

Allometric Equations for Estimating Aboveground Biomass of *Eucalyptus urophylla* S.T. Blake in East Nusa Tenggara

Ronggo Sadono¹, Wahyu Wardhana¹, Pandu Yudha Adi Putra Wirabuana^{1*}, Fahmi Idris²

¹Department of Forest Management, Faculty of Forestry, Universitas Gadjah Mada, Jl. Agro No. 1 Bulaksumur, Yogyakarta, Indonesia 55281

²Department of Research and Development, TROFSIT Institute, Jl. Kaliurang Km 16, Yogyakarta, Indonesia 55281

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Abstract

Understanding the essential contribution of eucalyptus plantation for industry development and climate change mitigation requires the accurate quantification of aboveground biomass at the individual tree species level. However, the direct measurement of aboveground biomass by destructive method is high cost and time consuming. Therefore, developing allometric equations is necessary to facilitate this effort. This study was designed to construct the specific allometric models for estimating aboveground biomass of *Eucalyptus urophylla* in East Nusa Tenggara. Forty two sample trees were utilized to develop allometric equations using regression analysis. Several parameters were selected as predictor variables, i.e. diameter at breast height (D), quadrat diameter at breast height combined with tree height (D^2H), as well as D and H separately. Results showed that the mean aboveground biomass of *E. urophylla* was 143.9 ± 19.44 kg tree⁻¹. The highest biomass were noted in stem (80.06%), followed by bark (11.89%), branch (4.69%), and foliage (3.36%). The relative contribution of stem to total aboveground biomass improved with the increasing of diameter class while the opposite trend was recorded in bark, branch, and foliage. The equation $\ln \hat{Y} = \ln a + b \ln D$ was best and reliable for estimating the aboveground biomass of *E. urophylla* since it provided the highest accurate estimation (91.3%) and more practical than other models. Referring to these findings, this study concluded the use of allometric equation was reliable to support more efficient forest mensuration in *E. urophylla* plantation.

Keywords: forest mensuration, accurate quantification, eucalyptus, industry development, climate change

*Correspondence author, email: pandu.yudha.a.p@ugm.ac.id, tel. +62-274-548815, fax. +62-274-54881

Introduction

Integration of industry development and climate change mitigation currently become the most priority issue of eucalyptus plantation management, particularly in tropical countries such as Indonesia, Vietnam, and Brazil (Wirabuana et al., 2019). In this context, the existence of eucalyptus plantation is not only expected to stabilize timber supply for industry but also to reduce greenhouse gas emissions in the atmosphere (Sanquetta et al., 2018). However, the meaningful contribution of eucalyptus plantation for those objectives generally varies in each site depending on its biomass production. Many literatures confirm higher biomass accumulation indicates greater contribution of plantation forest in maintaining industry viability and reducing carbon emissions (Pirralho et al., 2014; Nunes et al., 2019; Wirabuana et al., 2020). It signifies the availability information about biomass is importantly required to understand the important contribution of eucalyptus plantation for industry sustainability and climate change

alleviation.

The accurate quantification of forest attributes, mainly related to biomass are basically determined by the precise measurement at the individual tree level (Altanzagas et al., 2019). The higher precision of the individual tree measurement will generate better accuracy in calculating stand attributes (St-Onge & Grandin, 2019). Thus, the activity of forest mensuration using destructive method is commonly conducted to obtain more accurate data from individual trees (Goussanou et al., 2016). Nevertheless, the implementation of forest inventory using destructive approach requires high cost and is time consuming (Wardhana et al., 2020). This method is also not relevant to conduct in compartments which dominated by young trees since it has a potential to decline the regeneration capacity (Duncanson et al., 2015). In contrast, the information are necessary to forest managers as the basis of planning determination, especially regarding to yield regulation. The data of forest biomass are also helpful to compute the

capacity of forest for carbon absorption that frequently used as one of the indicators in forest certification. Therefore, developing allometric equations is necessary to facilitate the estimation of timber production, biomass accumulation, and carbon storage in eucalyptus plantation.

Some references have evidenced the use of allometric equation is reliable to conduct the accurate estimation of individual tree parameters (Nugroho, 2014; Manuri et al., 2016; Zhao et al., 2019). For example, in Brazilian plantation forests, the use of allometric equations provides a good accuracy to estimate aboveground biomass of *E. grandis* (Ribeiro et al., 2015). The similar outcomes are also reported from Spain, in which the utilization of allometric models is helpful to obtain the accurate quantification of above and belowground biomass in *E. globulus* (Vega-Nieva et al., 2015). Moreover, the reliability of allometric models for estimating biomass in every component and total of eucalyptus tree has been also reported in Indonesia. For example, a study from commercial eucalyptus plantation in South Sumatra reveals that the usage of allometric equations provides an accuracy more than 70% for quantifying aboveground biomass in every component of *E. pellita* (Inail et al., 2019). Another study conducted in natural forest in East Nusa Tenggara also reports the accuracy of biomass estimation in *E. urophylla* using allometric models reached 86.3% (Almulqu et al., 2019). These explanations verify that the development of allometric equations has a potential to contribution to facilitating more efficient forest mensuration, primarily in eucalyptus plantation.

Several studies explain the accuracy of allometric models as a proxy approach to estimate individual tree parameters has certain limitations since those equations are developed based on the growth performance of tree species in the surveyed area (Forrester et al., 2017; Altanzagas et al., 2019; Daba & Soromessa, 2019). In this context, the different plant species, site condition, type of forest, and silviculture treatment will influence the reliability of allometric models for resulting the accurate estimation (Roxburgh et al., 2015). A study from Khangai, Mongolia, have evidenced the different species will generate a specific form of allometric models in which each equation has diverse accuracy in predicting biomass from various species (Altanzagas et al., 2019). Another study from community forests in Madiun also records the adoption of allometric equations from other location provides lower accuracy for estimating total individual tree biomass than the best models generated in study site (Wirabuana et al., 2020). These examples confirm that there are some limitations to apply allometric equations for estimating tree biomass.

This study aims to develop allometric equations for estimating aboveground biomass of *E. urophylla* that managed by KPH Timor Tengah Selatan. It was designed to support more efficient forest mensuration in the context of industry development and climate change mitigation. Compared to the previous studies related to the development of allometric models for predicting *E. urophylla* biomass in East Nusa Tenggara (Marimpan, 2010; Almulqu et al., 2019), our study has several different aspects. First, this study was carried out in plantation forest with monoculture species while both previous studies were undertaken in natural forest with mixed plant species. Second, the stand attributes of *E.*

urophylla in this study was relatively homogenous reviewed from age of stand, spacing, and silviculture regime while the previous studies had heterogenous stand condition. Third, this study used more number of tree samples for developing allometric equations than both previous studies. At the end, the specific objectives of our study are 1) to quantify aboveground biomass in every component and total of *E. urophylla*, 2) to assess the relative contribution of every tree component to total aboveground biomass of *E. urophylla*, and 3) to formulate the best allometric models for estimating total aboveground biomass of *E. urophylla*.

Methods

Study area This study was conducted in *E. urophylla* plantation, managed by KPH Timor Tengah Selatan. It is situated in Timor Tengah Selatan District, approximately 180 km at the Northeastern Kupang, the capital city of East Nusa Tenggara Provinces. The study site has a geographic position in S9°50'0" to S9°50'15" and E124°15'30" to E124°16'0" (Figure 1). It has total area of *E. urophylla* plantation around 250 ha which is distributed in 2 different villages, i.e. Buat and Fatukoto. However, the area of *E. urophylla* plantation is divided into 3 compartments referring to the planting time, i.e. Buat 1982 (75 ha), Fatukoto 1983 (100 ha), and Fatukoto 1997 (25 ha). In every site, the initial planting density is relatively equal (1,333 tree ha⁻¹) even though there is a different planting periods. The treatment of fertilization, thinning, and pruning were never conducted in each area since at the beginning those compartments were managed as protected forest.

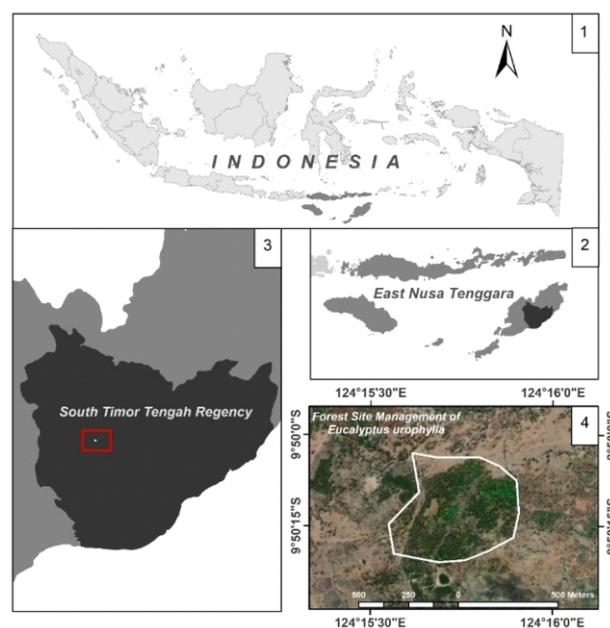


Figure 1 The study site of *E. urophylla* plantation managed by KPH Timor Tengah Selatan. The white polygon demonstrated the primary compartments of *E. urophylla* plantation which designed as a commercial plantation forest.

Altitude varies from 800 to 1,000 m above sea level. Topography is relatively gradient with slope level ranging from 15 to 45%. Soil type is dominated by cambisol which has high phosphorus content and great cation exchange capacity (Table 1). This area is classified into humid condition with the mean air humidity around 85.5%. The average daily temperature is 29 °C with a minimum of 23 °C and a maximum of 30 °C. The annual rainfall varied from 1,500 to 3,000 mm year⁻¹ during the past ten years from 2010 to 2019. Most rainfall occurs from November to January with the highest rainfall is recorded in January. Dry periods is noted for 7 months from March to September (Kalima et al., 2019).

At the preliminary periods, before converted into *E. urophylla* plantation, the study location was a bare land without trees vegetation. The land cover was predominantly by *Imperata cylindrica*. Starting from 1980s, the local government implemented forest and land rehabilitation program by selecting *E. urophylla* as the primary species for reforestation. Besides having rapid growth, *E. urophylla* is also a native species from this site. This effort was continuously conducted until the late of 2016 without having an economic objectives. However, since 2017, after initiating the development of KPH Timor Tengah Selatan and considering the economic values of *E. urophylla*, the aims of management has been transformed into commercial plantation forest for encouraging the effort of economic development in rural area (Sadono et al., 2020).

Data collection 42 sample trees were selected for destructive sampling. The sample trees were determined by considering the diameter distribution to derive the balance growth dimension from small to big trees (Guendehou et al., 2012). In this study, we classified trees diameter into five different classes, i.e. 6–10 cm, 11–15 cm, 16–20 cm, 21–25 cm, and 26–30 cm (Altanzagas et al., 2019). The process of destructive sampling was conducted step by step in chronological manner. After the selected trees were cut down, their tree components were separated into stem, bark, branch, and foliage. The stem and bark were split since our study aimed to obtain more detail information about biomass in every tree component. However, before both component was separated, the wood volume of every tree was calculated by Smalian method as shown in Equation [1].

$$V = \frac{\pi}{8} (D_L^2 + D_S^2) L \quad [1]$$

note: V was stem volume, D_L represented size of stem diameter at the large end, D_S indicated size of stem diameter at the small end, and L was the length of stem.

The fresh weight of every part was quantified using a hanging balance in the field. Then, 500 g sub-sample from each part was taken to the laboratory for drying (Wirabuana et al., 2019). The drying process was done using an oven at 70 °C for 48 hours before weighting for biomass calculation (Hakamada et al., 2017). Total biomass accumulation in every component of sample trees was determined by multiplying the ratio of dry-fresh weight from sub-sample with the total fresh-weight of each part which recorded from the field survey (Altanzagas et al., 2019). The outcomes of biomass calculation were used to count carbon storage within each component since almost 50% of biomass was composed by carbon element (Viera & Rodríguez-Soalleiro, 2019).

Data analysis Statistical analysis was carried out using R software version 4.0.2 with a significant level of 5% (R Core Team, 2017). The easyreg package was selected to support data analysis (Arnhold, 2018). Descriptive test was undertaken to identify several data attributes, i.e. minimum, maximum, mean, standard deviation, and standard error (Mishra et al., 2019). It was intended to demonstrate the results of destructive sampling for each observation parameters. The data normality was examined using Shapiro-Wilk test (Ghasemi & Zahediasl, 2012).

Data were divided into two groups to construct allometric models. The first group was used to develop equations (30 sample trees) while the second group was utilize to validate models (12 trees). In this study, three general allometric models were evaluated for predicting total aboveground biomass of *E. urophylla*. Several independent variables were selected to formulate equations, namely diameter at breast height (D), squared diameter at breast height combined with tree height (D^2H), as well as D and H separately (Xue et al., 2016; Altanzagas et al., 2019; Wirabuana et al., 2020). The measurement unit of D and H for each was cm and m. Both parameters were measured before tree felled. The measurement of D was conducted at 1.3 m from aboveground using diameter tape while the measurement of H was undertaken from aboveground to top crown using hagameter. Details of allometric equations were expressed in Equation [2], Equation [3], and Equation [4].

$$\hat{Y} = aD^b \quad [2]$$

Table 1 Soil chemical properties in the study site referring to the results of laboratory analysis for soil pH, soil organic carbon (SOC), total nitrogen (N), available phosphorus (P), total potassium (K), and cation exchange capacity (CEC)

Parameter	Unit	Estates		
		Buat 1982	Fatukoto 1983	Fatukoto 1997
pH	-	5.10	4.32	6.50
SOC	%	1.96	1.02	0.62
N	%	0.36	0.22	0.39
P	ppm	40.83	29.12	41.60
K	cmolc kg ⁻¹	1.10	0.51	0.59
CEC	cmolc kg ⁻¹	34.90	33.12	34.56

Source: Kurniadi & Pujiono (2009)

$$\hat{Y} = a(D^2H)^b \quad [3]$$

$$\hat{Y} = aD^bH^c \quad [4]$$

note: \hat{Y} was the estimated parameters and a, b, and c were the fitted parameters.

In general, the use of nonlinear tree growth models based on arithmetic units did not have constant error variance values over all observations in most cases (Altanzagas et al., 2019). It was commonly referred to as heteroscedasticity. To eliminate the influence of heteroscedasticity, the use of data transformation in natural log-form was conducted on a regular basis to change the nonlinear model into linear regression when quantifying parameters for equations (He et al., 2018). Therefore, Equation [2], Equation [3], and Equation [4] were converted into the models as shown in Equation [5], Equation [6], and Equation [7].

$$\ln\hat{Y} = \ln a + b \times \ln D \quad [5]$$

$$\ln\hat{Y} = \ln a + b \times \ln(D^2H) \quad [6]$$

$$\ln\hat{Y} = \ln a + b \times \ln D + c \times \ln H \quad [7]$$

note: $\ln\hat{Y}$ was the estimated values in the logarithmic unit and a, b, c, were the fitted parameters. The previous studies have been reported the similar method (log-transformed linear regression) for modeling tree characteristics (He et al., 2018; Altanzagas et al., 2019; Wirabuana et al., 2020). The antilog transformation of the estimated logarithmic values into arithmetic units leads to a systematic bias which could generally be corrected by the correction factor as shown in Equation [8] (Altanzagas et al., 2019).

$$CF = \exp\left(\frac{RMSE^2}{2}\right) \quad [8]$$

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

Six indicators were selected to evaluate the best allometric models, i.e. the significant of fitted parameters (a, b, c) had to be significant, adjusted coefficient of determination (R^2_{adj}), residual standard error (RSE), root mean square error (RMSE), mean absolute bias (MAB), akaike information criterion (AIC) (González-García et al., 2013; Ekoungoulou et al., 2015; Altanzagas et al., 2019). The indicator R^2_{adj} and RSE were used to evaluate the stage of model fitting while RMSE, MAB, and AIC were applied to examine the validation stage. The details formula for computing those statistical parameters were expressed in Equation [9], Equation [10], Equation [11], Equation [12], and Equation [13].

$$R^2_{adj} = 1 - \left[\frac{(1-R^2)(n-1)}{n-k-1} \right] \quad [9]$$

$$RSE = \sqrt{\frac{1}{n-2} \sum (\ln Y - \ln \hat{Y})^2} \quad [10]$$

$$RMSE = \sqrt{\sum (\ln Y - \ln \hat{Y})^2 / (n - p - 1)} \quad [11]$$

$$MAB = \sum (|\ln Y - \ln \hat{Y}|) / n \quad [12]$$

$$AIC = n \log \left(\frac{RSS}{n} \right) + 2k + \frac{2k(k+1)}{n-k-1} \quad [13]$$

note: \ln indicated the actual log-transformed parameters, $\ln Y$ was the estimated log-transformed parameters from the fitted model, n was the sample size, $\ln \hat{Y}$ was the mean actual log-transformed parameters, R^2 was coefficient determination, p was the number of terms in the model, RSS was the residual sum of squares from the fitted model, and k was the number of parameters. Furthermore, we also compared our best models with another allometric equations of *E. urophylla* from different locations in East Nusa Tenggara which are published by Almulqu et al. (2019). The previous research was implemented in natural forests of *E. urophylla* in Mutis Timau.

Results and Discussion

Stand characteristics Summarized results of the observation showed the average stem volume of *E. urophylla* in the surveyed area was $0.23 \pm 0.03 \text{ m}^3 \text{ tree}^{-1}$ with a mean diameter of $16.0 \pm 0.9 \text{ cm}$ and height of $23.8 \pm 1.0 \text{ m}$ (Table 2). The highest mean biomass was noted in stem ($118.76 \pm 16.91 \text{ kg}$), followed by bark ($13.02 \pm 1.26 \text{ kg}$), branch ($2.37 \pm 0.79 \text{ kg}$), and foliage ($2.77 \pm 0.51 \text{ kg}$). The similar pattern was also observed in the distribution of carbon storage in every tree component (Table 3). This trend was frequently found since carbon was the main component of biomass (Viera & Rodríguez-Soalleiro, 2019). This study also realized more than 70% of total aboveground biomass were accumulated in stem (Table 4). It was consistently similar to other previous studies which reported from eucalyptus plantation at different forest regions (Ribeiro et al., 2015; Vega-Nieva et al., 2015; Tesfaye et al., 2020). The distribution of biomass in stem was considerably higher than other components because it is the main tree component in supporting translocation process and maintaining tree stability.

This study observed the allocation of total aboveground biomass into tree components along diameter class indicated that stem had the greatest accumulation approximately 70–82% (Table 4). Interestingly, the trend of biomass distribution in every part was relatively different across the increasing diameter classes. The relative contribution of bark and foliage biomass slightly declined from the smallest-diameter class to the largest one. In contrast, the biomass allocation in stem and branch improved with the increasing diameter classes. These findings verified there was a strong relationship between the dimension size of tree diameter with the process of biomass distribution. It was equal to the previous studies which focused on biomass distribution within trees (He et al., 2018; Altanzagas et al., 2019; Wirabuana et al., 2020). The percentage of branch and foliage biomass declined with the increment of tree diameter indicated that relatively more biomass was allocated to the trunk (stem + bark) for improving the growth and accelerating the translocation process (Wirabuana et al., 2020).

Allometric equations for estimating aboveground biomass The results clearly presented that every allometric equations had good fit ($p < 0.05$) (Table 5). Surprisingly, the best allometric equations for estimating total aboveground

Tabel 2 Minimum (min), maximum (max), average (mean), standard deviation (SD), and standard error (SE) of wood volume, aboveground biomass, and carbon storage in *Eucalyptus urophylla* at the sampling location

Parameter	Unit	Min	Max	Mean	SD	SE
<i>Individual tree dimension</i>						
Diameter	cm	6.8	25.9	16.0	4.7	0.9
Height	m	13.4	34.4	23.8	5.3	1.0
Volume	m ³ tree ⁻¹	0.02	0.72	0.23	0.17	0.03
<i>Aboveground biomass allocation</i>						
Stem	kg tree ⁻¹	12.68	411.94	118.76	92.65	16.91
Bark	kg tree ⁻¹	1.28	31.16	13.02	6.90	1.26
Branch	kg tree ⁻¹	0.53	78.62	7.88	14.43	2.63
Foliage	kg tree ⁻¹	0.45	11.19	4.23	2.77	0.51
Total	kg tree ⁻¹	14.93	430.73	143.90	106.50	19.44
<i>Carbon storage distribution</i>						
Stem	kg tree ⁻¹	3.80	123.58	35.63	27.79	5.07
Bark	kg tree ⁻¹	0.38	9.35	3.91	2.07	0.38
Branch	kg tree ⁻¹	0.16	23.59	2.37	4.33	0.79
Foliage	kg tree ⁻¹	0.13	3.36	1.27	0.83	0.15
Total	kg tree ⁻¹	4.48	129.22	43.17	31.95	5.83

Tabel 3 Relative contribution of every tree component namely stem, bark, branch, and foliage into total carbon storage in *Eucalyptus urophylla* at the surveyed area

Tree component	Relative contribution to carbon storage (%)				
	Min	Max	Mean	SD	SE
Stem	50.43	95.64	80.06	9.15	1.67
Bark	2.27	45.82	11.89	7.90	1.44
Branch	1.16	20.70	4.69	3.67	0.67
Foliage	0.93	9.16	3.36	1.66	0.30

Tabel 4 Biomass distribution in every tree component (Mean SD) across the diameter classes of *Eucalyptus urophylla*

Diameter class (cm)	Stem/AGB		Bark/AGB		Branch/AGB		Foliage/AGB	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
< 10	71.17	13.91	19.93	13.77	4.59	2.42	4.31	3.00
11–15	82.12	7.91	11.42	5.59	3.61	2.33	2.85	1.13
15–20	82.70	4.50	8.93	2.25	5.09	5.05	3.28	1.18
21–25	81.59	9.94	10.26	5.92	4.90	3.01	3.25	1.20
> 26	80.73	6.47	7.81	3.45	8.32	1.26	3.14	0.78

Note: Data were presented in percentage

biomass *E. urophylla* was $\ln \hat{Y} = \ln a + b \cdot \ln D$. This models showed an accurate estimation up to 91.3%. It verified the best selected model could explain the growth variation of *E. urophylla* in the study area, specifically related to total aboveground biomass. Our finding was relatively different with other previous studies about allometric models of *E. urophylla* in East Nusa Tenggara which conducted in natural forest (Marimpan, 2010; Almulqu et al., 2019).

This study also found there were similar pattern of biomass estimation using our best models with another model from the previous study of *E. urophylla* in natural

forest at Mutis Timau, East Nusa Tenggara (Almulqu et al., 2019) (Figure 2). However, the value of estimated biomass from our model was considerably lower than allometric equations from Almulqu et al. (2019). It verified that our best model was only reliable to estimate aboveground biomass of *E. urophylla* in plantation forest while the model resulted by Almulqu et al. (2019) was only relevant to be used in natural forest of *E. urophylla*. This fact confirmed that the utilization of allometric equations for estimating tree biomass had limitations, such as type of forest, stand characteristics, management practice, and number of sample for destructive

Table 5 Summary statistics of every allometric models for estimating aboveground biomass of *E. urophylla* plantation in East Nusa Tenggara

Response variable	Equations**	lna	b	c	R ² _{adj}	RSE	RMSE	MAB	AIC	CF
AGB	$\ln \hat{Y} = \ln a + b \cdot \ln D$	-0.751*	2.016*	-	0.913	0.517	0.499	0.353	-1.323	1.132
	$\ln \hat{Y} = \ln a + b \cdot \ln(D^2H)$	5.211*	0.757 ^{ns}	-	0.946	0.500	0.483	0.337	-1.387	1.123
	$\ln \hat{Y} = \ln a + b \cdot \ln D + c \cdot \ln H$	-5.182*	-0.534*	3.619 ^{ns}	0.967	0.480	0.455	0.321	-1.441	1.109

Note: ** indicated that the *p*-value for all models was < 0.05; * signified the *p*-value of fitted parameters was < 0.05; ^{ns} verified the *p*-value of fitted parameters was > 0.05

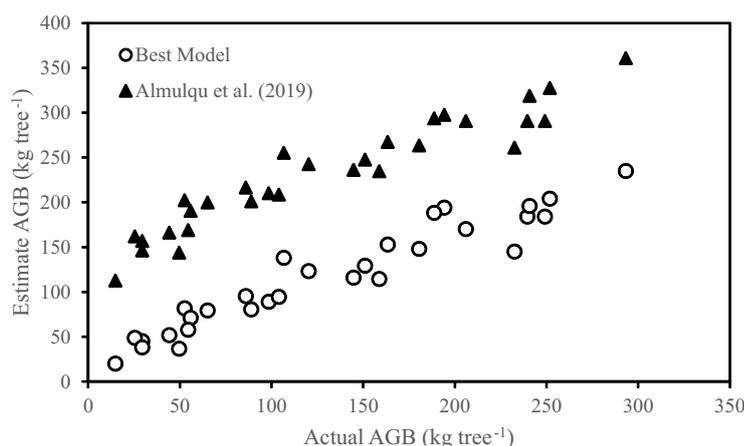


Figure 2 Comparison between the estimated total aboveground biomass using best model and other equations from previous studies at different site.

method (Altanzagas et al., 2019).

Referring to the results, our study realized the use of allometric models with single independent variable, $\ln \hat{Y} = \ln a + b \cdot \ln D$ had enough accuracy to estimate total aboveground biomass in *E. urophylla*. The additional of tree height as predictor variable in the equations provided more accurate estimation around 2–3%, but the coefficient was not significant. Therefore, it would be better to use only diameter at breast height as predictor variable. In addition to its more simplicity, this parameter was relatively easier to be measured in forest inventory than tree height. Nevertheless, the allometric models constructed in this study had certain regional limitation since these models were developed based on the growth performance of *E. urophylla* stand in this site. Therefore, the model need further validation test to be used in the other regions, including other *E. urophylla* plantations.

Conclusion

The biomass distribution of *E. urophylla* in the surveyed area is highly varied in which most biomass were recorded in tree stem, followed by bark, branch, and foliage. The relative contribution of stem and bark to total aboveground biomass increased following the diameter class increment, while the dissimilar pattern was discovered in branch and foliage. The equation $\ln \hat{Y} = \ln a + b \cdot \ln D$ was reliable for estimating total aboveground biomass of *E. urophylla*. Those models provided good accuracy until 91.3% and had potential contribution to facilitating the more efficiency of forest inventory in *E. urophylla* plantations. We suggested to adopt these allometric equations for supporting sustainable eucalyptus plantation management at the study site.

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