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ALLOMETRIC MODEL OF WOOD BIOMASS AND CARBON FOR GLIRICIDIA (*GLIRICIDIA SEPIUM* (JACQ.) KUNTH EX WALP.) AT BIOENERGY PLANTATION IN INDONESIA

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Abstract

The paradigm of multipurpose forest management in gliricidia plantation can be developed to produce woody biomass and carbon stock. Production estimation of gliricidia plants in producing woody biomass and carbon stocks needs to be estimated through allometric models. The research objective is determining the best allometric equations of wood biomass and carbon stocks with predictors of stem diameter. The materials used in the study were the gliricidia stand with age 1–5 years at Forest Management Unit Semarang. The method used in measuring and estimating forest carbon stocks refers to Indonesian National Standard (SNI) No 7724: 2011 and the SNI No 7725: 2011. The results showed that the biomass of gliricidia plants was distributed in stems (10.75 %), branches (86.30 %), and leaves (2.93 %). Furthermore, the average carbon content in stems was 57.40 %, in branches – 56.30 %, and in leaves – 52.90 % of the dry weight. R^2_{adj} of allometric models were 0.780 (linear); 0.730 (exponential); 0.532 (logarithmic); 0.799 (polynomial); and 0.959 (power). While the RMSE values were 38.89 %, 1.20 %, 56.66 %, 37.16 %, and 0.48 %, respectively. The allometric model validation showed that power model is the best allometric model for wood biomass and total carbon content. Thus, it can be considered to estimate wood biomass and total carbon with predictors of stem diameter. Further research by adding other predictors is needed to make the result of allometric models more accurate.

Key words: coppice system, multipurpose forest, multi-stem, short rotation coppice.

Introduction

An option for obtaining renewable energy, which could substitute fossil fuels in the future, is the utilization of biomass for bioenergy. Indonesia, as a tropical country, has great potential in producing biomass from the agriculture and forestry sectors by utilizing the biomass and biomass waste into bioenergy (Febijanto 2007) and utilize marginal land for bioenergy plantation (Narendra et al. 2019). In the new policy scenario of the government of the Republic of Indonesia, between 2011 and 2035 renewable energy will increase by 75 % and the main source will come from bioenergy (Dewan Energi Nasional 2014) and by 2050 the utilization of bioenergy can reach at least 31 % (Government of Indonesia Decree No 79 2014).

The forestry sector can play an important role in support of renewable energy policies, particularly bioenergy, by the use of biomass with multipurpose forest management. Forest can be utilized considering various objectives such as wood and non-wood (Miina et al. 2010, Tahvanainen et al. 2018), wood and wildlife conservation (Toyoshima et al. 2013), as well as wood with environmental services to absorb forest carbon (Tiryana 2016, Nölte et al. 2018). Carbon sequestration is a potential indicator in measuring environmental services for regulating global climate change (Groot et al. 2010).

Some countries with boreal and temperate forests have been developing short rotation coppice (SRC) plantation in marginal land using multipurpose forest management approaches to mitigate climate change. For instance, Canada developed willow and poplar cultivation for bioenergy source, land rehabilitation, and carbon sequestration (Amichev et al. 2010, Lupi et al. 2015, Jego et al. 2017). European countries also have been developing SRC plantation, for instance Poland (Stolarski et al. 2018), Bulgaria (Marinov et al. 2013), Belgium (Laureysens et al. 2005), Italy (Bacenetti et al. 2016), Germany (Faasch and Patenaude 2012) for mitigating climate change. Development of SRC plantation provides multiple effects such as bio-economy and environmental services.

Since 2012, Indonesia Forest Enterprise (Perhutani) started using Gliricidia (*Gliricidia sepium* (Jacq.) Kunth ex Walp.) species for SRC plantation in Forest Management Unit (FMU) Semarang. The management purposes of gliricidia plantations are to produce wood biomass for bioenergy and to provide environmental services such as carbon storage. Generally, the potential of carbon sequestration has not yet been integrated into forest management plans, even though the function of forests as carbon sinks has an important role (Baskent et al. 2008). For instance, Tiryana (2016) has examined the multipurpose forest management for teak plantation in Perhutani that considers aspects of teak production and carbon sequestration. Furthermore, Tiryana (2016) states that modeling between carbon sequestration and logging schedule can help forest managers to obtain optimal volumes and maintain the age structure of teak stands at the end of the cycle, so this modeling needs to be applied to other plantations.

Unfortunately, achieving multipurpose forest management on gliricidia plantation faces difficulty due to a lack of information on gliricidia's allometric model. The development of allometric models is an important phase in estimating the volume and biomass from forests (Rutishauser et al. 2013) and developing short-rotation plantation (Amichev et al. 2010, Jego et al. 2017). The allometric models for estimating volume/biomass and forest carbon stocks in Indonesia have been carried out by terrestrial measurements (Akbar 2012) and using satellite imagery (Wahyuni and Suryawan 2012, Wahyuni 2014, Yuwono et al. 2015). The biomass allometric model is built based on easily measured data (diameter, height, age) and could be used for both practical and scientific purposes (Saint-Andre et al. 2005, Istrefi et al. 2018).

Mostly, allometric models in Indonesia that consider diameter as a predictor are used to estimate the tree volume dimension of a single stem (Siswanto and Imanuddin 2008, Hardjana et al. 2012, Qirom et al. 2012, Qirom and Supriyadi 2012, Kuswandi 2016, Samsoedin et al. 2016, Qirom 2018). Whereas, gliricidia tree is multi-stem and the biomass is the main feature for bioenergy production. Thus, this study aims to determine the allometric model of wood biomass with diameter predictors and then to apply the model for estimating the carbon stock of the gliricidia tree.

Material and Methods

Research site

The study was conducted at the Forest Management Unit Semarang for five months (April – September 2019) and distributed for all ages (Fig. 1). Gliricidia plants used in the research were planted in 2013, 2014, 2015, 2016, and 2017.

Data collection

Primary data for the preparation of biomass allometric models and carbon stocks in gliricidia plantations refer to Indonesia National Standard (SNI) No 7724 concerning measurement and calculation of carbon stocks – field measurements for estimating forest carbon stocks and SNI No 7725 concerning the preparation of allometric equations for estimating forest carbon stocks based on field measurements (Badan Standarisasi Nasional

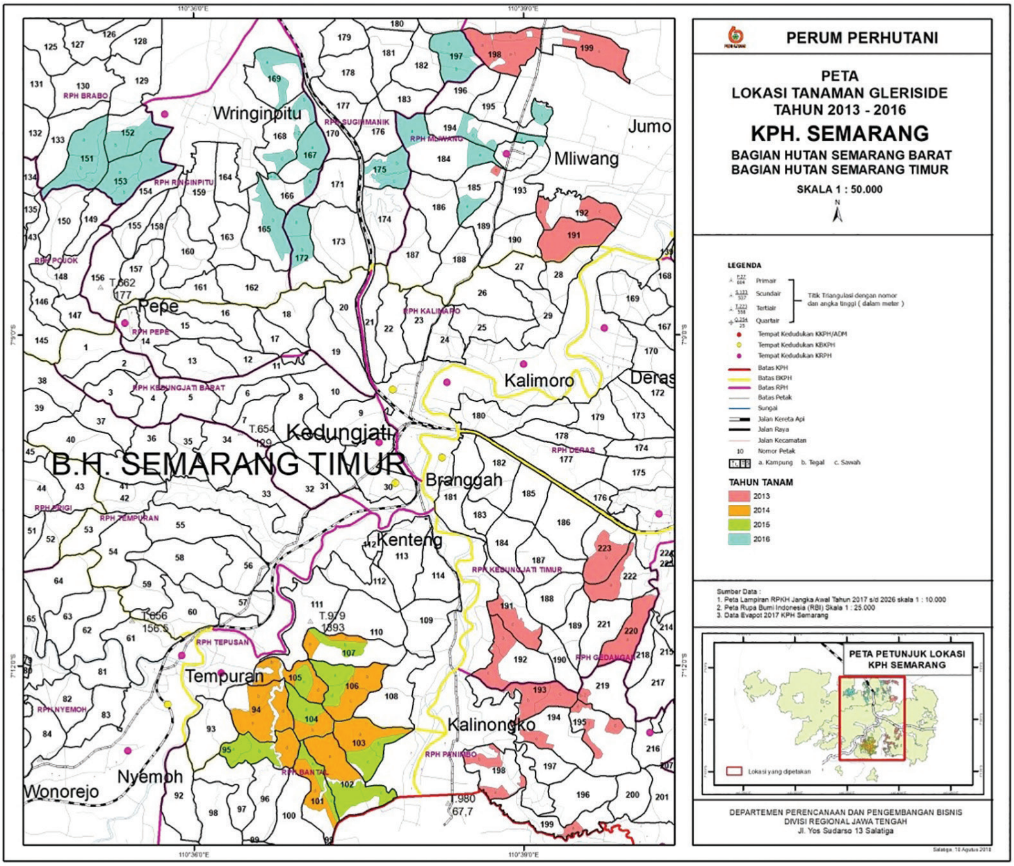

Fig. 1. Research site.

2011a, 2011b). Usually, the diameter was measured at breast high (DBH), but for multi-stem tree's diameter measurement is considered at 0.3 m above the ground (Brown 1997, Amichev et al. 2010, Jego et al. 2017). Furthermore, in this research, the stem diameters were measured on 0.3 m.

The sample included 66 gliricidia trees, of which 33 trees were used to develop wood biomass and carbon stock allometric models and 33 trees for validity test. Furthermore, wood biomass allometric models developed from fresh-cut and dry weight were used for the carbon stock allometric model. Drying of samples was carried out in the laboratory in the Department of Forest Product Technology Universitas Gadjah Mada (UGM), whereas carbon organic content testing was carried out in the Laboratory of soil science, Faculty of Agriculture UGM.

Data analysis

Primary data from laboratory tests were analyzed using the regression approach to estimate the gliricidia's woody biomass and carbon content. Firstly, data were checked for normal distribution and then tested for some regression model (linear, exponential, logarithmic, polynomial, and power) using equations (1–5).

$$\text{Linear: } B = \beta_0 + \beta_1 D, \tag{1}$$

$$\text{Exponential: } B = \beta_0 e^{\beta_1 D}, \tag{2}$$

$$\text{Logarithmic: } B = \beta_0 + \beta_1 \ln(D), \tag{3}$$

$$\text{Polynomial: } B = \beta_0 + \beta_1 D + \beta_2 D^2, \tag{4}$$

$$\text{Power: } B = \beta_0 D^{\beta_1}, \tag{5}$$

where: B is biomass of fresh-cut weight or carbon content (kg), D is stem base diameter (cm), β_0 is intercept/constant, and β_1 and β_2 are gradient.

Criteria for evaluating biomass allometric models were the root mean square error (RMSE) and coefficient of determination (R^2) (Krisnawati et al. 2012, Almulqu et al. 2019): bias, aggregate deviation (*AD*), and relative deviation (*RD*) (Qirom et al. 2012, Qirom 2018).

The reliability test of the allometric model uses the parameters of aggregate deviation (*AD*), relative deviation (*RD*), and bias. A good allometric model has an *AD* value of <1 %, *RD*<10 %, and minimal bias (Sumadi and Siahaan 2010, Kuswandi 2016, Qirom 2018). The selection of the best model based on the ranking has been made on the research of allometric models on the Red balau tree (*Shorea balangeran* (Korth.) Burck) in Central Kalimantan (Qirom 2018), commercial species in Papua (Kuswandi 2016), and Blackboard tree (*Alstonia scholaris*) in South Sumatra (Sumadi et al. 2010). The ranking is done with a score of 1–5 so that the best model is the allometric model with the lowest total score.

Results and Discussion

The overview of gliricidia plantation at FMU Semarang

The gliricidia plantation was established in FMU Semarang in collaboration with the Korean Green Promotion Agency (KGPA). A few years later, KGPA changed into Korean Forestry Promotion Institute (KOFPI). Initially, gliricidia plantation was established on marginal land in the FMU Semarang's forest area that covered 477.60 ha. Every year, KOFPI establishes gliricidia plantations in some areas and by 2017 the total area planted at FMU Semarang reached almost 2000 ha.

Research data obtained from the inventory of gliricidia stands at all stand ages (1, 2, 3, 4, and 5 years) at FMU Semarang were stem diameter and weight of biomass produced from stems, branches, and leaves, and the number of plants per sample plot. Gliricidia stands of different age possessed specific characteristics on the number of areas, stand density, and productivity (Fig. 2).

Figure 2 shows that the gliricidia plantations in FMU Semarang are dominated by young stands (around 50 %). The stand density on the research site at different ages is more than 2000 trees/ha.

Allometry model for wood biomass and carbon stock of gliricidia

Based on the results of the inventory of Gliricidia plantation performed in 2018, the diameter distribution was classified into 11 diameter classes with an interval of 2 cm. For each diameter class, harvested trees were measured in detail on the stem, branches, and leaves (Table 1).

Gliricidia plantation is categorized as a short rotation coppice system in which the stem can produce several branches and they can be harvested in less than five years. The average length of the main stem was 103.5 cm with the number of

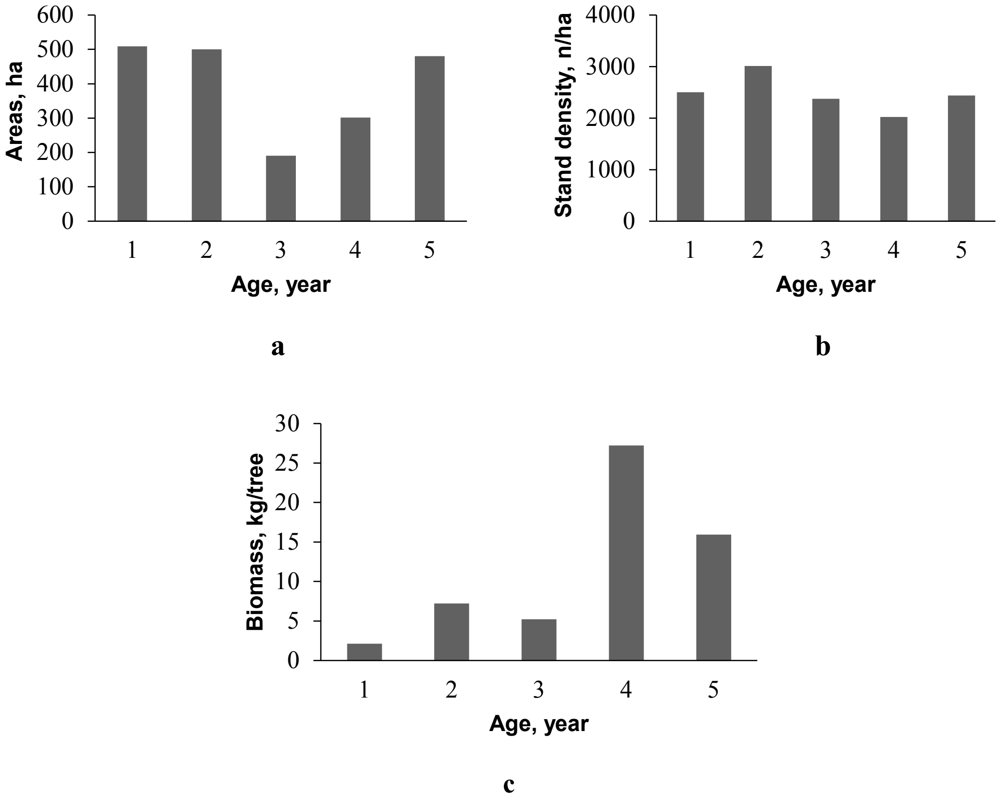

Fig. 2. Stand distribution of gliricidia plantation at FMU Semarang by (a) number of area, (b) stand density, and (c) tree biomass.

Table 1. Characteristics of samples.

Variables	Minimum	Maximum	Average	Standard deviation
Stem diameter, cm	0.640	21.940	11.126	6.450
Branch diameter, cm	0.380	14.30	6.409	2.909
Fresh-cut weight of stem, kg/tree	0.007	42.350	8.560	9.187
Fresh-cut weight of branch, kg/tree	0.001	175.000	24.726	30.305
Fresh-cut weight of leave, kg/tree	0.002	8.917	2.330	2.674

branches varying between 2 and 6. In addition, the average length of branches reached 626.9 cm and the total biomass of branches per tree became larger than the biomass of stem. Although the average stem diameter was greater than the average branch diameter (Table 1), the biomass of the branch section was more dominant than the stem section (Fig. 3).

Fig. 3. The distribution of fresh-cut biomass (a) and total carbon (b) in gliricidia plant.

The composition of fresh-cut weight and the total carbon content of stem, branches, and leaves showed similar trends. Changing the percentage of total fresh-cut weight to total carbon was affected by the drying process and organic carbon content in each part of the plant. The water content of the stems, branches, and leaves were 88.95 %, 103.72 %, and 338.53 %, respectively.

There was a positive relationship between stem diameter and biomass (total fresh-cut weight and total carbon). The biomass production and total carbon increased with increasing of the stem diameter (Fig. 4). Such positive relationship between diameter and volume was also found in *Shorea balangeran* (Qirom 2018), *Dyera polyphylla* (Qirom and Supriyadi 2012), and *Ficus variegata* (Qirom and Supriyadi 2013).

Normality test showed that the values of diameter at stem base and the total, and fresh-cut weight of gliricidia are normally distributed. Arrangement of allometric models for estimating wood biomass (fresh-cut weight) with predictors of stem diameter using linear and non-linear regression equations are shown in Table 2.

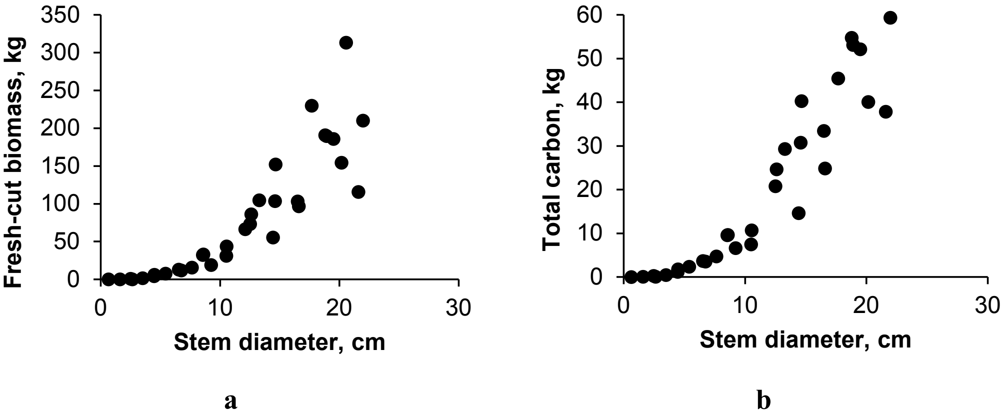

Fig. 4. Distribution pattern between stem diameters and fresh-cut biomass (a), total carbon (b).

Table 2. Correlation between stem diameters and fresh-cut weight of gliricidia tree.

No	Model	Equation	R^2_{adj}	RMSE, %
1	Linear	$B = -47.441 + 11.390D$	0.780	38.889
2	Exponential	$B = 0.793e^{0.308D}$	0.730	1.203
3	Logarithmic	$B = -79.797 + 73.564\ln(D)$	0.532	56.655
4	Polynomial	$B = -13.181 + 2.799D + 0.362D^2$	0.799	37.163
5	Power	$B = 0.068D^{2.722}$	0.959	0.479

Note: RMSE is root mean square error.

Carbon content in plants was obtained by using the guideline in the SNI 7724:2011. Based on the results of testing in the laboratory, the average carbon content in stems was 57.40 %, in branches – 56.30 %, and in leaves – 52.90 % of the dry weight of gliricidia plants. Therefore, the total carbon allometric equation will be different from the wood biomass allometric model (Table 3).

Prospective allometric models can be selected based on the value of R^2_{adj} and RMSE. The greater value of the corrected determination coefficient (R^2_{adj}) indicates stronger relationship. The smaller RMSE value is considered to choose the allometric model. For the allometric wood biomass ($B = 0.068D^{2.722}$) and total carbon stock models ($B = 0.019D^{2.719}$), the power model produces R^2_{adj} above 0.9 and the RMSE value below 1 %. Allometric model for willow (a multi-stem species) in Canada shows the similar pattern, and power model can explain the relationship between stem diameter at 30 cm height (D_{30}) and dry mass (*DM*) (Amichev et al. 2010, Jego et al. 2017).

In Indonesia, allometric models were developed to predict stem volume by a diameter at breast height (DBH), or tree height predictors were added (Sumadi et al. 2010; Sumadi and Siahaan 2010; Qirom et al. 2012; Qirom and Supriyadi 2012, 2013; Kuswandi 2016; Qirom 2018). The power model in estimating the volume of the *Shorea balangeran* has an

Table 3. Correlation between stem diameters and total carbon of gliricidia tree.

No	Model	Equation	R^2_{adj}	RMSE
1	Linear	$B = -13.391 + 3.167D$	0.767	11.192
2	Exponential	$B = 0.224e^{0.307D}$	0.726	1.210
3	Logarithmic	$B = -22.129 + 20.337\ln(D)$	0.517	16.126
4	Polynomial	$B = -2.135 + 0.403D + 0.119D^2$	0.796	10.480
5	Power	$B = 0.019D^{2.7192}$	0.958	0.472

R^2_{adj} of 0.837 (Qirom 2018). Application of power model to estimate volume of *Alstonia scholaris* plants produced R^2 of 0.964 (Sumadi et al. 2010). The power model also fits to estimate biomass of *Ziziphus mauritiana*, with R^2 0.920 (Kurniawan and Pujiono 2019).The allometric model reliability test was carried out on 33 sample trees to find out the actual value of wood biomass and total carbon with the estimated value based on allometric equations. The difference between the actual value and the estimated value can be seen in the results of the aggregate deviation (*AD*), relative deviation (*RD*), or bias (Table 4 and Table 5).

Table 4. Reliability test of an allometric model for stem diameters and fresh-cut weight.

No	Model	Equation	*AD*, %	*RD*, %	Bias, %
1	Linear	$B = -47.441 + 11.390D$	45.727	3.907	5.313
2	Exponential	$B = 0.793e^{0.308D}$	-81.637	1.288	-37.765
3	Logarithmic	$B = -79.797 + 73.564\ln(D)$	75.144	8.775	362.126
4	polynomial	$B = -13.181 + 2.977D + 0.362D^2$	40.241	2.258	57.824
5	Power	$B = 0.068D^{2.722}$	1.172	0.786	-2.214

Note: *AD* is aggregate deviation, *RD* is relative deviation.

Table 5. Reliability test of an allometric model for stem diameters and total carbon.

No	Model	Equation	*AD*, %	*RD*, %	Bias, %
1	Linear	$B = -13.391 + 3.167D$	-47.304	4.196	21.210
2	Exponential	$B = 0.224e^{0.307D}$	69.354	1.182	-32.630
3	Logarithmic	$B = -22.129 + 20.337\ln(D)$	-76.385	9.391	408.438
4	polynomial	$B = -2.135 + 0.403D + 0.119D^2$	-40.689	2.170	73.463
5	Power	$B = 0.019D^{2.7192}$	-7.000	0.858	6.633

The reliability test of the wood biomass allometric model and carbon stock shows that the power model predicts carbon stocks that meet the *AD* (-7.00 %) and *RD* (0.858 %) requirements. However, the power model for estimating woody biomass does not meet *AD* requirements below 1 % and *RD* below 10 %. The same result was also found in the development of the *Shorea balangeran* tree volume estimator model with a single predictor of the trunk diameter, where the *AD* and *RD* values did not meet the requirements of a reliable model (Qirom 2018). Furthermore, ranking can be applied to determine the best allometric model (Table 6).

Table 6. The allometric model ranking.

No	Equation	Score					
		AD, %	*RD*, %	Bias, %	R^2_{adj}	RMSE	Total
1	$\mathbf{B = -47.441 + 11.390D}$	4	4	3	3	4	18
	$B = -13.391 + 3.167D$	2	4	3	3	4	16
2	$\mathbf{B = 0.793e^{0.308D}}$	1	2	1	4	2	10
	$B = 0.224e^{0.307D}$	5	2	1	4	2	14
3	$\mathbf{B = -79.797 + 73.564\ln(D)}$	5	5	5	5	5	25
	$B = -22.129 + 20.337\ln(D)$	1	5	5	5	5	21
4	$\mathbf{B = -13.181 + 2.977D + 0.362D^2}$	3	3	4	2	3	15
	$B = -2.135 + 0.403D + 0.119D^2$	3	3	4	2	3	15
5	$\mathbf{B = 0.068D^{2.722}}$	2	1	2	1	1	7
	$B = 0.019D^{2.7192}$	4	1	2	1	1	9

Note: the formulas for fresh-cut weight are in bold, while the formulas for total carbon are not bolded.

Of all models tested in this study (Table 6), power model ranks first as the best one for estimating wood biomass and total carbon of gliricidia plants. The least appropriate model is the Logarithmic one, as illustrated by the resulting *AD*, *RD*, bias, R^2_{adj}, and RMSE values, which do not meet the allometric model reliability requirements.

Conclusion

We have tested some allometric model to predict the biomass and carbon of gliricidia plants. The best allometric model for gliricidia plants in FMU Semarang, which has 1–5 years with a diameter range of 0.1–22.5 cm is the power model. The power model fits in the first rotation of gliricidia stand management and specific site.

Recommendation

Further research to obtain a better allometric model can be done by adding predictors of plant height, branch diameter, or the number of branches per tree.

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