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COMPETITION INFLUENCES TREE DIMENSION, BIOMASS DISTRIBUTION, AND LEAF AREA INDEX OF *EUCALYPTUS UROPHYLLA* IN DRYLAND ECOSYSTEMS AT EAST NUSA TENGGARA

SUMMARY

Competition is one of the important factors that determine the productivity of forest stands. However, the effect of competition on the growth dynamics at the individual tree level is rarely documented. This study investigated the influence of competition on the tree dimension, biomass, distribution, and leaf area index (LAI) of *Eucalyptus urophylla* established in dryland ecosystems in East Nusa Tenggara. Data collection was conducted by N-tree sampling method with the number of center points reaching 36 units. The competition among trees was quantified using Hegyi index. Several parameters were measured to describe tree characteristics, including diameter, height, aboveground biomass, and LAI. The results demonstrated a significant influence of competition on the tree dimension, biomass distribution, and LAI of *E. urophylla*. The individual tree performance declined along with the increase in competition. By contrast, the increased competition gradually improved the relative contribution of branch biomass to the total aboveground biomass. The exponential model best described the linkage between competition and the tree characteristics of *E. urophylla* in the study site. Referring to these findings, this study concluded that the growth dynamics of *E. urophylla* at the individual tree level in dryland ecosystems is substantially influenced by competition.

Keywords: Growth Dynamics, Hegyi index, N-trees Sampling, *Eucalyptus urophylla*, Leaf Area Index

INTRODUCTION

Understanding the growth dynamics at the individual tree level is principally required to optimize the activity of stand management, particularly in

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commercial plantation forests (Cao, 2014). Every tree has a different growth performance depending on its adaptability to the environmental condition, mainly for obtaining resources, such as light, water, and nutrients (Craine and Dybzinski, 2013). However, the availability of resources in forest ecosystems is relatively limited (Álvarez-Yépiz *et al.*, 2017). Thus, trees should compete with each other to derive adequate resources for supporting their growth process (Lamonica *et al.*, 2020). Trees having good adaptability will show superior performance, whereas weak trees will die naturally or exhibit inferior growth (Rozendaal *et al.*, 2020). This condition directly confirms that the distributions of tree dimensions at the stand level are unequal although they were established at a similar time period. The information about tree growth variation is generally used as a basic consideration to determine the best silviculture prescriptions for improving the productivity of plantation forests.

The occurrence of competition in forest ecosystems is a natural mechanism that plays an essential role in biogeochemical cycle (Andrés, 2019). A study reported that an intense competition will construct a high dense canopy (Looney *et al.*, 2016) and potentially increase the ability of forests for carbon absorption (Farrior *et al.*, 2013). A dense canopy also provides an important contribution to creating a micro-climate condition under the forest stand (Arx *et al.*, 2013). Another study reported that a dense canopy has the potential to minimize rainfall kinetic energy into a forest floor that causes run-off and erosion (Li *et al.*, 2019). The competition among trees is also one of the primary factors that influence the litter quantity in forest ecosystems wherein a high competition improves the rate of canopy litterfall (Silver *et al.*, 2014). This condition indicates an indirect linkage between tree competition and nutrient dynamics in forests.

Despite providing ecological benefits, the occurrence of competition among trees should be controlled intensively because it has a negative effect on forest productivity, which is primarily related to the economic aspect (Forrester *et al.*, 2013). A high competition substantially increases the mortality rate at the stand level (Das *et al.*, 2011, Ruiz-Benito *et al.*, 2013, Wang *et al.*, 2017, Maringer *et al.*, 2021). A high competition also decreases the production of merchantable wood from forest ecosystems (Bembenek *et al.*, 2014). In addition, an increased intense competition has the potential to inhibit stand growth due to the low availability of resources for trees (Yang *et al.*, 2019). Therefore, most forest managers commonly undertake thinning and pruning activities to reduce the competition level (Keyser and Zarnoch, 2012; Nogueira *et al.*, 2015; Filho *et al.*, 2018). These explanations demonstrate that the availability of information about competition is exceptionally required to support the implementation of sustainable forest management, particularly in plantation forests.

Several references explain that the study of competition in forest ecosystems is immensely specific given that every tree species has a variety of tolerance to competition (Kunstler *et al.*, 2012, Barabás *et al.*, 2016, Fichtner *et al.*, 2017). Moreover, the level of competition in forests is influenced by site quality and intensity of maintenance (Moreno-Fernández *et al.*, 2014, Zhang *et* *al.*, 2016). In another word, the different types of forest and management strategies will result in different competition rates. This study investigated the influence of competition on individual tree performance of *Eucalyptus urophylla* S.T. Blake established in dryland ecosystems in East Nusa Tenggara. As one of the fast-growing species, *E. urophylla* is a native species from Indonesia and is commercially developed in several countries, such as Vietnam and China. However, the study on the competition of *E. urophylla* is rarely documented, particularly from Indonesia. This study aimed to assess the influence of nearest-neighbor competition on the tree dimensions, biomass distribution, and leaf area index (LAI) of *E. urophylla*.

MATERIAL AND METHODS

The study location is situated in an *E. urophylla* plantation which is developed for dryland ecosystems in East Nusa Tenggara. This area is located in Timor Tengah Selatan District, around 180 km at the northeastern Kupang, the capital city of East Nusa Tenggara Provinces. The geographic coordinates of the research site are in S9°50′0″ to S9°50′15″ and E124°15′30″ to E124°16′0″ (Figure 1). The total area of *E. urophylla* plantation in this location is 25 ha and managed by Timor Tengah Selatan Forest Management Unit. In the initial periods, before being converted into an *E. urophylla* plantation, the vegetation cover in this area was dominated by Imperata cylindrica (Sadono *et al.*, 2020). In 1997, the local government conducted reforestation using *E. urophylla* as the primary species for rehabilitation. In addition to having a rapid growth, *E. urophylla* is a native species from this location (Almulqu *et al.*, 2019). Therefore, the implementation of reforestation is also expected to support conservation for indigenous species from East Nusa Tenggara.

The study site has an altitude of 800 m above sea level. Topography is dominated by a hilly area with a slope level of 15%. The soil type is classified as cambisol with a high cation exchange capacity and rich phosphorus content (Table 1). This location is categorized into a humid condition with an average air humidity of around 85.5%. The mean daily temperature is 29°C. Annual rainfall ranges from 1,300 mm year^{-1} to 1,800 mm year^{-1} during the past five years from 2016 to 2020. The highest rainfall occurs in January. The study site has dry periods for 7 months from March to September.

Data collection was undertaken by a field inventory using N-trees sampling method. In this sampling technique, the process of tree measurement was conducted at the nearest trees from the center point (Mirzaei and Eslam, 2016). The principle of this method is similar to the point-centered quarter method, which is frequently used in ecological surveys, primarily for tree vegetation (Haxtema *et al.*, 2012).

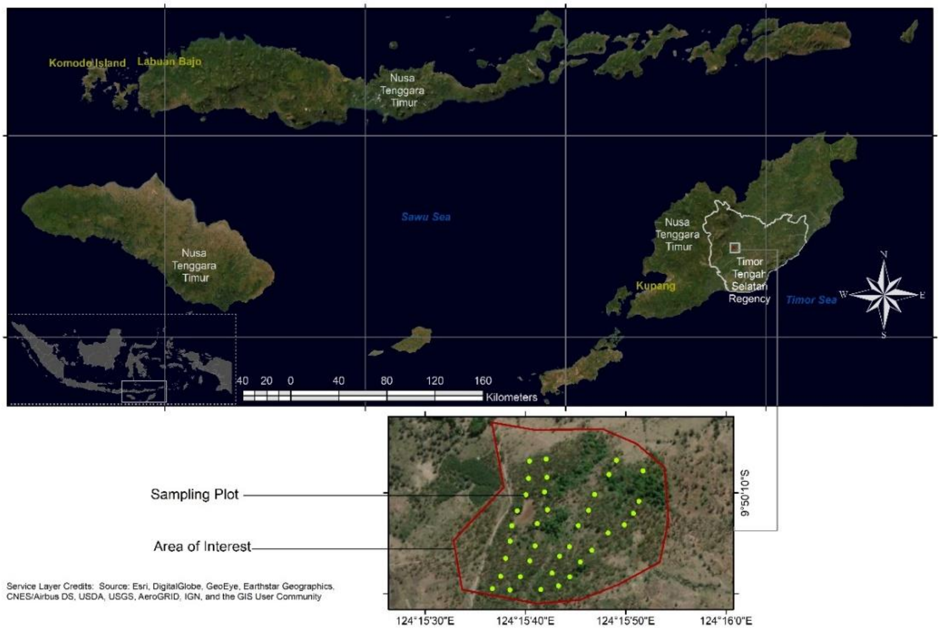

Figure 1. Study location of *E. urophylla* plantation managed by Timor Tengah Selatan Forest Management Unit. The red polygon indicates the border compartment of *E. urophylla* stand, which is allocated as a limited production forest. The green point signifies the coordinate of sampling plots quantified from the subject tree

Table 1. Soil characteristics of the study location based on the acidity level, soil organic carbon, total nitrogen, available phosphorus, exchangeable potassium, and cation exchange capacity

Soil parameter	*Symbol*	*Units*	*Value*
Soil acidity	pH H_2O	-	6.24±0.59
Soil organic carbon	SOC	%	0.84±0.35
Total nitrogen	TN	%	0.59±0.39
Available phosphorus	Av-P	ppm	41.79±0.68
Exchangeable potassium	Exc-K	cmolc(+) kg^{-1}	0.70±0.46
Cation exchange capacity	CEC	cmolc(+) kg^{-1}	34.51±0.59

However, the numbers of sample trees from both methods were considerably different. The use of N-tree sampling method involved six sample trees, whereas the use of point-centered quarter method measured four sample trees (Silva *et al.*, 2017).

In this study, the main subject tree was positioned as the center point, whereas the competing trees were assumed as the nearest-neighbor trees (Figure 2). The total subject trees observed in this study were 36 trees with an average distance of 50 m between subject trees.

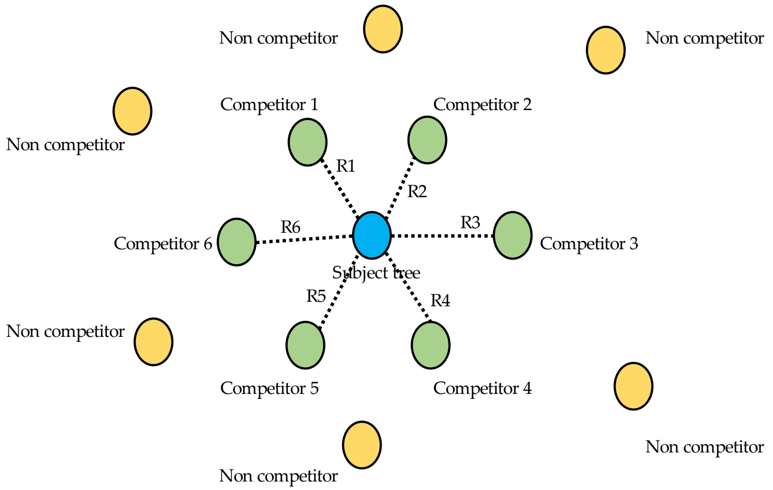

Figure 2. Illustration of N-tree sampling method for the quantification of tree characteristics and competition among trees in the *E. urophylla* plantation. The blue circle indicates the subject tree as the main focus of research, whereas the green circles show the competing trees. The yellow circles show the non-competitor trees, and R_n represents the distance between the subject tree and competing trees

Several parameters were quantified from each subject tree, i.e., diameter, height, aboveground biomass, and LAI. For competitor trees, the parameter measurement was focused on diameter and distance between each competing tree with the subject tree. The diameter of every tree was measured using a diameter tape at 1.3 m from aboveground. The distance between the subject tree and competing trees was quantified by a laser distance meter. The tree height was estimated from the aboveground to the top crown by a Haglof vertex. The biomass distribution from every subject tree was estimated at aboveground in each component (stem, branch, and foliage) using allometric equations (Table 2). Meanwhile, the LAI was quantified by hemispherical photography. To facilitate this stage, we obtained the crown photograph using the Nikon Camera with a fish-eye lens (FC-08).

For every subject tree, the collection of crown image was conducted at four different positions (Figure 3) (Rody *et al.*, 2014). This measurement was implemented to increase the accuracy of crown image analysis, which was processed by Hemisfer software version 3.1. To obtain a more stable image, we supported the camera by a tripod set up at 1 m from the aboveground (Hakamada *et al.*, 2016). All images were analyzed alternately. Then, LAI of subject tree was determined based on the mean value of LAI from four photographs.

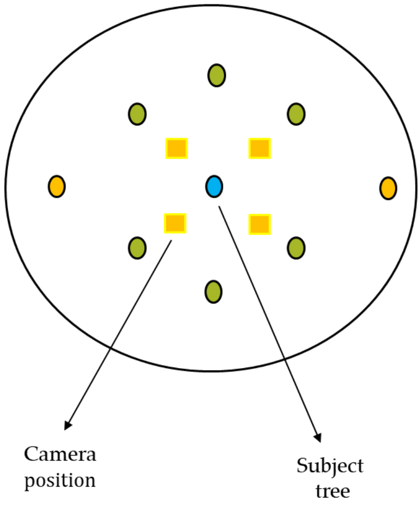

Figure 3. Camera positions for capturing the crown image of every subject tree. The blue circle is a subject tree, whereas the yellow square indicates the camera position. The green circle shows the competing trees, there the orange circle represents the non-competitor trees.

Table 2. Allometric equations for estimating biomass accumulation in the stem, branch, and foliage of *E. urophylla* in dryland ecosystems in East Nusa Tenggara. The symbol "Y" indicates the sum of biomass in the tree component, whereas "D" represents the tree diameter as a predictor variable

Tree component	*Equations*	R^2	*AIC*	*RMSE*
Stem	Y = 0.035 + 0.008D	0.95	−135.27	0.014
Branch	Y = −0.016 + 0.003D	0.44	−121.83	0.021
Foliage	Y = 0.0002 + 0.001D	0.85	−201.74	0.002

Source: Almulqu et al. (2019)

In this study, the competition between the subject tree and competitor trees was estimated by Hegyi index (McTague and Weiskittel, 2016). This parameter is commonly used to calculate the competition level among trees in various forest ecosystems (Ledermann and Stage, 2001, Das *et al.*, 2011, Fraver *et al.*, 2014, Kang *et al.*, 2017). The Hegyi index was selected to quantify the competition given that it is simpler than the other parameters, wherein the competition between the subject tree and competitor trees was calculated based on their diameter and distance (Maleki *et al.*, 2015). The mathematical formula for Hegyi index is expressed below:

$$CI_H = \sum_{j=1}^{n} \left[\frac{\left(\frac{d_j}{d_i}\right)}{R_{ij}} \right] \quad (1)$$

where CI_H is the Hegyi index, d_j indicates the diameter of competitor tree *j* (cm), d_i represents the diameter of subject tree *i* (cm), R_{ij} shows the distance between the subject tree *i* and competitor tree *j* (m), and n refers to the number of trees included in the quantification process (excluding subject tree). Then, the outcomes of Hegyi index were categorized into three classes to describe the competition level, namely, low (CI_H < 0.5), moderate (0.5 ≤ CI_H ≤ 1.0), and high (1.0 > CI_H).

Statistical analysis was applied with a significant level of 5%. A descriptive test was conducted to identify the data attributes, including the minimum, maximum, mean, and standard deviation. The normality of data was tested using Shapiro–Wilk test. The homogeneity of variance among competition level was evaluated by Bartlett's test. Comparison averages of individual tree dimension, aboveground biomass, and LAI in *E. urophylla* among the competition classes were examined using analysis of variance (ANOVA) and followed by honestly significant difference (HSD) Tukey's. Moreover, the analysis of regression was applied to identify the relationship between competition and individual tree characteristics. Three different models were tested in this stage, namely, linear, power, and exponential. The detailed equation for every model is demonstrated below:

$$Y = a + bX \tag{2}$$

$$Y = aX^b \tag{3}$$

$$Y = ae^{bX} \tag{4}$$

where Y indicates the individual tree characteristics (diameter, height, aboveground biomass, and LAI), a and b are the fitted parameters, e demonstrates an Euler's number (2.71828), and X shows the Hegyi index. Several indicators were used to determine the best model, i.e., the significant result of ANOVA test, the significant result of fitted parameters test (a and b), adjusted R squared (R^2 adj), residual standard error (RSE), akaike information criterion (AIC), mean absolute bias (MAB), and normalized root mean square error (NRMSE).

The indicators of ANOVA test in fitted parameters test, namely, R^2 adj, RSE, and AIC, were used to examine the model fitting. Meanwhile, MAB and NRMSE were applied to assess the validation test. The equations for calculating those parameters are presented below:

$$R^2\,adj = 1 - \left[\frac{(1 - R^2)(n - 1)}{n - k - 1}\right] \tag{5}$$

$$RSE = \sqrt{\frac{1}{n-2}\sum\nolimits_{i=1}^{n}\left(\Upsilon - \hat{\Upsilon}\right)^2} \tag{6}$$

$$AIC = n\log\left(\frac{RSS}{n}\right) + 2k + \frac{2k + (k+1)}{n-k-1} \tag{7}$$

$$MAB = \sum_{1}^{n}\frac{(\Upsilon - \hat{\Upsilon})}{n} \tag{8}$$

$$NRMSE = \frac{RMSE}{\theta} \tag{9}$$

where Υ is the actual tree characteristics obtained from field inventory, $\hat{\Upsilon}$ indicates the estimated tree parameters from the fitted model, n represents the sample size, k shows the number of parameters, R^2 is the coefficient of determination, RSS signifies the residual sum of squares from the fitted model, $RMSE$ is the root mean square error, and θ shows the mean observation value of the tree characteristics.

Given that the sample size was relatively small (36 trees), the validation test was conducted by the leave-one-out cross-validation method (LOOCV). LOOCV is frequently applied to regression analysis with a small sample size (Castillo-Santiago *et al.*, 2010, Altanzagas *et al.*, 2019, Tetemke *et al.*, 2019). The best model had to demonstrate the significant results of ANOVA and fitted parameter test, the highest R^2 adj, and the lowest RSE, AIC, MAB, and NRMSE.

RESULTS

The summarized observation results demonstrated that the competition level of *E. urophylla* in the study area relatively varied although these plants were developed in sites with similar qualities (Table 3). This study recorded that the majority of trees had a moderate competition level. The lowest value of Hegyi index obtained from the field survey was 0.39, whereas the highest value was 1.53. Compared with other competition levels, the total subject trees at the low competition level were considerably lower by approximately nine trees.

Table 3. Summary statistics of Hegyi index estimation in every competition level. Data are presented as the number of trees, minimum, maximum, mean, and standard deviation

Competition	CI_H	Number Of Tree	Min	Max	Mean	SD
Low	<0.5	9	0.39	0.49	0.43	0.03
Moderate	0.5-1.0	17	0.52	0.78	0.72	0.12
High	>1.0	10	1.08	1.53	1.27	0.15

Note: CI_H showed Hegyi index

The occurrence of competition indicates a significant effect on individual tree characteristics (Table 4). The high competition level substantially declined tree dimension, biomass accumulation, and LAI of *E. urophylla* in dryland ecosystems. A similar trend was also observed with the relative contribution of stem and foliage biomass to total aboveground biomass (Figure 4). By contrast, this study discovered that the relative contribution of branch biomass to the total aboveground biomass significantly improved along with the increase in the competition level.

Table 4. Comparison of the means of the individual tree characteristics in each competition class. Data are presented in diameter, height, biomass in each component, total aboveground biomass, and LAI

Parameter	*Competition level*			*P*
	Low	*Moderate*	*High*	
D (cm)	43.87 ± 9.84a	40.68 ± 6.45a	25.66 ± 5.00b	<0.001**
H (m)	40.94 ± 6.31a	37.86 ± 7.32a	23.55 ± 5.25b	<0.001**
SB (Mg)	1.46 ± 0.91a	1.15 ± 0.46a	0.35 ± 0.19b	<0.001**
BB (Mg)	0.29 ± 0.15a	0.23 ± 0.08a	0.08 ± 0.04b	<0.001**
FB (Mg)	0.04 ± 0.02a	0.04 ± 0.01a	0.01 ± 0.01b	<0.001**
AGB (Mg)	1.81 ± 1.43a	1.43 ± 0.56a	0.45 ± 0.25b	<0.001**
LAI	1.19 ± 0.20a	1.13 ± 0.15a	0.70 ± 0.17b	<0.001**

Note: D (diameter at breast height); H (tree height); SB (stem biomass); BB (branch biomass); FB (foliage biomass); AGB (total aboveground biomass); LAI (leaf area index)

Although they differed significantly, our study realized that the individual tree characteristics of *E. urophylla* at the low and moderate competition levels were statistically similar (Table 4). These findings were also followed by the relative contribution of every tree component to the total aboveground biomass (Figure 4).

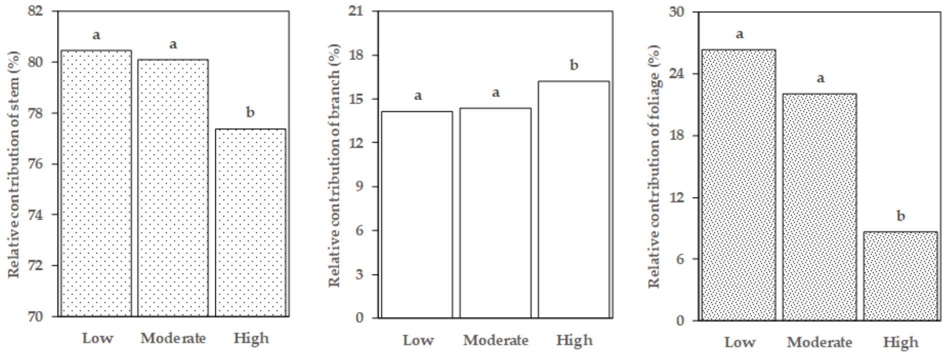

Figure 4. Comparison means of the relative contribution of biomass in every component (stem, branch, and foliage) to the total aboveground biomass of *E. urophylla* at the different competition levels; A similar letter above graph showed no significant different according to the honestly significant difference (HSD) Tukey’s

Table 5. Parameter estimates and model evaluation statistics of every equation for describing the relationship between the competition and individual tree characteristics of *E. urophylla* in dryland ecosystems in East Nusa Tenggara

Parameters	*Equations*	*a*	*b*	*R^2 adj*	*RSE*	*AIC*	*MAB*	*NRMSE*
D	$Y = a + bX$	57.480	−25.402	0.561	7.449	175.266	0.131	0.160
	$Y = aX^b$	29.740	−0.570	0.599	0.197	−6.488	0.045	0.053
	$Y = ae^{bX}$	**64.033**	**−0.738**	**0.626**	**0.190**	**−8.255**	**0.041**	**0.048**
H	$Y = a + bX$	54.191	−24.443	0.571	7.029	172.366	0.114	0.005
	$Y = aX^b$	27.356	-0.597	0.584	0.212	−2.671	0.045	0.053
	$Y= ae^{bX}$	**61.363**	**−0.778**	**0.620**	**0.203**	**−4.948**	**0.034**	**0.041**
AGB	$Y = a + bX$	3.298	−2.233	0.408	0.880	68.461	0.409	0.041
	$Y = aX^b$	0.726	−1.457	0.599	0.502	40.431	2.558	0.022
	$Y = ae^{bX}$	**5.150**	**−1.884**	**0.626**	**0.485**	**38.672**	**0.137**	**0.028**
LAI	$Y = a + bX$	1.568	−0.687	0.626	0.177	−11.803	0.204	0.227
	$Y = aX^b$	0.814	−0.578	0.596	0.200	−5.547	0.177	0.156
	$Y = ae^{bX}$	**1.779**	**−0.754**	**0.635**	**0.190**	**−8.083**	**0.115**	**0.209**

Note: D (diameter at breast height); H (tree height); AGB (total aboveground biomass); LAI (leaf area index); Bold equations indicate the best model for describing the relationship between competition and individual tree attributes; All models indicate the significance of ANOVA and fitted parameters.

Nevertheless, the growth performance of *E. urophylla* at a low competition level was higher than that at the moderate competition level by approximately 7%–22%. Meanwhile, the occurrence of high competition affected the loss of growth by around 16%–76%. At a high competition level, the relative contribution of branch biomass increased almost to 12.5% compared with the low and moderate competition levels.

The results demonstrated that every model provided a good fit to describe the linkage between the competition and tree characteristics of *E. urophylla* (Table 5). However, the use of exponential model indicated the best accuracy for explaining the effect of competition on individual tree dimension, biomass accumulation, and LAI in *E. urophylla*. This model can explain more than 60% of the growth variation in *E. urophylla*, which affected by competition levels (Figure 5). Moreover, the exponential model showed the lowest RSE, AIC, MAB, and NRMSE. These findings imply that the exponential model is more reliable and valid than the linear and power models in describing the relationship between competition level and individual tree characteristics of *E. urophylla*. According to the best model, the high competition significantly declined the individual tree dimension, total aboveground biomass, and LAI of *E. urophylla* in dryland ecosystems at East Nusa Tenggara.

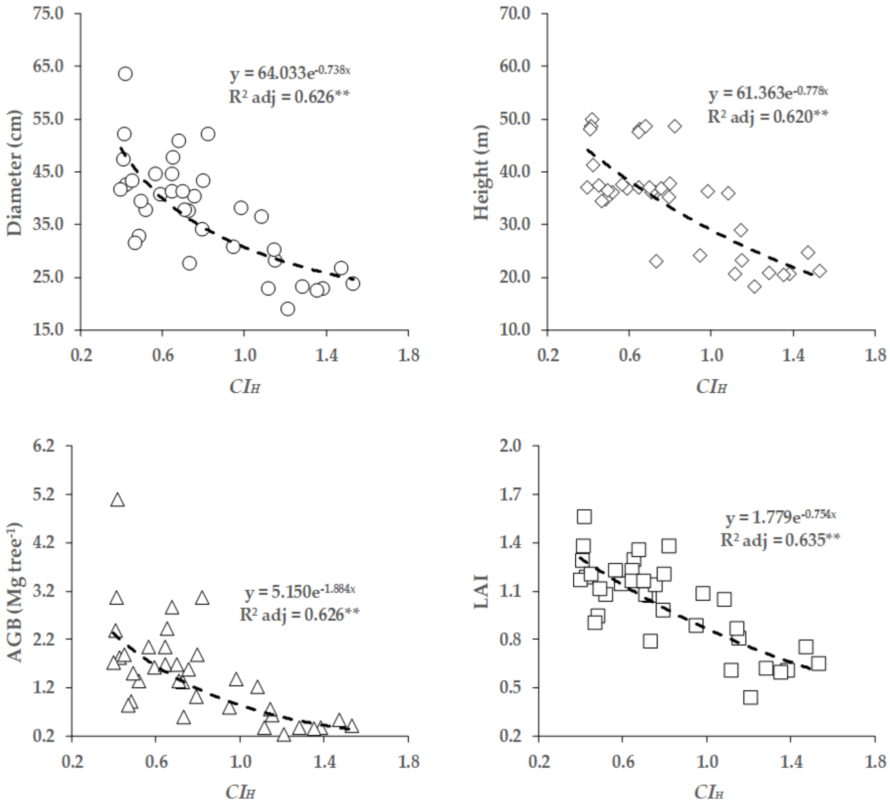

Figure 5. Scatter plots describing the pattern of relationship between competition and individual tree attributes, i.e. diameter, height, AGB (aboveground biomass), and LAI (leaf area index).

DISCUSSION

Competition among trees is a natural process that commonly in every type of forest ecosystem due to the limited availability of resources for supplying trees requirement. In general, two classifications of competition, including interspecific and intraspecific, transpire in forests (Skálová *et al.*, 2013). Interspecific competition occurs between individual trees from different species (Barabás *et al.*, 2016). This competition can be found in natural or mixed forests with multiple tree species. Meanwhile, intraspecific competition refers to the competition between individual trees from the same species (Yang *et al.*, 2019). This type of competition can be discovered in plantation forests with a monoculture species. The explanations showed that the primary focus of this study was to understand the intraspecific competition between E. urophylla trees developed in dryland ecosystems at East Nusa Tenggara.

The occurrence of intraspecific competition is generally more intense than interspecific competition (Saha *et al.*, 2014, Barabás *et al.*, 2016, Adler *et al.*, 2018, Yang *et al.*, 2019). Intraspecific competition normally occurs because individual trees have the same niche; as a result, trees are competing for exactly the same resources (Zhou *et al.*, 2018). This study showed that the level of competition between individual trees highly varied although they were planted at the same location. This circumstance can possibly occur given the gradient of biophysical characteristics in micro-site conditions. Our argument was also supported by the previous studies which reported a variety of soil fertilities in a compartment (Washitani and Tang, 1991, Gömöry *et al.*, 2011, Salekin *et al.*, 2019). Difference in soil fertility would provide the various resource supply for supporting tree growth. This statement was also emphasized by the description of the study site, in which the land configuration of the study location was dominated by hilly area. Thereby, the slope variation can influence the intensity of leaching and erosion in forest soil and cause the different soil fertilities in the site.

The growth performance of *E. urophylla* significantly declined along with the increased competition level. This finding was observed because at the high competition level, trees obtain smaller resources than at a lower competition (Forrester *et al.*, 2013). Consequently, the size of tree dimension, biomass production, and LAI were relatively lower than those of trees having low competition levels. Previous studies also reported similar outcomes to our findings, wherein a high competition considerably declined the growth performance of individual trees (Yan *et al.*, 2015, Resende *et al.*, 2018, Truax *et al.*, 2018). However, the increased competition improved the relative contribution of branch biomass to the total aboveground biomass, whereas a different trend was observed in stems and foliage. Survival during an intense competition is a natural mechanism of trees. As an explanation, the more intense the competition, a tree will expand its crown to obtain more light and space and to support this process, and branch development will occur more intensively than stems and foliage. This process explains why the relative contribution of branch biomass slightly increased along with the rising competition. However, a more intense competition accelerates the rate of canopy litterfall, thus stimulating natural pruning (Silva *et al.*, 2014). This condition confirms why the branch biomass significantly declined with the higher competition although a different pattern was recorded for its relative contribution to the total aboveground biomass.

CONCLUSIONS

This study concluded that the occurrence of competition significantly influences the individual tree characteristics of *E. urophylla* developed in dryland ecosystems in East Nusa Tenggara. A high competition substantially decreased the individual tree dimension, total aboveground biomass, and LAI of *E. urophylla*. The relative contribution of branch biomass to the total aboveground biomass significantly improved along with the increased competition level. The exponential model best described the relationship between the competition level and individual tree dimension.

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