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The Allometric Equations for Estimating the Leaf Area Index of Community Forest Tree Species

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Abstract

LAI measurement using a direct method is time-consuming, while other instruments like Ceptometer, Hemispherical Photography, and LI-COR require high investment. This study aims to develop allometric equations for estimating the *LAI* of community forest tree species. Destructive sampling was conducted on 45 trees from three different species, i.e., *Tectona grandis, Swietenia macrophylla,* and *Falcataria moluccana*. The allometric equations were developed using regression analysis with two predictor variables, namely diameter at breast height (*D*) and tree height (*H*). *LAI* varied among species, wherein the highest average of *LAI* was recorded in *S. macrophylla* (1.03±0.03), followed by *T. grandis* (0.28±0.07) and *F. moluccana* (0.23±0.03). Our study found that the equation $LAI = 0.01D^{1.15}$ was reliable as a generalized allometric equation to estimate the *LAI* of three species with an RMSE of 0.39. We concluded that the allometric equation could facilitate *LAI* estimation in community forests.

Keywords: Efficiency, *LAI*, model, photosynthesis, reliability.

1. INTRODUCTION AND OBJECTIVES

Leaf area index (*LAI*) is an essential parameter to assess the effectiveness of plant photosynthesis (Vyas et al., 2010). This parameter also strongly relates to transpiration and net primary productivity (Moualeu-Ngangue et al., 2017). Thus, *LAI* is essential in determining the growth rate and energy exchange between plants and the atmosphere. Higher *LAI* indicates a more extraordinary plant ability to absorb light intensity (De Mattos et al. 2020). *LAI* is also frequently measured to evaluate plant physiology over time.

In forest management, *LAI* can be measured using direct and indirect methods. The direct measurement is conducted by destructive sampling or using litter traps (Shin et al., 2020). However, the methods are challenging to implement on a large scale since they require high cost and time. Measuring *LAI* by destructive sampling may also reduce forest regeneration, although this method helps obtain the most accurate *LAI* value. Meanwhile, the indirect measurement can be done using tool kits like Hemispherical Photography, LAI-200, and Ceptometer (Hakamada et al., 2016). They also work more efficiently time for data acquisition (Mason et al., 2012) but require optimum light intensity for more precise results (Ariza-Carricondo et al., 2019). Unfortunately, the instruments are rarely available for farmers in community forests since they need high investment. Other alternative methods like remote sensing and terrestrial ecosystems model can also be implemented to estimate *LAI* (Richardson et al., 2009; Qu and Zhuang, 2018) but both methods require high analytical skill and are only applicable for a stand level. Therefore, another approach should be explored to tackle this problem, one of which is allometric equations.

Developing allometric equations becomes a realistic solution for *LAI* estimation since this approach has been widely used to estimate individual tree parameters (Zahabu et al. 2018; Istrefi et al. 2019; Wirabuana et al. 2020). The allometric equations have been widely applied in the forestry sector for quantifying biomass (Altanzagas et al., 2019; Romero et al., 2020; Sadono et al., 2021), carbon (Khan et al., 2018; Widagdo et al., 2020; Karyati et al., 2021), and crown characteristics across different forest ecosystems in the tropics and temperate (Riikonen et al., 2011; Coombes et al., 2019; Pretzsch, 2019). The previous study also reported that allometric equations are reliable in estimating the *LAI* of *Tectona grandis* and *Dendrocalamus strictus* in India (Vyas et al., 2010). However, developing allometric equations for *LAI* estimation in Indonesia has yet to be carried out, primarily in community forests with many tree species.

This study aims to develop the best allometric equations for estimating the *LAI* of community forest tree species. This research will address three essential questions: (i) What is the reliability of allometric equations in estimating *LAI* variation in the study site? (ii) what are the best allometric equations for estimating the *LAI* of each community forest tree species? Moreover, (iii) can these best equations be simplified into a single reliable model for all species? We hypothesize that (i) at least 60% *LAI* variation in every species can be explained using the selected equations, (ii) the best allometric equation for every species was relatively different, and (iii) the best-selected model for every species can not be simplified into a single reliable model. The result provides an instrument for community forest managers to estimate *LAI* more efficiently in time and cost.

2. MATERIALS AND METHODS

2.1. Study site

This study was conducted in community forests at Srobyong Village, Jepara District, Central Java, Indonesia. It had geographic position in S6°31'35"-6°31'37" and E110°41'39"-110°43'22" (Figure 1). The site is classified into a lowland area with an altitude of 70 m above sea level. Topography is predominantly flat, with a slope level of 0–8%. Annual rainfall is 2,446 mm year^{-1} with a mean air humidity of 84%. The average daily temperature is 29°C with a minimum of 22°C and a maximum of 34°C. Alfisols dominate soil type with a pH of 5.5–6.0. Around 52% of this area is dominated by community forests, providing timber for local industries. Three commercial species are extensively cultivated by farmers in the study area, namely *Swietenia macrophylla*, *Tectona grandis*, and *Falcataria moluccana* (Wirabuana et al., 2021). These plants become species preferences since they have good market availability. However there are also other plant species in this location, but they have lower populations than these three species.

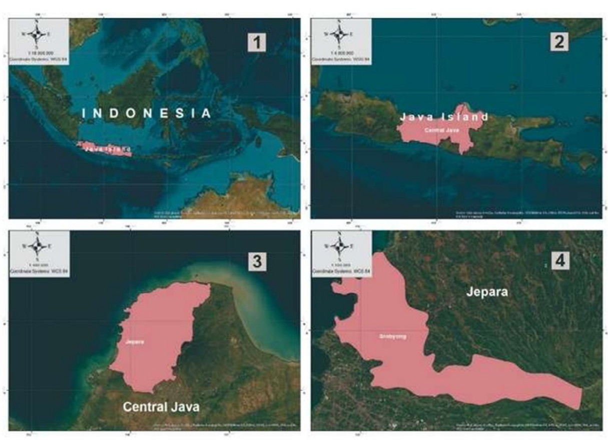

Figure 1. The study site in community forests at Srobyong Village.

2.2. Data collection

Destructive sampling was conducted on 45 trees from three species, i.e., *T. grandis*, *S. macrophylla*, and *F. moluccana*. The number of tree samples was evenly distributed for each species, wherein 15 sample trees represented each species. These sample trees were selected by considering the diameter distribution to obtain representative samples from small to big trees (Setiahadi, 2021). This was classified into four classes, namely 0–10 cm, 11–20 cm, 21–30 cm, and ≥31 cm (Wirabuana et al., 2020b). Every class consisted of at least three tree samples for each species. The sample size was relatively small due to the limited resources available. However, several studies also used a small sample size to develop allometric equations (Youkhana and Idol, 2011; Stas et al., 2017; Sadono et al., 2022).

Before the sample tree was felled, several parameters were recorded, like diameter at breast height (*D*), tree height (*H*), and crown radius (*CR*). Tree diameter was measured at 1.3 m aboveground using a diameter tape, while tree height was quantified from aboveground to top crown using a spiegel relascope. The crown radius was determined as the quadratic mean of crown radius from eight directions (Figure 2) (Pretzsch et al., 2015). This parameter was used to calculate the crown projection area (*CPA*) for determining the occupation area of every tree crown (Wirabuana et al., 2021). The mathematical functions for computing both variables are presented below:

$$CR = \sqrt{\frac{R_1 + R_2 + \cdots + R_8}{8}} \tag{1}$$

$$CPA = \pi . CR^2 \tag{2}$$

Where *CR* is a quadratic mean crown radius of every tree sample (m), *R* is the length of crown radius in a certain direction (m), and *CPA* is the crown projection area of an individual tree (m^2).

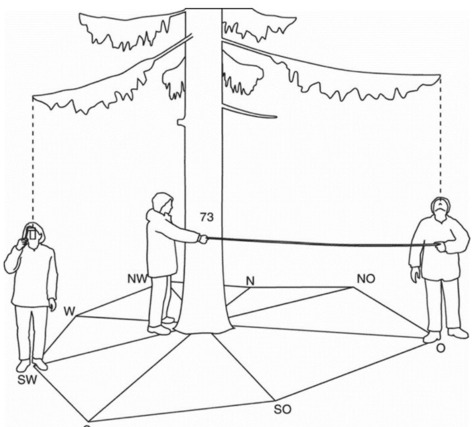

Figure 2. The illustration of crown radius measurement (Source: Pretzsch et al. 2015).

The destructive process was conducted using a chainsaw from small to large tree samples. After the sample tree was felled, crown length was measured from the base to the endpoint. Then, it was stratified into three layers with the same proportions, i.e., base, middle, and top (Figure 3). Ten leaf samples were taken randomly from every layer to support the individual leaf area measurements (Wirabuana et al., 2019). Thereby, there were 30 leaf samples for each tree. Afterward, the foliage was harvested and weighed to determine the fresh weight using a hanging balance. The leaf samples were also included when determining the total foliage fresh weight. Then, around 500 g foliage subsamples were collected and brought to the laboratory for drying (Sadono et al., 2021).

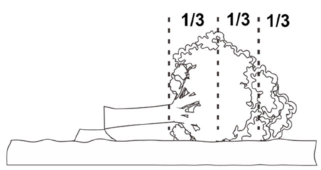

Figure 3. The illustration of canopy layer stratification for supporting leaf sampling.

Before drying, every leaf sample was scanned to get its picture. The step was undertaken to facilitate the measurement of individual leaf area (LA). We used the Image J software to support LA calculation. Then, the leaf samples and foliage subsamples were dried using an oven for 48 hours at 70°C before measuring their dry weight (Wirabuana et al., 2019). The foliage biomass (*WF*) was determined by multiplying the ratio of dry-fresh weight from the subsample with the total foliage fresh weight from every tree sample. The specific leaf area (SLA) was calculated by dividing LA by the individual leaf dry weight (*LW*) (Rosbakh et al., 2015). SLA indicates the level of leaf thickness of a plant species. Furthermore, LAI from every tree sample was determined based on the relationship among SLA, *WF*, and *CPA* (Hakamada et al., 2016). The equations for determining these parameters are described below.

$$WF = \frac{DW}{FW} \, x \, TFW \quad (3)$$

$$SLA = \frac{LA}{LW} \quad (4)$$

$$LAI = \frac{WF.SLA}{CPA} \quad (5)$$

Where *WF* is foliage biomass (kg), *DW* is the dry weight of foliage subsample (kg), *FW* is the fresh weight of foliage subsample (kg), TFW is total foliage fresh weight (kg), *SLA* is a specific leaf area ($m^2 \, kg^{-1}$), *LA* is the individual leaf area (m^2), *LW* is the individual leaf dry weight (kg), and *CPA* the crown projection area of an individual tree (m^2).

2.3. Data analysis

A descriptive test was conducted to identify the data attributes from the observed variables, including minimum, maximum, mean, standard deviation, and standard error. The normality of data was evaluated using the Shapiro-Wilk test. Correlation analysis was also applied to assess the relationship between independent and dependent variables. It was also supported by the scatter diagram to recognize the relationship between both variables. The diameter at breast height (D) and tree height (H) were placed on the X-axis, while LAI was put on the Y-axis. Both methods were commonly used in previous studies before developing the allometric equations (Vega-Nieva et al., 2015; Lisboa et al., 2018; Tetemke et al., 2019; Ogana and Ercanli, 2022).

Three allometric equations were evaluated in this study. The number of independent variables for both equations was relatively different. The first equation only used D as the single predictor, while the second model used squared diameter at breast height combined with tree height (D^2H) as the predictors. For the third equation, D and H were used as the predictors separately. The allometric equations were developed using two paths, i.e., for certain species and all species combined. The form of equations is presented below:

$$Y = a.D^b \quad (6)$$

$$Y = \ a.(D^2H)^b \quad (7)$$

$$Y = \ a.D^b.H^c \quad (8)$$

Where Y is the LAI value of the individual tree, D is the diameter at breast height (cm), H is tree height (m), while a, b, and c are fit coefficients.

Seven indicators were selected to evaluate the best allometric equations, namely the significant result of the 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 error (MAE), and root mean square error ($RMSE$). The ANOVA test, fitted parameters, R^2, RSE, and AIC were used to evaluate the model fitting, while MAE and $RMSE$ were selected to examine the validation (Wirabuana et al., 2020a; Sadono et al., 2021). Our study used the leave-one-out cross-validation (LOOCV) method due to the small sample size. Other studies also applied LOOCV when developing models with a low sample size (Altanzagas et al. 2019; Tetemke et al. 2019). Detailed formulas for calculating these indicators are expressed below:

$$R^2 = 1 - \left(\frac{\sum(Y - \bar{Y})^2}{\sum\left(Y - \hat{Y}\,\right)^2} \right) \quad (9)$$

$$RSE = \sqrt{\frac{1}{(n-2).\sum(Y-\bar{Y})^2}} \quad (10)$$

$$AIC = n.\log\left(\frac{RSS}{n}\right) + 2k + \frac{2k\,(k+1)}{n-k-1} \quad (11)$$

$$MAB = \frac{\sum(|Y-\hat{Y}|)}{n} \quad (12)$$

$$RMSE = \sqrt{\frac{\sum(Y-\hat{Y})^2}{n-p-1}} \quad (13)$$

Where Y is the observed *LAI*, $\bar{Y}$ is the average observed *LAI*, $\hat{Y}$ is the estimated *LAI* from the fitted model, n is the sample size, *RSS* is the residual sum of squares from the fitted model, k is the number of parameters, and p is the number of terms in the model. High R^2 values, small *RSE*, *AIC*, *MAB*, and *RMSE* indicate high model precision.

Furthermore, the Extra Sums of Square (ESS) method was also applied to determine the most efficient allometric equations for estimating the *LAI* of community forest tree species. ESS was done to quantify the marginal reductions in Error Sums of Squares when an additional set of predictors was added to the model (Hector et al., 2016; Wirabuana et al., 2021; Sadono et al., 2022). It aimed to evaluate whether the addition of *H* as the predictor variable provided a significant contribution to improving the model's reliability. When the result is insignificant, using a single predictor in the allometric equation was sufficient to obtain a good estimation.

3. RESULTS

3.1. Tree sample distribution

The number of sample trees in every diameter class relatively varied for each species (Table 1). Overall, most tree samples were classified into the diameter class of 0–10 cm, while the lowest was found in the diameter class of ≥31 cm. Total tree samples declined with the increasing diameter class and followed the J-curve pattern. It indicated that the forest structure in the study site had a heterogeneous condition with uneven-aged stand. Our study also noted that *S. macrophylla* had almost equal tree samples for all diameter classes except for the biggest diameter class. Meanwhile, a different proportion was observed *in T. grandis*, wherein only the lowest diameter class did not have an equal number of tree samples.

Summarized results of the observation found that *LAI* among species exhibited a high variation (Table 2). The highest mean *LAI* was recorded in *S. macrophylla* (1.03±0.03), followed by *T. grandis* (0.28±0.07) and *F. moluccana* (0.23±0.03). *LAI* was also highly correlated with other tree parameters (Figure 4). However, the relationship between parameters was relatively different. Higher *D, H, CPA,* and *WF* significantly increased *LAI*. In contrast, *LAI* gradually declined along with increasing *SLA*. The strong correlation between *D* and *H* with *LAI* confirmed that both variables could be used as predictors to develop allometric equations.

Table 1. Tree sample distribution in every diameter class.

Species	Diameter classes (cm)			
	0–10	11–20	21–30	≥31
T. grandis	6	3	3	3
S. macrophylla	4	4	4	3
F. moluccana	5	4	3	3
Total	15	11	10	9

LAI variation among species.

Table 2. Summary statistics of tree characteristics from the destructive sampling.

Species	Unit	*D* (cm)	*H* (m)	*CPA* (m²)	*WF* (kg)	*SLA* ($m^2\ kg^{-1}$)	*LAI*
T. grandis	Mean	14.64	7.08	7.68	3.67	0.71	0.28
	SD	7.13	1.42	5.30	3.91	0.02	0.13
	SE	2.25	0.45	1.68	1.24	0.01	0.04
	Min	8.91	5.60	3.79	0.92	0.70	0.14
	Max	27.68	9.70	19.07	11.22	0.76	0.48
S. macrohylla	Mean	38.55	14.40	46.31	74.87	0.63	1.03
	SD	2.52	1.28	9.77	12.47	0.02	0.07
	SE	1.03	0.52	3.99	5.09	0.01	0.03
	Min	35.95	13.10	36.50	62.80	0.60	0.93
	Max	41.36	15.60	57.61	87.17	0.67	1.13

Table 2. Continued...

Species	Unit	*D* (cm)	*H* (m)	*CPA* (m^2)	*WF* (kg)	*SLA* (m^2 kg^{-1})	*LAI*
F. moluccana	Mean	17.55	7.21	14.78	5.93	0.70	0.23
	SD	9.98	1.83	11.30	6.17	0.02	0.12
	SE	2.67	0.49	3.02	1.65	0.00	0.03
	Min	5.41	4.60	6.17	0.39	0.67	0.04
	Max	36.59	10.60	42.65	19.16	0.72	0.46
All Species	Mean	20.78	8.61	18.72	18.96	0.69	0.41
	SD	12.04	3.33	17.01	29.29	0.04	0.33
	SE	2.20	0.61	3.11	5.35	0.01	0.06
	Min	5.41	4.60	3.79	0.39	0.60	0.04
	Max	41.36	15.60	57.61	87.17	0.76	1.13

Note: *D* (diameter at breast height), *H* (tree height), *CPA* (crown projection area), *WF* (foliage biomass).

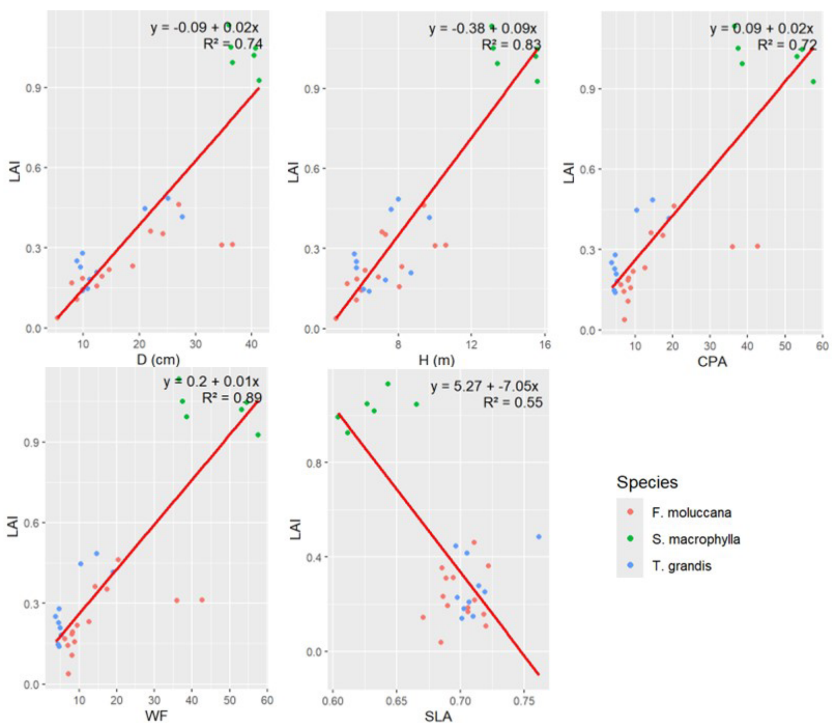

Figure 4. Scatter plot for showing the relationship between *LAI* and other parameters.

3.2. Allometric equations for LAI estimation

This study reported that every allometric equation provided a good fit, wherein more than 60% *LAI* variation in every species could be explained using these equations (Table 3). This finding confirmed that the allometric equations were reliable to facilitate *LAI* estimation of community forest tree species. Interestingly, the addition of *H* as a predictor variable in the equation only provided a substantial contribution to improving the accurate *LAI* estimation in *S. macrophylla* (Tab. 4). Meanwhile, using a single predictor like *D* was better for estimating *LAI* in *T. grandis* and *F. moluccana*. This fact caused the best-fit equation for each species to be relatively different.

The results also found that a generalized allometric equation could be developed to estimate *LAI* in all species (Table 3). This equation only required *D* as a predictor variable (Table 4), but it could explain approximately 79% *LAI* variation from all species. The estimated *LAI* from this equation also demonstrated a high correlation with the actual *LAI* value (Figure 5). However, it provided a lower estimation when used to predict the *LAI* of *S. macrophylla*. In contrast, the equation showed a better fit when used to estimate *LAI* in *T. grandis* and *F. moluccana*.

Table 3. Summary evaluation statistics of every allometric equation for estimating LAI.

Species	Equations	*a*	*b*	*c*	R^2	*RSE*	*AIC*	*MAB*	*RMSE*
T. grandis	$LAI = a.D^b$	0.03	0.84	-	0.65	0.28	6.72	0.28	0.30
	$LAI = a.(D^2H)^b$	0.02	0.33	-	0.59	0.30	8.37	0.32	0.33
	$LAI = a.D^b.H^c$	0.10	1.28	-1.22	0.75	0.25	5.45	0.24	0.29
S. macrophylla	$LAI = a.D^b$	0.18	0.50	-	0.71	0.20	-2.34	0.17	0.20
	$LAI = a.(D^2H)^b$	0.20	0.18	-	0.67	0.21	-0.17	0.18	0.22
	$LAI = a.D^b.H^c$	0.15	1.80	-1.73	0.92	0.11	-18.92	0.10	0.12
F. moluccana	$LAI = a.D^b$	0.02	0.85	-	0.72	0.34	14.04	0.31	0.40
	$LAI = a.(D^2H)^b$	0.01	0.35	-	0.70	0.35	15.13	0.33	0.42
	$LAI = a.D^b.H^c$	0.05	1.33	-1.17	0.75	0.33	14.31	0.40	0.30
All Species	$LAI = a.D^b$	0.01	1.17	-	0.79	0.37	30.13	0.31	0.40
	$LAI = a.(D^2H)^b$	0.01	0.46	-	0.80	0.36	28.01	0.29	0.38
	$LAI = a.D^b.H^c$	0.01	0.77	0.74	0.81	0.37	29.66	0.30	0.39

Note: all equations indicated a significant ANOVA result, and fitted parameters test.

Table 4. Summary results of the ESS test for the allometric equations.

Species	Predictor	RSS	Df	Sum of Sq	F	p-value
T. grandis	D	0.62				
	D, H	0.45	1	0.17	2.7	0.14
S. macrophylla	D	0.46				
	D,H	0.14	1	0.32	26.48	<0.001**
F. moluccana	D	1.36				
	D, H	1.20	1	0.15	1.55	0.23
All species	D	2.83				
	D, H	3.50	1	0.32	2.52	0.12

Note: ** indicates the addition of *H* as a predictor variable provides a significant contribution.

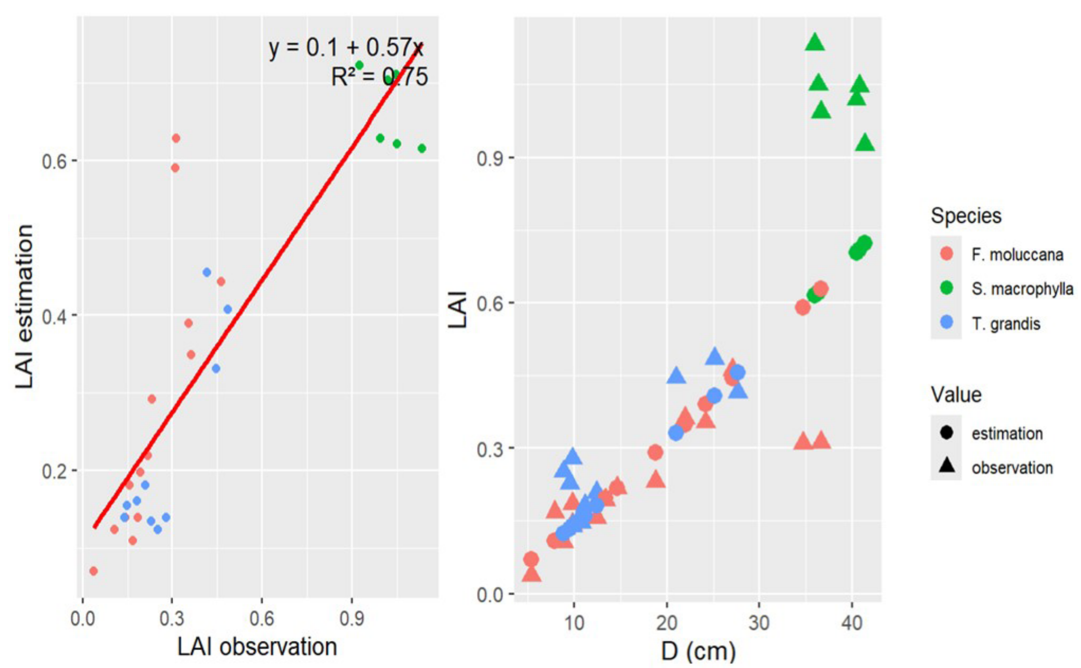

Figure 5. Correlation between observed and estimated *LAI* and their comparison in every species.

4. DISCUSSION

The allometric equations indicated good reliability in estimating the *LAI* of community forest tree species in the study site. More than 60% *LAI* variation for each species could be predicted using these equations (Table 2). It was directly suitable to our first hypothesis. This finding was also similar to other previous studies, wherein the allometric equations could be applicable to facilitate *LAI* estimation (Xiao et al., 2006; Vyas et al., 2010; Colaizzi et al., 2017). However, we also realize the model reliability principally varies depending on site species and type of forest ecosystems. For example, the best-fit equation for estimating the *LAI* of *T. grandis* in this study had a lower precision than the *LAI* model of *T. grandis* in India (Vyas et al., 2010). It may occur because there is a different growth rate of species between both locations. The allometric equation is principally constructed from the relationship between tree attributes; thus, differences in growth response can generate a distinguished model.

LAI is highly correlated with other observed tree parameters (Figure 4). It confirmed a significant influence of *LAI* variation on plant growth. Higher *LAI* would generate better growth because the plants can absorb more light intensity to support their photosynthesis process (Vyas et al., 2010). Thus, they can produce more biomass and allocate the results to increase height and diameter (De Mattos et al. 2020). It addressed why higher *LAI* values also followed the greater *D* and *H*. This fact also becomes the basis consideration in developing the allometric equations. Compared to other parameters, *D* and *H* are more accessible to measure and always recorded when conducting forest inventory.

Our study also noted that the best-fit equations for each species were different (Table 3). It also confirmed our second hypothesis. *For S. macrophylla*, both *D* and *H* were required to obtain good *LAI* estimation (Table 4). Meanwhile, a single D predictor is sufficient for good *LAI* predictions in *T. grandis* and *F. moluccana*. These outcomes indicated that the addition of *H* as an independent variable only provided a significant contribution to improving the reliability of allometric equations for specific species. It was different from the previous studies, which reported that the addition of *H* consistently increased the accurate estimation of allometric equations (Bi et al., 2004; Chave et al., 2014; Meng et al., 2021).

Moreover, we also reported that generalized allometric equations could be developed for all species. The generalized model also showed good reliability, wherein approximately 79% of *LAI* variation among species could be explained (Table 3). It rejected our third hypothesis that the generalized equation could not be developed. Interestingly, this equation only needed *D* as the predictor variable; thus, it was also more applicable in the field. Using a generalized equation also had a lower cost and time consumption than the specific species model since it only needed to collect a single variable. For a practical reason, measuring *H* in forests is not easy since we will also face canopy overlap between trees that can cause a potential error (Mugasha et al., 2013; Magalhães, 2017; Dey et al., 2021; Cui et al., 2022; Kafuti et al., 2022). Many studies also recommend using a simple model for supporting forest inventory as long as it can explain the majority of object variations (Lumbres et al., 2015; Forrester et al., 2017; Romero et al., 2020; Wirabuana et al., 2021; Sadono et al., 2022). Therefore, we suggest using a generalized allometric equation to estimate the *LAI* of community forest tree species in the study site.

Nevertheless, we also realized that our study had several limitations, wherein it only used a small sample size (45 trees) from three different species. It was also conducted in one location; thus, we could not assess whether the best equation was reliable for different sites and forest ecosystems. Further investigation is still required to validate the reliability of allometric equations for estimating *LAI* with more diverse species and higher sample sizes. We also hope that future research can be implemented in multiple sites to evaluate the extensive validity of this approach.

5. CONCLUSION

This study concluded that the allometric equations were reliable in facilitating *LAI* estimation of community forest tree species in Jepara District. The best-fit models could explain more than seventy percent of *LAI* variation in every species. Although the best equation of each species was relatively different, estimating *LAI* for all species could also use a single generalized model with a diameter at breast height as a predictor. Although the best model was reliable to facilitate *LAI* estimation in this research site, further validation is required to examine the model for different sites and forest ecosystems. Other investigation are also required to evaluate whether *LAI* can be estimated using allometric equations with tree diameter as a predictor.

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Pandu Wirabuana: Conceptualization (Lead), Data curation (Supporting), Formal analysis (Supporting), Funding acquisition (Lead), Methodology (Lead), Project administration (Supporting), Supervision (Equal), Validation (Lead), Writing - original draft (Supporting), Writing - review & editing (Lead).

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