2017, Wirabuana et al. 2021b). Sixteen of these plots were distributed randomly at each community forest site, and every village had a total sampling area of approximately 1 ha. The total plots used for the field survey were 64 units. Furthermore, there were three important parameters measured for every tree in each measuring plot, namely type of species, DBH (presented below for brevity as *D*), and height (*H*). *D* was measured using a phi band at 1.3 m from aboveground, while *H* was estimated to top crown using a haglof vertex. Moreover, an identification number was also given to every measured tree using paint to facilitate the identification.

Data were compiled from four sites after completing the field survey. Subsequently, the *D* was classified into four groups as follows, <10 cm, 11–20 cm, 21–30 cm, and >30 cm (Altanzagas et al. 2019, Wirabuana et al. 2020). This step aimed to describe the variation of tree dimensions from small to big. Consequently, samples were selected from every diameter group, with a minimum number of 3 for each species (Table 1). In addition, the distribution of samples in every site was also considered for the selection (Table 2). The total samples from every species were 15, while there were 45 for destructive sampling for the three species. The number of samples used was relatively lower than other studies in the allometric model development of plantation forests. However, several studies explained that a fit model for the equation could be developed using a low number of tree samples (Ketterings et al. 2001, Stas et al. 2017).

Destructive sampling

The process of destructive sampling was conducted systematically from small to

Table 1. Distribution of sample trees by diameter class.

Species	*D*			
	<10 cm	11–20 cm	21–30 cm	>30 cm
S. macrophylla	4	4	4	3
F. moluccana	5	4	3	3
T. grandis	6	3	3	3
Total	15	11	10	9

Table 2. Total sample trees.

Village	Number of tree samples for every species		
	S. macrophylla	*F. moluccana*	*T. grandis*
Sinanggul	4	3	4
Jambu	3	5	3
Srobyong	4	2	6
Karanggondang	4	5	2
Total	15	15	15

big selected trees. The trees were felled using a chain saw with stump height at 0.1 m from aboveground. Subsequently, the components were separated into stem, branch, and foliage, while the stem was divided into several sortiments to facilitate the measurement of merchantable wood. The diameter of every sortiment was measured at two positions (large and small end) using a caliper, while the length measurement was conducted through a measuring tape. Subsequently, the wood volume of the sortiment was calculated using Smallian formula (equation 1) and was classified as merchantable wood when it has a minimum diameter and length of 10 cm and 1.5 m respectively. This criterion was determined based on the minimum requirements of suitable wood for industrial needs in Jepara. The total merchantable wood for every sample was computed based on the accumulation volume that fulfilled the industrial requirements (equation 2).

$$V = \frac{\pi}{8} \cdot \left(D_L^2 + d_S^2 \right) \cdot l \,, \tag{1}$$

$$MV = V_1 + V_2 + \ldots + V_n, \tag{2}$$

where: V was the wood volume of sortiment (m^3), d_L and d_S indicated the diameter size at the large and small ends (cm) respectively, l represented the length (m), while MV was the total merchantable wood of every sample tree ($m^3 \cdot tree^{-1}$). Besides measuring merchantable wood, the residual wood from the samples was also calculated. This type is commonly used as firewood by local communities.

Moreover, the fresh weight of the components was measured using a hanging balance in the field. In contrast with quantification of merchantable wood, the measurement of stem biomass was conducted for all sortiments. In this case, the existence of wood sortiment would facilitate an easier measurement of biomass since it was difficult to measure stem weight simultaneously. The fresh weight data from the components were recorded. Moreover, the 500 g sub-sample from each part was taken to laboratory for drying (Sadono et al. 2021, Wirabuana et al. 2021a).

Biomass determination

Biomass is defined as a constant dry-weight of each tree component. To determine biomass, the sub-sample from the field was dried using an oven at 70 °C for 48 h before weighting (Wirabuana et al. 2019). Subsequently, each component was quantified by multiplying the ratio of dry-fresh weight from subsample with the total fresh weight of tree component from field survey (equation 3). Meanwhile, the total aboveground biomass of an individual tree sample was calculated by summing the biomass of every component (equation 4). In addition, the biomass expansion factor (*BEF*) was determined as the ratio of total aboveground and stem biomass (equation 5).

$$W_c = \left(\frac{DW_S}{FW_S}\right) \cdot FW_C\ , \tag{3}$$

$$W_t = W_s + W_b + W_f, \tag{4}$$

$$BEF = \frac{W_t}{W_S}\ , \tag{5}$$

where: *Wc* was the biomass of tree component (t), *DWs* and *FWs* indicated dry and fresh weight of sub-sample components (g) respectively, *FWc* represented fresh-weight of tree component (kg), *Wt* was total aboveground biomass of individual tree sample (t), while *Ws*, *Wb*,*Wf* were biomass in stem, branch, and foliage (t) respectively.

Data analysis

Statistical analysis was conducted using a significant level of 5 %. The descriptive test was applied to identify the data attributes, including minimum, maximum, mean, standard deviation, and standard error. The normality of data from the total observed variable was evaluated by Shapiro-Wilk test, while homogeneity of variance among species and diameter classes was examined using Bartlett. Comparison mean of the relative contribution from tree components to total aboveground biomass among diameter classes and species was tested using ANOVA and HSD Tukey. A similar method was also applied to compare the relative contribution of merchantable and residual woods with total tree volume. Furthermore, the analysis of correlation was applied to evaluate the relationship among observed variables. Meanwhile, the allometric models for estimating merchantable wood and aboveground biomass from every species were developed using regression analysis.

Three general allometric equations (6–8) were evaluated, and several independent variables were used for their development, such as D, $D^2 \cdot H$, as well as D and H separately (Dong et al. 2015, Xue et al. 2016, Altanzagas et al. 2019, Sadono et al. 2021).

$$\overline{Y} = a \cdot D^b, \tag{6}$$

$$\overline{Y} = a(D^2 \cdot H)^b, \tag{7}$$

$$\overline{Y} = a \cdot D^b \cdot H^c, \tag{8}$$

where: $\overline{Y}$ was the estimated value of merchantable wood (m^3) or total aboveground biomass (t) and *a, b, c* were the fitted coefficient.

The use of non-linear models in developing allometric equations commonly resulted in heteroscedasticity (Zeng and Tang 2012). Therefore, to eliminate its influence, the use of data transformation in natural log-form was generally applied in previous studies to convert the non-linear model into a linear equation when determining the fitted parameter for every equation (He et al. 2018, Altanzagas et al. 2019, Wirabuana et al. 2020, Sadono et al. 2021). Therefore, the equations 6 to 7 were changed into the following models (equations 9–11):

$$\ln\overline{Y} = \ln a + b \cdot \ln D, \tag{9}$$

$$\ln\overline{Y} = \ln a + b \cdot \ln(D^2 \cdot H), \tag{10}$$

$$\ln\overline{Y} = \ln a + b \cdot \ln D + c \cdot \ln H, \tag{11}$$

where: $\ln\overline{Y}$ indicated the predicted value of merchantable wood or total aboveground biomass in the logarithmic unit, while *a, b, c* were the fitted parameters.

Nevertheless, some works explained that the use of anti-log transformation of the predicted logarithmic values into arithmetic units resulted in a systematic bias which could be corrected by the correction factor as presented in equation (12) (Xue et al. 2016, He et al. 2018, Altanzagas et al. 2019).

$$CF = \exp\left(\frac{RMSE^2}{2}\right), \tag{12}$$

where: *CF* was the correction factor, *RMSE* indicated the root mean square error from the logarithmic regression, and *n* was the sample size.

The best allometric equations were determined using seven indicators, namely the significant result of ANOVA test for the model, the significant outcome of fitted parameters (*a, b, c*), coefficient of determination (R^2), residual standard error (RSE), akaike information criterion (*AIC*), mean absolute bias (*MAB*), and root mean square error (*RMSE*) (González-García et al. 2013, Ekoungoulou et al. 2015). Meanwhile, the fitted parameters, ANOVA test, R^2, *RSE,* and *AIC* were used to evaluate the model fitting while MAB and RMSE were used to examine the validation (Sadono et al. 2021). Since the sample size was relatively small (15 trees for every species), the validation test was processed using the leave-one-out cross-validation (LOOCV). This method is commonly applied in developing equations with a small sample size (Castillo-Santiago et al. 2010, Altanzagas et al. 2019, Tetemke et al. 2019). Detailed formula for calculating these indicators are expressed in equations 13–17:

$$R^2 = \frac{1 - \sum\left(\ln Y - \ln y\right)^2}{\sum\left(\ln Y - \ln \overline{Y}\right)^2}, \tag{13}$$

$$RSE = \left[\frac{1}{(n-2)\cdot\sum\left(\ln Y - \ln \overline{Y}\right)^2}\right]^{0.5}, \tag{14}$$

$$AIC = n \cdot \log\left(\frac{RSS}{n}\right) + 2k + \frac{2k(k+1)}{n-k-1}, \tag{15}$$

$$MAB = \frac{\sum\left(\left|\ln Y + \ln \overline{Y}\right|\right)}{n}, \tag{16}$$

$$RMSE = \left[\frac{\sum\left(\ln Y - \ln \overline{Y}\right)^2}{n-p-1}\right]^{0.5}, \tag{17}$$

where: $\ln Y$ was the actual log-transformed merchantable wood, $\ln \overline{Y}$ represented the predicted total aboveground biomass from the fitted model, *n* indicated the sample size. Furthermore, $\ln Y$ was the average of actual log-transformed merchantable wood or total aboveground biomass, *p* signified the number of terms in the model, *RSS* was the residual sum of squares from the fitted model, while *k* exhibited the number of independent variables. The best allometric model should demonstrate the significant results of ANOVA and fitted parameter test, the highest R^2, as well as the lowest *RSE, AIC, MAB,* and *RMSE*. They would also be compared with other equations from the previous studies as external validation, such as Chave et al. (2014), Ardelina et al. (2015), Khan et al. (2018), and Zahabu, et al. (2018).

To determine the most efficient model for estimating merchantable wood and total aboveground biomass of each species, Extra Sums of Square (*ESS*) method was conducted to measure the marginal reduction in Error Sums of Squares (*SSE*) when an additional set of predictors was added to the model (Hector et al. 2016). In this context, this method aimed to assess whether the addition of *H* as the predictor variable provided a meaningful contribution to improve the estimation accuracy. However, in the case of insignificant results, the use of a single predictor in the allometric equations was enough to obtain good accuracy.

Results and Discussion

Wood production from three species

The results showed the total wood production at the individual level of community forest tree species was relatively varied. Its highest average was discovered in *S. macrophylla* (0.58 ±0.14 m^3), followed by *F. moluccana* (0.25 ±0.08 m^3), and *T. grandis* (0.29 ±0.10 m^3) (Table 3). A similar pattern was also observed in the trend of merchantable and residual wood. Interestingly, this study discovered that the relative contribution of merchantable and residual wood to the total wood production differed significantly among the species (Table 4). Despite the biggest mean of total wood production, the percentage of merchantable wood in *S. macrophylla* was considerably lower than *F. moluccana* and *T. grandis* by approximately 66 %. Contrastingly, the proportion of merchantable wood in *F. moluccana* was relatively higher than other species with approximately 71 %. Moreover, this species also indicated the smallest percentage of residual wood than others. This study documented that the relative contribution of merchantable and residual wood across the diameter classes was not significantly different even though there was a fluctuating trend with the increasing diameter classes (Fig. 2). Overall, the relative contribution of merchantable to total wood production was consistently higher than the residual in every diameter class.

The variation of wood production of the species could be affected by several

Table 3. Summary statistics of tree dimensions, wood production, and biomass.

Species	Value	*D*, cm	*H*, m	*TV*, m^3	*MV*, m^3	*RV*, m^3	*SB*, t	*BB*, t	*FB*, t	*AGB*, t
S. macrophylla	Mean	25.8	9.9	0.58	0.41	0.17	0.21	0.08	0.04	0.33
	SD	12.6	4.2	0.56	0.38	0.18	0.18	0.07	0.03	0.29
	SE	3.3	1.1	0.14	0.10	0.05	0.05	0.02	0.01	0.07
	min	8.9	4.8	0.02	0.01	0.01	0.01	0.01	0.00	0.02
	max	41.4	15.6	1.47	1.00	0.54	0.49	0.19	0.09	0.77
F. moluccana	Mean	19.0	7.5	0.25	0.16	0.08	0.04	0.01	0.01	0.06
	SD	11.2	2.0	0.31	0.21	0.11	0.05	0.02	0.01	0.07
	SE	2.9	0.5	0.08	0.05	0.03	0.01	0.00	0.00	0.02
	min	5.4	4.6	0.01	0.01	0.00	0.00	0.00	0.00	0.00
	max	40.1	11.1	0.98	0.62	0.36	0.15	0.05	0.02	0.22
T. grandis	Mean	18.8	8.2	0.29	0.20	0.09	0.10	0.07	0.01	0.18
	SD	11.9	2.5	0.41	0.28	0.12	0.14	0.10	0.01	0.24
	SE	3.1	0.7	0.10	0.07	0.03	0.04	0.02	0.00	0.06
	min	8.9	5.6	0.02	0.02	0.01	0.01	0.01	0.00	0.02
	max	40.4	13.0	1.17	0.83	0.34	0.39	0.27	0.02	0.69

Note: *TV* – total tree volume, *MV* – merchantable wood, *RV* – residual wood, *SB* – stem biomass, *BB* – branch biomass, *FB* – foliage biomass, *AGB* – total aboveground biomass.

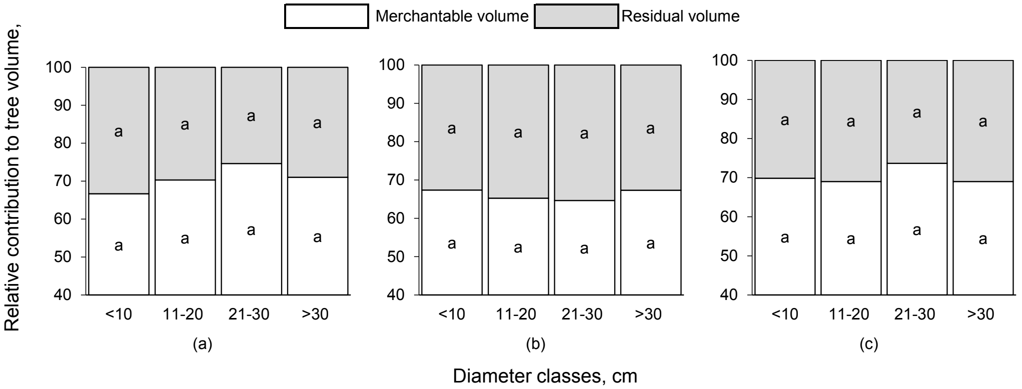

Fig. 2. Relative contribution of merchantable and residual wood to total tree volume.

Note: (a) *S. macrophylla*; (b) *F. moluccana*; (c) *T. grandis*. A similar letter indicated that there was no significant difference in the relative contribution of merchantable and residual wood among diameter classes.

factors, such as genetics, site suitability, age, and silviculture prescription (Xu et al. 2012, Thompson 2013, Resende et al. 2018, Bouriaud et al. 2019). According to the results, community forest species in Jepara consisted of two types, namely slow-growing (*S. macrophylla* and *T. grandis*) and fast-growing species (*F. moluccana*). Genetically, the growth rate of fast-growing species was relatively higher than the slow-growing (Karlinasari et al. 2018), therefore, it was generally harvested in the short rotation of approximately 5–8 years (Siregar et al. 2007). A similar case was also recorded in the community forest at Jepara District, where the majority of the farmers harvested *F. moluccana* at 5–6 years. In contrast, the rotation of *S. macrophylla* and *T. grandis* ranged from 15 to 20 years, which directly confirmed why the average total wood production of *F. moluccana* at the individual tree level was lower than others.

In addition, this study noted that the site suitability was also principally different. The range of altitude in Jepara (70–100 m a.s.l.) was highly suitable for supporting the growth of *T. grandis* and *S. macrophylla* since both were naturally distributed in the lowland area (Krishnamoorthy et al. 2016, Navarro-Martínez et al. 2018). However, the site suitability in this area was relatively lower for facilitating the growth of *F. moluccana* since it was naturally from the upland area (Munir 2018). Lower site suitability provides more limiting factors which influence plant growth (Abd-Elmabod et al. 2019). Consequently, their growth rate would be substantially lower compared to the higher site suitability. Therefore, the implementation of intensive silviculture prescription is exceptionally required to improve the growth performance of commercial species. Unfortunately, there was no intensive maintenance in the forest; hence, the growth performance of the plant was dominantly affected by its adaptability to the site conditions. This also confirmed why the mean total wood production of *F. moluccana* was the lowest.

Biomass distribution and accumulation

This study recorded that the highest mean total aboveground biomass was observed in *S. macrophylla* (0.33 ±0.07 t), followed by *T. grandis* (0.18 ±0.08 t), and *F. moluc-*

cana (0.06 ±0.02 t) (Table 3). This pattern was similar to the trend of wood production among the species. It signified that higher wood production would improve the accumulation of tree biomass. This could be feasible since more than 61 % of aboveground biomass for all species was distributed in the stem as the primary tree component for generating wood products (Table 4). This is consistent with some previous studies which stated that there was a significant relationship between wood production and total aboveground biomass at the individual tree level (Viswanath 2011, Romero-Sanchez and Ponce-Hernandez 2017).

Table 4. Relative contribution of tree components to total aboveground biomass.

Species	*MV/TV*	*RV/TV*	*SB/AGB*	*BB/AGB*	*FB/AGB*
S. macrophylla	0.66±0.04a	0.34±0.04b	0.61±0.07a	0.25±0.08b	0.14±0.04a
F. moluccana	0.71±0.06b	0.29±0.06a	0.61±0.05a	0.26±0.03b	0.13±0.02a
T. grandis	0.70±0.05ab	0.30±0.05ab	0.61±0.08a	0.34±0.08a	0.05±0.02b

Note: *TV* – total tree volume, *MV* – merchantable wood, *RV* – residual wood, *SB* – stem biomass, *BB* – branch biomass, *FB* – foliage biomass.

According to the results, the accumulation of biomass in-branch and foliage were significantly lower than stem in the species with approximately 25–34 % and 5–14 % respectively (Table 4). This confirmed that all trees allocated more biomass in the stem than the crown, to accelerate the translocation process for water, nutrients, and carbohydrates (Poorter et al. 2012, Kocurek et al. 2020, Wirabuana et al. 2020). The more efficient this process would facilitate better growth performance for every tree (Hasanuzzaman et al. 2018, Tränkner et al. 2018, Sadono et al. 2021). The results were also consistent with other previous studies which stated that the highest biomass accumulation for woody species was discovered in stem (Krejza et al. 2017, Altanzagas et al. 2019, Han and Park 2020, Magalhães et al. 2021). Interestingly, this study documented that *BEF* in the species was almost equal even though the average *BEF* of *S. macrophylla* was slightly lower (1.64) than others (1.67) (Table 5). However, the results for the three species were higher compared to Krisnawati et al. (2012) with a distance of 0.20–0.31. Different site quality, stand dynamics, and age have the potential to become factors affecting the variety of *BEF* from every species (Teobaldelli et al. 2009).

Table 5. Biomass expansion factor.

Species	*BEF*			
	Mean	SD	min	max
S. macrophylla	1.64	0.13	1.43	1.9
F. moluccana	1.67	0.20	1.45	2.04
T. grandis	1.67	0.27	1.32	2.51

Note: SD – standard deviation.

It was also reported that the relative contribution of tree components to total aboveground biomass highly varied across the diameter classes. The relative contribution of stem, branch and foliage to total aboveground biomass in *S. macrophylla* was significantly different along with the increasing of diameter classes (Fig. 3). Meanwhile, different results were noted in *F. moluccana* and *T. grandis,* where a significant difference was only indicated in branch or foliage. This showed every species had a different pattern of biomass allocation in its component. Nevertheless, the percentage of foliage bio-

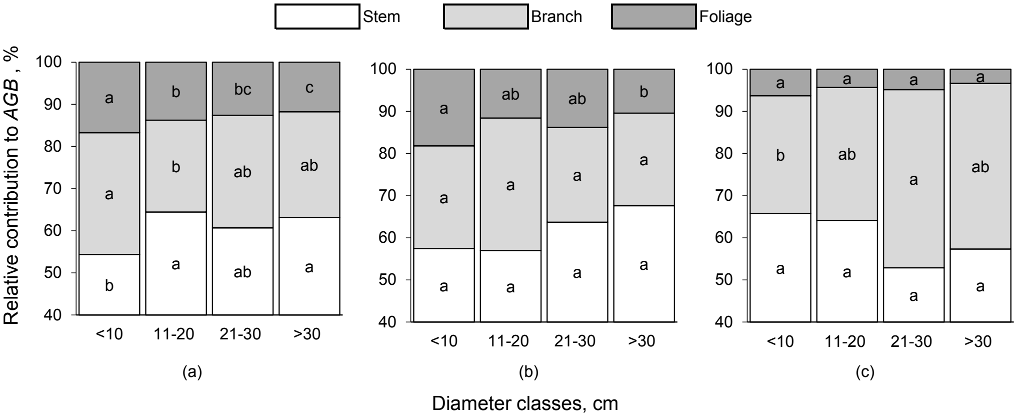

Fig. 3. Biomass distribution in every tree component across the diameter classes.
Note: (a) *S. macrophylla*; (b) *F. moluccana*; (c) *T. grandis*. A similar letter showed that there was no significant difference in biomass allocation among diameter classes.

mass gradually declined across with the increase in diameter classes. This trend naturally occurred since trees would generally allocate their biomass in the trunk along with the increment of diameter to optimize the source and sink distribution.

Allometric models for estimating wood and biomass production

In summary, there was a nonlinear relationship between diameter and height with merchantable wood as well as the total aboveground biomass in the species (Fig. 4). It was clarified that the greater diameter and height resulted in higher wood and biomass production. This was supported by the output of correlation analysis which indicated a significant relationship between the variables with a value greater than 0.9 (Table 6). These results also implied that both can be used as predictor variables for developing allometric equations. Several studies also explained that they were fundamental parameters in the forest inventory and had a high influence on other tree attributes, such as wood volume, biomass production, and carbon storage (Zeng and Tang 2012, Vega-Nieva et al. 2015, Abrantes et al. 2019, Zhao et al. 2019).

This study reported that every allometric equation demonstrated a good fit (Table 7). More than 90 % of the variation in merchantable wood and total aboveground biomass could be explained using this equation. The value was excellent because the stand characteristics of community forest principally had great variation in species composition and growth distribution (Wirabuana et al. 2021b, Setiahadi 2017). However, the outcome of *ESS* test confirmed that the addition of *H* as a predictor variable in the equations did not provide a meaningful contribution to improve the accurate estimation of the wood and biomass (Table 8). These results also demonstrated that the use of a single predictor for allometric equations in the community forest was better and more efficient than two. These results were different from several previous studies which explained that the addition of *H* as an independent variable provided a significant contribution to increase the accurate estimation of allometric models (Bi et al. 2004, Chave et al.

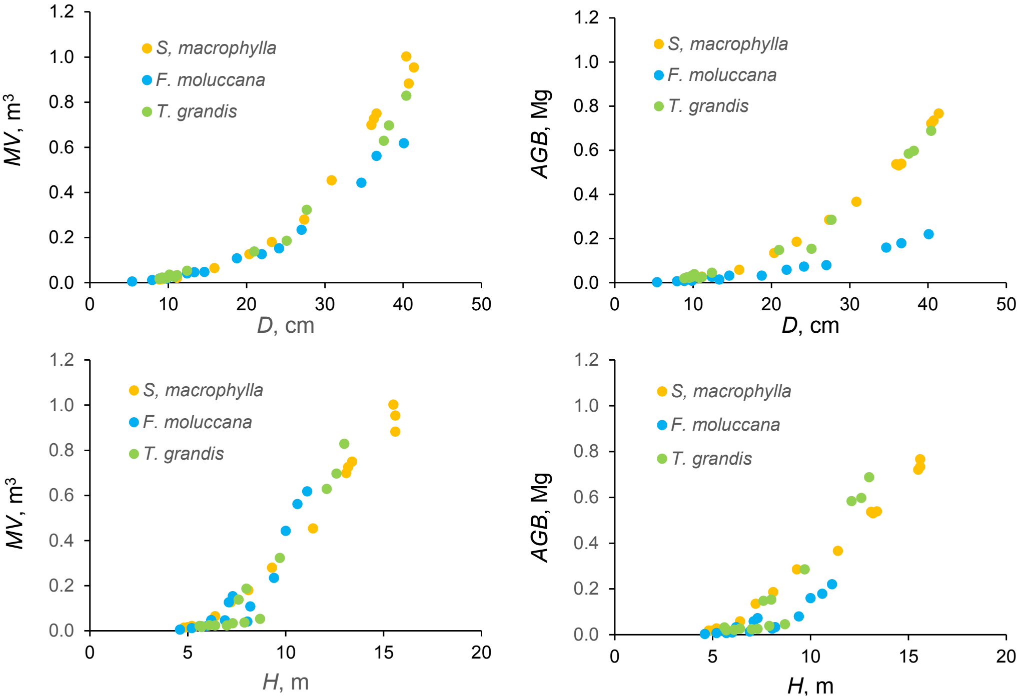

Fig. 4. Scatter plot for demonstrating the relationship between *D* and *H* with *MV* and total *AGB*.

Table 6. Coefficient of correlation between independent and dependent variables for developing allometric equations.

Predictor variable	*TV*	*MV*	*RV*	*SB*	*BB*	*FB*	*AGB*
S. macrophylla							
D	0.951**	0.963**	0.883**	0.971**	0.973**	0.979**	0.974**
H	0.984**	0.990**	0.929**	0.994**	0.992**	0.996**	0.995**
$D^2 \cdot H$	0.999**	0.993**	0.970**	0.996**	0.990**	0.991**	0.995**
F. moluccana							
D	0.956**	0.955**	0.943**	0.962**	0.950**	0.979**	0.965**
H	0.911**	0.908**	0.901**	0.898**	0.895**	0.915**	0.903**
$D^2 \cdot H$	0.999**	0.997**	0.989**	0.995**	0.973**	0.984**	0.994**
T. grandis							
D	0.964**	0.966**	0.951**	0.960**	0.977**	0.986**	0.970**
H	0.948**	0.950**	0.935**	0.950**	0.943**	0.941**	0.949**
$D^2 \cdot H$	0.999**	0.998**	0.994**	0.994**	0.997**	0.987**	0.997**

Note: ** indicated a significant correlation. *TV* – total tree volume, *MV* – merchantable wood, *RV* – residual wood, *SB* – stem biomass, *BB* – branch biomass, *FB* – foliage biomass, *AGB* – total aboveground biomass.

Table 7. Summary evaluation statistics of every allometric equation for estimating merchantable wood and total aboveground biomass.

Variable	Equations**	ln*a**	*b**	*c**	R^2	*RSE*	*AIC*	*MAB*	*RMSE*	*CF*
S. macrophylla										
MV	$\ln\overline{Y} = \ln a + b \cdot \ln D$	-10.439	2.800	-	0.998	0.081	-28.924	0.082	0.088	1.004
	$\ln\overline{Y} = \ln a + b \cdot \ln D^2 \cdot H$	-10.301	1.017	-	0.997	0.079	-29.431	0.071	0.086	1.004
	$\ln\overline{Y} = \ln a + b \cdot \ln D + c \cdot \ln H$	-10.376	2.410	0.520	0.998	0.066	-34.077	0.059	0.073	1.003
AGB	$\ln\overline{Y} = \ln a + b \cdot \ln D$	-9.533	2.485	-	0.998	0.062	-36.972	0.043	0.065	1.002
	$\ln\overline{Y} = \ln a + b \cdot \ln D^2 \cdot H$	-9.401	0.902	-	0.995	0.099	-22.842	0.084	0.103	1.005
	$\ln\overline{Y} = \ln a + b \cdot \ln D + c \cdot \ln H$	-0.952	2.418	0.089	0.998	0.639	-35.261	0.046	0.078	1.003
F. moluccana										
MV	$\ln\overline{Y} = \ln a + b \cdot \ln D$	-9.342	2.395	-	0.995	0.106	-20.644	0.098	0.114	1.007
	$\ln\overline{Y} = \ln a + b \cdot \ln D^2 \cdot H$	-10.166	0.992	-	0.998	0.065	-35.150	0.060	0.073	1.003
	$\ln\overline{Y} = \ln a + b \cdot \ln D + c \cdot \ln H$	-10.078	2.031	0.883	0.998	0.067	-33.539	0.065	0.079	1.003
AGB	$\ln\overline{Y} = \ln a + b \cdot \ln D$	-9.559	2.170	-	0.979	0.200	-1.822	0.142	0.202	1.021
	$\ln\overline{Y} = \ln a + b \cdot \ln D^2 \cdot H$	-10.291	0.897	-	0.977	0.208	-0.604	0.164	0.211	1.023
	$\ln\overline{Y} = \ln a + b \cdot \ln D + c \cdot \ln H$	-9.763	2.069	0.245	0.979	0.207	-0.030	0.174	0.262	1.035
T. grandis										
MV	$\ln\overline{Y} = \ln a + b \cdot \ln D$	-9.341	2.450	-	0.988	0.161	-8.354	0.137	0.168	1.014
	$\ln\overline{Y} = \ln a + b \cdot \ln D^2 \cdot H$	-10.201	1.005	-	0.998	0.067	-34.639	0.050	0.070	1.002
	$\ln\overline{Y} = \ln a + b \cdot \ln D + c \cdot \ln H$	-10.299	1.954	1.127	0.998	0.067	-33.525	0.057	0.075	1.003
AGB	$\ln\overline{Y} = \ln a + b \cdot \ln D$	-8.922	2.291	-	0.979	0.203	-1.285	0.160	0.212	1.023
	$\ln\overline{Y} = \ln a + b \cdot \ln D^2 \cdot H$	-9.706	0.937	-	0.982	0.185	-4.204	0.141	0.191	1.018
	$\ln\overline{Y} = \ln a + b \cdot \ln D + c \cdot \ln H$	-9.515	1.983	0.698	0.983	0.189	-2.639	0.154	0.208	1.022

Note: ** indicated significant results of ANOVA test for all models, * showed a significant result of t-test, R^2 was the coefficient of determination, *CF* – correction factor.

Table 8. Summary evaluation statistics in *ESS* among allometric equations.

Variable	Predictor	Res. Df	RSS	Df	Sum of Sq	F	Pr (>F)
S. macrophylla							
MV	D	13	0.085				
	$D^2 \cdot H$	13	0.082	0	0.022		
	D & H	12	0.083	1	0.029	0.689	0.203^{ns}
AGB	D	13	0.050				
	$D^2 \cdot H$	13	0.048	0	0.078		
	D & H	12	0.049	1	0.079	0.380	0.101^{ns}
F. moluccana							
MV	D	13	0.148				
	$D^2 \cdot H$	13	0.056	0	0.092		
	D & H	12	0.055	1	0.001	0.315	0.584^{ns}
AGB	D	13	0.521				
	$D^2 \cdot H$	13	0.565	0	-0.044		
	D & H	12	0.514	1	0.051	1.196	0.295^{ns}
T. grandis							
MV	D	13	0.337				
	$D^2 \cdot H$	13	0.058	0	0.278		
	D & H	12	0.055	1	0.003	0.730	0.409^{ns}
AGB	D	13	0.540				
	$D^2 \cdot H$	13	0.444	0	0.095		
	D & H	12	0.432	1	0.012	0.353	0.563^{ns}

Note: ns indicated that the addition of H as a predictor variable did not provide a significant contribution.

2005, Meng et al. 2021). Nevertheless, another study conducted at Madiun community forest reported that the development of allometric models with a single predictor, such as D was more relevant to apply since it was difficult to obtain the accurate measurement of tree height in this type of forest due to the great variation of canopy and irregular plant distribution (Wirabuana et al. 2020).

Regarding the results, the best allometric equations for quantifying the merchantable wood and total aboveground community forest tree species in Jepara District were $\ln Y = \ln a + b \cdot \ln D$. Besides the simplicity, this model also provided an excellent accuracy with approximately 97.9–99.8 %. The best equation was more reliable to facilitate a rapid estimation of wood and biomass production since it only required D as a single predictor. Several studies also proved that the use of D as an independent variable possessed an important role to develop an approximate method for quantifying individual tree characteristics (Lumbres et al. 2015, Forrester et al. 2017, Romero et al. 2020).

Compared to other existed allometric equations, the best model had a good validation because it described the similar pattern (Fig. 5). However, it indicated the lower prediction of merchantable wood in *F. moluccana* and *T. grandis*. In contrast, it generated higher estimation in *S. macrophylla*. Fascinatingly, the prediction of aboveground biomass in *S. macrophylla* and *T. grandis* using the best model and

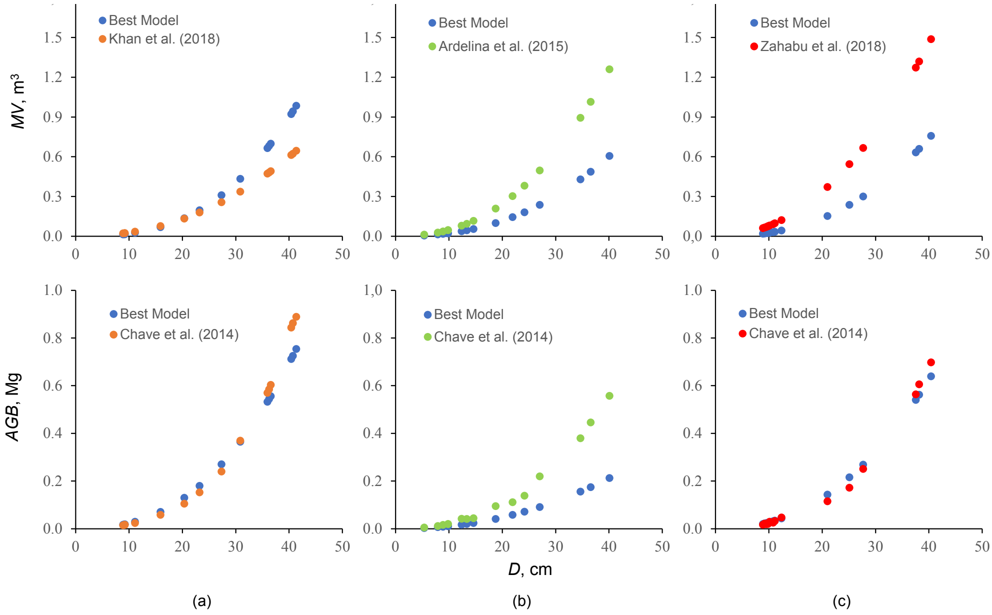

Fig. 5. Comparison of the best model with other equations for estimating merchantable wood and total aboveground biomass from three community forest species.
Note: (a) *S. macrophylla*; (b) *F. moluccana*; (c) *T. grandis.*

Chave et al. (2014) was almost equal. Unfortunately, similar results were not found in the estimation for *F. moluccana,* where the best model showed lower prediction. The different estimation results could be influenced by certain factors, such as sample size, type of forest, and site quality.

In practical, best allometric equation could be used to facilitate a more efficient estimation of merchantable wood and aboveground biomass at the study site. Besides not disturbing forest regeneration, this equation could also support the measurement of both parameters from different periods since it developed using independent variable that generally could represent tree attributes. However, a further validation test was required if this model would be used in the other regions since the influence of site quality had potential to cause a bias estimation.

Conclusion

This study showed the development of species-specific allometric equations had the potential to facilitate more efficient estimation of merchantable wood and total aboveground biomass in community forest tree species. By using the best model, the farmers can conduct a rapid quantification of the wood for determining the trees' commercial value. Moreover, the government can also use this model to estimate the contribution of community forests for carbon reduction.

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