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Allometric Equation for Estimating Energy Production of *Eucalyptus urophylla* in Dryland Ecosystems at East Nusa Tenggara

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Abstract

A precise and accurate energy production quantification, particularly at the individual tree level is needed to understand the potential contribution of eucalyptus plantations to renewable energy development. However, measuring energy storage with a destructive method is inefficient because it requires a large amount of resources. The development of allometric equations is a realistic solution to solve this problem as it facilitates the efficient estimation of energy production from trees. Therefore, this study aims to develop an allometric equation for estimating the energy production of Eucalyptus urophylla in dryland ecosystems in East Nusa Tenggara. The destructive sampling was carried out on 25 sample trees which are evenly distributed from small to large dimensions, while the calorific value of each tree component was analyzed using the bomb calorimeter method. Furthermore, the energy production of each tree was counted by multiplying the calorific value with the total biomass accumulation. To develop an allometric equation, the analysis of regression was applied using several independent variables, such as diameter at breast height (D), combined squared diameter of breast and tree height (D^2H), as well as D and H separately. The results showed that the energy production of E. urophylla at the study site varied from 252.56 to 7,813.30 MJ tree^{-1} with more than 90% accumulated in the stem, followed by foliage (4.62%) and branches (4.05%). The higher the tree dimension, the greater the energy production. Moreover, the equation $ln\hat{Y} = lna + b.lnD + c.lnH$ was the best allometric model to estimate energy production with an accuracy of 95.2%. Based on the results, the allometric equation provides an accurate estimation of energy production in E. urophylla.

Keywords: *accurate estimation, biomass, bomb calorimeter, calorific value, renewable energy*

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Introduction

The management of eucalyptus plantations for supporting renewable energy development is of great concern in tropical countries, including Indonesia. This scheme, aside from providing good opportunities for industry development, has a positive impact on reducing greenhouse gas emissions in the atmosphere (Cavalett et al., 2018). According to several studies, the use of eucalyptus for bioenergy produces fewer carbon emissions than fossil fuels such as coal, petroleum, and gas (Leslie et al., 2012; Birdsey et al., 2018; Cavalett et al., 2018). Moreover, the energy production is also relatively high by approximately 1,011.73–1,175.90 Gcal ha^{-1} (Simetti et al., 2018). This indicates that the existence of eucalyptus plantations has a prospective role in facilitating renewable energy development that is environmentally friendly.

In practice, the management of eucalyptus plantation for bioenergy requires accurate quantification of energy storage as the basis to determine the best strategy of yield regulation (Romanelli et al., 2012). However, the measurement of energy storage at the individual tree level using the destructive method is expensive, time-consuming, and almost impossible to conduct in the overall area of planted forest as it negatively influences regeneration capacity (Mulyana et al., 2020). To solve these problems, the development of an allometric equation is an alternative solution for facilitating the more efficient estimation of energy storage in eucalyptus plantations.

The allometric equation is an approximate method commonly developed to quantify the biomass accumulation and carbon stock in a forest ecosystem, primarily at the individual tree level (Krejza et al., 2017; Wirabuana et al., 2020; Karyati et al., 2021). Several studies reported that this method has good accuracy for estimating the biomass and carbon of tree species in various forest ecosystems (Altanzagas et al., 2019; Romero et al., 2020; Sadono et al., 2021b). In the context of energy estimation at the eucalyptus plantation, the allometric equation potentially supports a more efficient measurement since the energy stock of the tree is stored in its biomass. Furthermore, the energy storage of

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trees naturally comes from the solar energy that is absorbed through photosynthesis (Ellison et al., 2017) and then converted to biomass as the net primary productivity of plants (Robakowski et al., 2018). Therefore, several studies reported that the energy storage of a tree is determined based on the total calorific value of its biomass (Günther et al., 2012; González-García et al., 2016; Magnago et al., 2016; Simetti et al., 2018). This implies that an allometric equation is capable of supporting the quantification of energy storage in the eucalyptus tree. Hence, this study aims to develop the best applicable allometric equation for estimating the energy storage of *Eucalyptus urophylla* in dryland ecosystems in East Nusa Tenggara. *E. urophylla* is a native species from Indonesia that is naturally distributed in Timor Island, East Nusa Tenggara. This species has commonly been developed as a commercial plant in planted forests (Sadono et al., 2020). At the study site, the management of *E. urophylla* plantation is important to accelerate rural development primarily from economic sectors. However, the utilization of the plant in this area is still limited despite its high potential in supporting renewable energy development. In addition to its rapid growth, *E. urophylla* is harvested in an unusual short rotation of approximately 58 years (Carneiro et al., 2014; Van Bich et al., 2019; Cuong et al., 2020). This species is cultivated using coppice systems (Schwegman et al., 2018). Hence, it has a high potential to become an alternative species for supporting renewable energy. However, there is no allometric equation for facilitating the estimation of energy storage in *E. urophylla* in Indonesia. Therefore, the results from this study are expected to help the forest manager in quantifying the energy production of *E. urophylla* plantations in the study location.

Methods

Study site This study was conducted on an *E. urophylla* plantation managed by Timor Tengah Selatan Forest Management Unit (TTS-FMU), located approximately 180 km northeast of Kupang, the main city of East Nusa Tenggara Provinces. This area has geographic coordinates of S9°50′0″ to S9°50′15″ and E124°15′30″ to E124°16′0″ (Figure 1), while the topography is dominated by hilly terrain with a slope level ranging from 15 to 45%. Moreover, the altitude reaches 800 m asl (Almulqu et al., 2019), while the area is classified as humid, with an average air humidity of 85.5% and a daily average temperature of 29 °C. The annual rainfall varies from 2,300 mm year^{-1} to 2,800 mm year^{-1} from 2016 to 2020 (Kalima et al., 2019), while the soil type is categorized into cambisol with a high cation exchange capacity and rich phosphorus content (Sadono et al., 2021a).

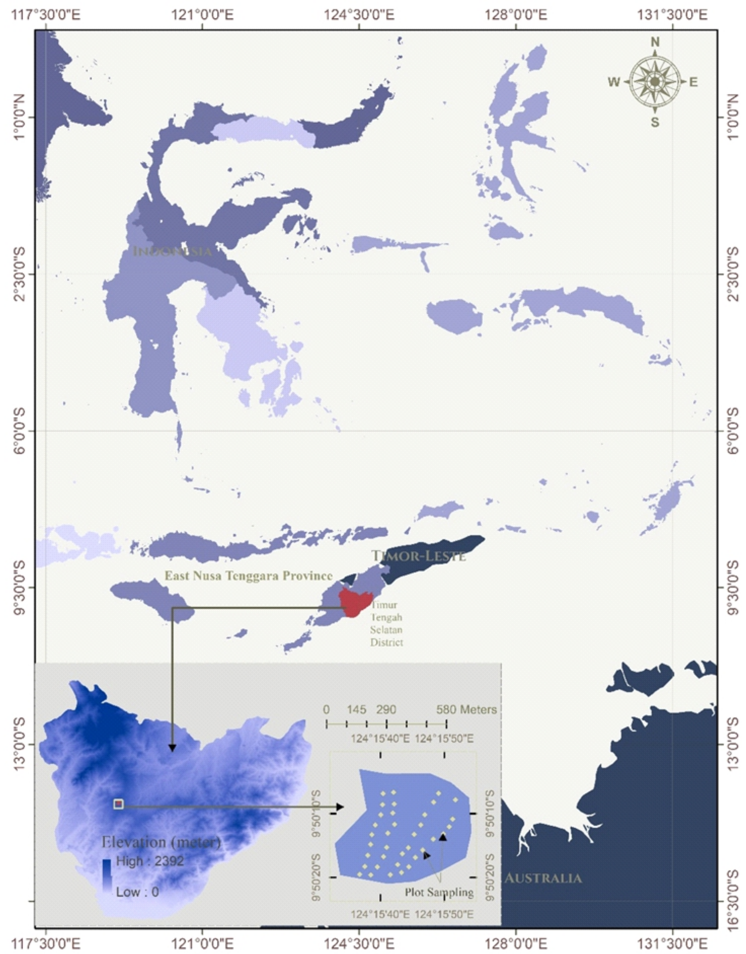

Figure 1 The study location of *Eucalyptus urophylla* plantation in Timor Tengah Selatan Forest Management Unit. The circle indicates sampling plots for forest inventory.

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Data collection The data collection is a further part of a multi-year study on *E. urophylla* in East Nusa Tenggara by Sadono et al. (2021b). The biomass above sea level was quantified using an allometric model, while this study aims to explore the allometric equation capacity in quantifying energy storage of *E. urophylla*. Therefore, the analysis of energy content was carried out on the biomass sample taken from the previous study.

Data collection was carried out stepwise in a chronological manner, and consequently, from the 42 sub-sample, only 25 were used for energy analysis due to the limited resources available. The samples were determined based on the secondary information about the diameter distribution from the previous study and were implemented to obtain the representative sub-sample from the small trees to big ones (Guendehou et al., 2012). To support the energy content analysis, four diameter classes were used to classify the sub-sample, namely < 10 cm, 11–15 cm, 16–20 cm, and > 20 cm, while the energy content of the sub-sample biomass was analyzed using the bomb-calorimeter method (Ju et al., 2016). This process was implemented for every sub-sample of the tree components, including stem, branch, and foliage. Furthermore, the energy storage of tree components was quantified by multiplying total biomass and calorific value from each component *[1]* (González-García et al., 2016; Magnago et al., 2016; Simetti et al., 2018). To calculate the energy storage at the individual tree level, the energy storage from stem, branch, and foliage was summarized *[2]*. The detail equations were expressed as shown in Equation *[1]* and Equation *[2]*.

$$E_c = CV_c \cdot W_c \qquad [1]$$

$$E_p = E_s + E_b + E_f \qquad [2]$$

note: E_c = energy storage in every tree component (MJ), Cv_c = the calorific value from every tree component (MJ kg^{-1}), E_s, E_b, E_f = energy storage in stem, branch, and foliage (MJ), E_p= total energy storage at the individual tree level of *E. urophylla* (MJ tree^{-1}).

Data analysis Statistical analysis was carried out using R software version 4.0.3 with a significant level of 5%. The descriptive test was conducted to describe the data attributes, including minimum, maximum, mean, and standard deviation, while the normality of data was examined using the Shapiro-Wilk test. Furthermore, the scatter plot was used to demonstrate the relationship between the independent and dependent variables. In this context, the independent variables consisted of several tree parameters generally used to develop an allometric equation, including diameter at breast height (*D*), tree height (*H*), and squared diameter of both (D^2H) (Goussanou et al., 2016; Altanzagas et al., 2019; Romero et al., 2020; Wirabuana et al., 2020; Sadono et al., 2021b). Meanwhile, the dependent variable was the total energy storage at the individual tree level.

The allometric equations in this study were developed using regression analysis. Three general equations were evaluated to estimate the energy storage of *E. urophylla,* and the details for each model are presented as shown in Equation *[3]*, Equation *[4]*, and Equation *[5]*.

$$\hat{Y} = aD^b \qquad [3]$$

$$\hat{Y} = a(D^2H)^b \qquad [4]$$

$$\hat{Y} = aD^bH^c \qquad [5]$$

However, the use of non-linear models for developing allometric equations usually causes heteroscedasticity (Zeng & Tang, 2012; Dong et al., 2018; Altanzagas et al., 2019). To address this issue, several previous studies used natural log-form data transformation to convert the non-linear model into a linear equation when determining the fitted coefficient for each equation (He et al., 2018). Therefore, equations 3 to 5 were transformed into the models as shown in Equation *[5]*, Equation *[6]*, and Equation *[7]*.

$$ln\hat{Y} = lna + b\ lnD \qquad [5]$$

$$ln\hat{Y} = lna + b\ lnD \qquad [6]$$

$$ln\hat{Y} = lna + b\ lnD + c\ lnH \qquad [7]$$

note: $ln\,Y$= the estimated value of energy storage in logarithmic unit; a,b,c = the fitted coefficient.

Nevertheless, some references state that systematic bias needs to be considered in converting the estimated logarithmic value to arithmetic units using an anti-log transformation. Therefore, the results are corrected by a correction factor determined using the formula as shown in Equation *[9]* (Xue et al., 2016).

$$CF = \exp\frac{(RMSE)^2}{2} \qquad [9]$$

note: *CF* = the value of correction factor, *RMSE* = the root mean square error from every allometric equation.

To determine the best allometric equation, seven important indicators were used, including the significant result of ANOVA test and the fitted coefficient (*a, b, c*), adjusted coefficient of determination (R^2_{adj}), 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; Sadono et al., 2021b). The criteria of the ANOVA test, fitted coefficient, R^2_{adj}, *RSE,* and *AIC* were used to evaluate the model fitting, while *MAB* and *RMSE* were used to examine the validation. Due to the small sample size, this study used the leave-one-out cross-validation method (LOOCV) (Altanzagas et al., 2019; Tetemke et al., 2019; Castillo-Santiago et al., 2010). The detailed formulas for calculating these indicators are demonstrated as shown in Equation *[10]* until Equation *[14]*.

$$R^2_{adj} = 1 - \left[\frac{(1-R^2)(n-1)}{n-k-1}\right] \qquad [10]$$

$$RSE = \sqrt{\frac{1}{n-2}\sum\left(lnY - ln\hat{Y}\right)^2} \qquad [11]$$

$$AIC = n\log\left(\frac{RSS}{n}\right) + 2k + \frac{2k + (k+1)}{n-k-1} \qquad [12]$$

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$$RMSE = \sqrt{\sum_{i=1}^{n}\left(lnY - ln\hat{Y}\right)^2 / (n-p-1)} \qquad [13]$$

$$MAB = \sum_{1}^{n}\frac{\left(\left|lnY - ln\hat{Y}\right|\right)}{n} \qquad [14]$$

note: lnY = the actual log-transformed energy storage at the individual tree level, $ln\hat{Y}$ = the estimated energy storage of *E. urophylla* from the allometric equation, *n* = the sample size, *p* = the number of terms in the model, R^2 = the coefficient of determination from the fitted model, *RSS* = the residual sum of squares from the fitted model, *k* = the number of independent variables.

The best allometric equation for estimating energy storage of *E. urophylla* needs to indicate the significant result of ANOVA and fitted parameter test, the highest R^2_{adj}, and the lowest *RSE, AIC, MAB,* and RMSE. Furthermore, the extra sums of square method (ESS) was applied to assess the marginal reduction in error sum of squares (SSE) when an additional set of independent variables is added to the equation (Hector et al., 2016). This method aims to test whether the addition of *H* as the independent variable in the allometric equation significantly improves the accuracy estimation. An insignificant result indicates that the use of a single predictor in the allometric equation is more efficient to obtain a good accuracy for estimating the energy storage of *E. urophylla.*

Results and Discussion

Distribution energy The results showed that the energy storage of *E. urophylla* at the individual tree level varies depending on the size of the tree dimension. The mean in the study location was 2,357.9 MJ tree^{-1} with a minimum of 252.6 MJ tree^{-1} and a maximum of 7,813.3 MJ tree^{-1} (Table 1). Furthermore, the majority of energy storage was accumulated in the stem with 91.33%, followed by foliage with 4.62% and branch 4.05% (Table 2), while the relative contribution of tree components to total energy storage showed a fluctuating trend across the diameter classes (Table 3). For example, the relative contribution of the stem to total energy storage gradually increased from the small diameter of < 10 cm to the medium size of 1620 cm but declined at the biggest diameter of > 20 cm. Meanwhile, the relative contribution of the branch and foliage components to total energy storage generally declined along with the increasing diameter. At the diameter class of 11–15 cm, the relative contribution of branch was slightly higher than foliage. These findings indicate that the percentage of energy distribution in *E. urophylla* extremely varies in the individual trees.

Previous studies reported that the energy storage in trees generally has a linear relationship with biomass accumulation (Wang et al., 2017; Yu et al., 2019; Kumar et al., 2020). Higher tree biomass indicates greater energy production (Simetti et al., 2018), given that trees naturally convert solar energy into biomass through the photosynthesis process as an autotroph organism (Ellison et al., 2017).

Table 1 Summary statistics of tree dimension and energy storage from sample trees

Statistic parameters	*D* (cm)	*H* (m)	*SE* (MJ)	*BE* (M)	*FE* (MJ)	*TE* (MJ)
Mean	16.0	23.8	2192.4	72.8	92.7	2357.9
SD	4.7	5.3	1710.1	49.1	60.2	1768.4
Min	6.8	13.4	232.7	9.7	10.2	252.6
Max	25.9	34.4	7635.2	177.8	243.4	7813.3

Note: *D* = diameter at breast height; *H* = tree height; *SE* = stem energy; *BE* = branch energy; *FE* = foliage energy; *TE* = total energy

Table 2 The relative contribution of tree component on total energy in *Eucalyptus urophylla*

Tree component	Relative contribution to energy storage (%)			
	Mean	SD	Min	Max
Stem	91.33	4.67	74.61	97.72
Branch	4.05	2.62	0.50	11.16
Foliage	4.62	2.46	1.12	14.24

Note: *D* = diameter at breast height; *H* = tree height; *SE* = stem energy; *BE* = branch energy; *FE* = foliage energy; *TE* = total energy

Table 3 Distribution of energy storage in each tree component across the diameter classes of *Eucalyptus urophylla*

Diameter class (cm)	SE/TE		BE/TE		FE/TE	
	Mean	SD	Mean	SD	Mean	SD
< 10	87.99	7.27	5.63	2.93	6.38	4.47
11–15	92.11	4.13	4.05	2.77	3.84	1.61
16–20	92.51	2.71	3.17	1.77	4.32	1.51
> 20	91.25	5.14	4.35	3.79	4.40	1.56

Note: *D* = diameter at breast height; *H* = tree height; *SE* = stem energy; *BE* = branch energy; *FE* = foliage energy; *TE* = total energy

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Therefore, the pattern of energy distribution is similar to biomass partitioning in every tree component. Consequently, most of the energy storage in E. urophylla was found in the stem, given that this component plays an essential role in maintaining tree stability and supporting the translocation process (Wirabuana et al., 2021). Hence, highly effective and efficient translocation generates better growth for *E. urophylla*, primarily at the site with low availability of resources.

Allometric equations for estimating energy storage There was a non-linear relationship between independent and dependent variables used to develop allometric equations (Figure 2). This indicates that the use of breast height (*D*), tree height (*H*), and squared diameter of both (D^2H) has the potential to become a predictor for estimating total energy storage of *E. urophylla* in the study site. Furthermore, based on the statistical analysis results, all the allometric equations demonstrated a good fit (Table 4). More than 90% of the variations in the energy storage were explained using the allometric models. The results also indicate that the use of allometric equations is reliable in estimating the energy storage of *E. urophylla* with high accuracy.

Based on the ESS test results, the addition of *H* as a predictor variable in allometric equations significantly improves accuracy prediction than the use of *D* as a single predictor (Table 5). This is consistent with other studies which stated that the application of multiple independent variables (*D* and *H*) tends to reduce the bias estimation compared to the single (*D*) (Ribeiro et al., 2015; Chen et al., 2017; Altanzagas et al., 2019). Therefore, the best allometric equation for estimating energy storage of *E. urophylla* at the study site is $ln\hat{Y} = lna + b.lnD + c.lnH$ as it showed an accuracy estimation of approximately 95.2%.

This model does not disturb forest regeneration and also supports the measurement of energy storage in different periods since it was constructed using independent variables that generally represent tree attributes, including energy storage. However, a further validation test is required to use this model in *E. urophylla* plantation in other regions since the site quality influences bias estimation.

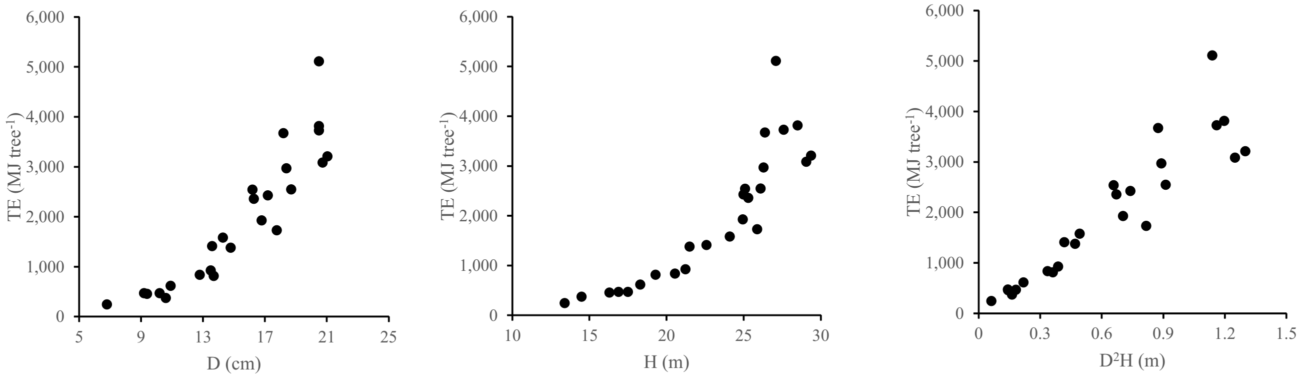

Figure 2 The relationship between independent and dependent variables for developing allometric models.

Table 4 Statistics evaluation of all allometric equations for estimating the total energy storage of *Eucalyptus urophylla*

Equations**	lna*	b*	c*	R^2adj	RSE	AIC	MAB	RMSE	CF
$ln\hat{Y} = lna + b.lnD$	-0.073	2.735		0.930	0.233	2.111	0.208	0.248	1.031
$ln\hat{Y} = lna + b.ln(D^2H)$	8.013	1.014		0.945	0.206	-4.214	0.184	0.219	1.024
$ln\hat{Y} = lna + b.lnD + c.lnH$	-2.786	1.114	2.274	0.952	0.196	-5.648	0.165	0.207	1.022

Note: ** indicated that *p*-value for all allometric models were < 0.05; * signified the *p*-value of fitted coefficient were < 0.05; R^2adj = adjusted determination coefficient; RSE = residual standard error; AIC = akaike information criterion; MAB = mean absolute bias; RMSE = root mean square error; CF = correction factor

Table 5 Statistic evaluation of extra sums of square among three allometric equations

Equations	Res. Df	RSS	Df	Sum of Sq	F	Pr (> F)
$ln\hat{Y} = lna + b.lnD$	23	1.253				
$ln\hat{Y} = lna + b.ln(D^2H)$	23	0.973	0.000	0.280	-	-
$ln\hat{Y} = lna + b.lnD$	23	1.253				
$ln\hat{Y} = lna + b.lnD + c.lnH$	22	0.848	1	0.405	10.505	0.004**
$ln\hat{Y} = lna + b.ln(D^2H)$	23	0.973				
$ln\hat{Y} = lna + b.lnD + c.lnH$	22	0.848	1	0.125	3.239	0.086

Note: ** indicated the addition of predictor variable provided a meaningful influence to improve the accuracy estimation; Res. Df = residual degree of freedom; RSS = residual sum of squares; Df = degree of freedom

Conclusion

Based on the results, the distribution of energy storage in all the tree components of *E. urophylla* relatively varies with the majority found in the stem. Furthermore, the use of allometric equations provides a significant and accurate estimation of energy storage at the individual tree level of *E. urophylla,* while $ln\hat{Y} = lna + b.lnD + c.lnH$ is the best allometric equation at the study site with an accuracy of 95.2%.

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