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Growth performance of *Dipterocarpus alatus* and *Hopea odorata* in degraded secondary forest land in Southern Vietnam

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Abstract: The two dipterocarp species, *Dipterocarpus alatus* and *Hopea odorata*, have been widely planted in degraded forest land in Southern Vietnam in the last decades. However, study on growth characteristics of these species and their associated factors is still limited. Therefore, the present study aimed to examine growth performance in different stand densities, and classify tree quality in 28-year old *D. alatus* and *H. odorata* plantations. Our results of analysis of covariance (ANCOVA) indicated that in pure stand aged 28 years, *D. alatus* outperformed *H. odorata* in tree growth, biomass and volume. In addition, except for four growth variables including tree height at the first branch (Hb), crown length (CL), crown ratio (CR) and linear crown index (LCI), the remaining variables were negatively affected by stand density. We observed that medium quality trees occupied the greatest proportion in both *D. alatus* (47%; n = 425) and *H. odorata* (50%; n = 400). Except for CR and LCI, the class of good quality trees had the greatest values in the remaining examined growth variables. In linear discriminant analysis (LDA) model, the classification accuracy of testing set was relatively high in both *D. alatus* (85%) and *H. odorata* (91%). The most important variables for tree quality classification in *D. alatus* were crown diameter (CD) and diameter at breast height (DBH). Meanwhile, the most important variables in *H. odorata* were CD and tree height (H). These obtained results suggest that controlling crown size is important for shaping individual tree quality. Our data evidenced that *D. alatus* and *H. odorata* planted in Southern Vietnam with density equal or less than 500 trees per ha could yield high proportion of good and medium quality trees.

Keywords: Dipterocarpus species, indigenous trees, aboveground biomass, tree biosocial position, tree quality classification

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Introduction

Vietnam is located in the Southeast Asia, lying between latitudes 8°N and 23°N and it has a total land area of about 330,000 km^2. Over the last decades, forest resources in Vietnam considerably declined in terms of area and diversity (Salek & Sloup, 2012). For instance, percentage of forest cover in Vietnam decreased from 43% in 1943 to 27 % in 1990 (Vietnamese Government, 2001). Large-scale logging of primary forests and subsequent conversion of forests to agricultural lands are the main causes of forest degradation in Vietnam (Nguyen & Gilmour, 1999; De Jong et al., 2006). In this context, Vietnam has made several attempts in forestry policy and practices for forest restoration and management (McNamara et al., 2006). Noticeably, afforestation has been widely implemented to increase forest cover and products in the country (De Jong et al., 2006). With several forest plantation programs, the total forest area in Vietnam has stabilized and then increased. In 2013, for instance, Vietnam's forest cover reached 13.96 million ha which occupied about 40.96% of the country's total area (FAO, 2014).

Forest plantation plays an important role not only in forest restoration and environmental services (Brown, 1999; West, 2014) but also in meeting the global demand for wood products that could triple by 2050 (Hakamada et al., 2017). In Vietnam, forest owners have reforested their land with high quality native species (Tam, 2007; Dong et al., 2016) and/or fast-growing exotic species (Dong et al., 2014). Recently, reforestation efforts have focused on large-scale monoculture plantations of native species, such as *Dipterocarpus alatus, Hopea odorata* (Dipterocarpaceae), *Erythrophleum fordii* (Leguminosae), *Chukrasia tabularis*, *Toona surenii* (Meliaceae), *Canarium album* (Burseraceae), *Paulownia fortunei* (Scrophulariaceae), *Afzelia xylocarpa* and *Dalbergia* spp. (Nghia, 2000).

Dipterocarp is a plant family of large tree species distributed widely in the tropical rain forests of Southeast Asia (Suzuki et al., 2006) that is considered as the richest ecosystems in terms of structure and species diversity (Kenzo et al., 2011; Tam et al., 2014). In Southern Vietnam, forest plantations of two dipterocarp species, *Dipterocarpus alatus* and *Hopea odorata,* have been established in different scales since the early 1930s (Nghia, 2003). Although some dipterocarp species (e.g., *D. alatus* and *H. odorata,*) have been widely planted (Appanah & Weinland, 1993; Appanah & Turnbull, 1998), knowledge on their growth and associated factors remains limited (Sakai et al., 2014). Lack of knowledge on growth characteristics of dipterocarp species may lead to the failure in reforestation. For instance, plantation of *H. odorata* in some areas of Vietnam had failed because of inappropriateness in planting sites and silvicultural treatment (Tam, 2007).

Previous studies have concerned with growth performance of dipterocarp plantation in degraded forest lands but mostly focused on growth stage of less than 20 years (Hamzah et al., 2009). Little is known about growth characteristics of dipterocarp plantation in old stand. Among tree growth variables, tree biomass is an important metric for determining the carbon storage, forest yield and estimating flammable materials in forest fires (de-Miguel et al., 2014). Estimation of aboveground biomass (AGB) is essential for studying carbon stocks (Ketterings et al., 2001) and comparing structural and functional attributes of forest ecosystems (Brown, 2002). In the present study, we therefore aimed to (1) evaluate the growth characteristics and aboveground biomass of *D. alatus* and *H. odorata* plantations in different stand densities on degraded forest land and (2) determined relative importance of growth variables on tree quality classification.

Materials and methods

Study site and data collection

The study site is Chang Riec Historical and Cultural Forest in Tay Ninh province in the Southwest region of Vietnam. In 1990, two dipterocarp species, *H. odorata* and *D. alatus*, were purely planted with different stand densities. Specifically, each species was initially planted in 10-m rows × 2.5-m columns and 8-m rows × 2.5 m-columns that yielded of 400 and 500 trees per hectare, respectively. The planting site (11°35.13'N, 106°07.10'E) has mean altitude of 50 m. The study site has two distinct seasons, including the dry season from December to April and the rainy season from May to November. The mean annual temperature is about 26°C and mean annual humidity is about 80%. The mean annual precipitation is 1967 mm with the average number of rainy days of about 154 days (IBST, 2009). The soil in the study site is ferralsols developed from acid magma and old alluvia.

To evaluate the growth performance of *D. alatus* and *H. odorata* plantations, three plots (50 × 40 m each) were randomly established within each stand of different densities which was homogeneous in environmental conditions (e.g., slope, aspect, elevation and soil type). In total, 12 plots (3 plots × 2 initial stand densities × 2 species) were set up for measurement. In spring 2017, we surveyed and measured all trees in 12 plots. It is noting that the density in these plots was not the same as the initial planting density due to mortality. Since the planting time, there were no treatments and/or disasters (e.g., storms, wildfires) in the planting site, thus the decrease in stand density may be due to natural thinning. Mortality percentage of these 12 plots ranged from 17.5 to 28.0% with mean value of 23.4%. Mortality proportion of *H. odorata* (25.7%) was higher than that (21.0%) of *D. alatus* (Wilcoxon rank-sum test, *P*-value = 0.012). Meanwhile, mortality did not statistically differ between initial planting densities (*P*-value = 0.091). In this study, we used recent surveyed density as the variable in all statistical analyses. All trees within each plot were measured for total tree height (H), tree height at the first branch (Hb), diameter at breast height (DBH) and crown diameter (CD). The CD of a tree individual was measured as the greatest

Table 1. Criteria for tree quality classification

Quality class	Stem form	Crown shape	Sociological position	Plant health
The first-good	Straight	Symmetric fully developed	Upper	Good health
The second-medium	Slightly tortuous	Asymmetric fully developed or deformed fully developed	Medium	Medium health
The third-bad	Tortuous	Undeveloped, flattened	Lower	Poor health, insect pest attack, rotten stem

spread of crown projection. Tree height was measured using the Häglof Vertex Hypsometer and DBH was measured using diameter tape. Based on criteria of stem form, crown shape, sociological position and plant health (Kupka et al., 2018; Roik et al., 2018), the quality of all trees within plot was classified into three quality classes (Table 1).

Tree volume (V, m^3) was calculated using the following equation (Eq.1) (Ostadhashemi et al., 2014):

$$V = BA_{1.3} \times H \times f_{1.3} \quad (1)$$

in which V is stem volume (m^3), $BA_{1.3}$ is basal area at DBH (m^2), H is total tree height (m) and $f_{1.3}$ is form factor ($f_{1.3} = 0.5$).

The important structural variables in relation to tree crown are crown length (CL, m), crown projection area (CPA, m^2), crown ratio (CR), crown spread ratio (CSR), crown thickness index (CTI) and linear crown index (LCI) that were respectively calculated using Eq. 2, Eq. 3, Eq. 4, Eq. 5, Eq. 6 and Eq. 7 (Van Laar & Akça, 2007).

$$CL = H - Hb \quad (2)$$

$$CPA = CD^2 \frac{\pi}{4} \quad (3)$$

$$CR = \frac{CL}{H} \quad (4)$$

$$CSR = \frac{CD}{H} \quad (5)$$

$$CTI = \frac{CD}{CL} \quad (6)$$

$$LCI = \frac{CD}{DBH} \quad (7)$$

In each species, the average DBH value of trees in each forest plot was calculated. In each plot, we then selected 3 sample trees having DBH closest to its average DBH value for aboveground biomass (AGB) estimation. In spring 2017, the chosen trees were felled down and divided into branches, twigs, stem and foliage components, and then weighed on field. The total aboveground biomass was determined as the sum of the stems, branches and leaves weights.

Statistical analysis

Analysis of Covariance (ANCOVA) was used to examine the effect of species and stand density on tree growth and aboveground biomass. Furthermore, one-way ANOVA was employed to test the difference in growth variables between tree quality classes. We used Tukey's HSD as the post-hoc analysis to identify statistical differences among tree quality classes. Statistical significance in all analyses was determined at $\alpha = 0.05$.

In our study, Linear Discriminant Analysis (LDA) was employed for constructing tree quality classification model based on four growth variables including tree height (H), crown length (CL), diameter at breast height (DBH) and crown diameter (CD). These traits are easy to measure and have been used in previous work (Nigh & Love, 2004; Kaźmierczak & Zawieja, 2016). Our data were split in two subsets including a training set (60%) and a testing set (40%). The training set was used to fit the model and the testing set was used to evaluate the accuracy of the model. The LDA analysis was implemented using the package *MASS* (Venables & Ripley, 2002) in R version 3.6.2 (R Core Team, 2019).

Results

Growth and aboveground biomass of *D. alatus* and *H. odorata*

The average values of tree growth variables in the two species were described in the Supplementary Table S1. Except for crown spread ratio (CSR), crown thickness index (CTI) and linear crown index (LCI), the remaining 12 tree growth variables of *H. odorata* were significantly smaller than that of *D. alatus* (Table 2). For instance, *H. odorata* had about 4 cm and 0.11 m^3 smaller DBH and tree volume, respectively, compared with *D. alatus*. Regarding total biomass, *H. odorata* was 109.89 kg lower than that of *D. alatus*. In contrast, it appeared that LCI and CTI of *H. odorata* were respectively 3.72 and 0.04 greater than those of *D. alatus*, while CSR was not significantly different between these two species.

We found that crown length (CL), crown ratio (CR) and linear crown index (LCI) were not significantly affected by stand density while tree height at

Table 2. The effects of species and stand density on tree growth characteristics and aboveground biomass using analysis of covariance (ANCOVA)

Response variables	Coefficient estimates (SE); Eta-squared	
	Species (*H. odorata* compared with *D. alatus*)	Stand density
Diameter at breast height – DBH (cm)	−4.00 (0.35)***; 0.092	−0.04 (0.01)***; 0.044
Tree height – H (m)	−0.86 (0.06)***; 0.059	−0.01(0.001)***; 0.012
Tree height at first branch – Hb (m)	−0.19 (0.08)*; 0.004	0.01(0.001)**; 0.008
Crown diameter – CD (m)	−0.28 (0.06)***; 0.011	−0.004(0.001)***; 0.073
Crown length – CL (m)	−0.63 (0.08)***	
Crown projection area – CPA (m²)	−2.76 (0.55)***; 0.018	−0.10(0.01)***; 0.098
Crown ratio – CR	−1.82 (0.52)**	
Crown spread ratio – CSR		−0.07 (0.006)***
Crown thickness index – CTI	0.04 (0.01)***; 0.006	−0.001(0.0002)***; 0.043
Linear crown index – LCI	3.72 (0.27)***	
Foliage biomass (kg)	−10.20 (1.21)***; 0.28	−0.11 (0.02)***; 0.12
Branch biomass (kg)	−3.16 (1.33)*; 0.02	−0.16 (0.02)***; 0.19
Stem biomass (kg)	−96.53 (5.91)***; 0.53	−0.34 (0.09)**; 0.02
Total fresh biomass – AGB (kg)	−109.89 (6.74)***; 0.42	−0.61(0.11)***; 0.05
Tree volume – V (m³)	−0.110 (0.008)***; 0.12	−0.001 (0.0001)***; 0.05

* – $P < 0.05$; ** – $P < 0.01$; *** – $P < 0.001$.

the first branch (Hb) of both species increased with stand density. The remaining tree growth, biomass and volume variables of *D. alatus* and *H. odorata* significantly decreased with increasing stand density (Table 2). In both species, for instance, a one-unit (one tree) increase of stand density could result in a decrease of 0.04 cm and 0.001 m³ in DBH and tree volume, respectively.

In this study, we used eta-squared as a criterion to determine relative importance variables in ANCOVA model. Our results showed that the relative importance of two predictors (species and stand density) varied with examined variables. For DBH and tree volume, species variable showed higher eta-squared values (0.092 and 0.120, respectively) than that (0.044 and 0.05) of stand density. In contrast, for crown diameter, crown projection area and branch biomass, stand density had greater eta-squared values than that of species variable.

The medium quality class occupied the highest proportion in both *D. alatus* (47%; n = 425) and *H. odorata* (50%; n = 400). Using pooled data of both species, we found that the first class (good quality trees) had the greatest values, following by the second class (medium quality trees) for all examined growth and volume variables, except for CR and LCI (Table 3). We observed that crown ratio (CR) in all three classes was, on average, equal or greater than 0.47 and no statistical significance was found between them. Linear crown index (LCI) of the first quality class (0.23) was significantly smaller than that of the second (0.26) and third classes (0.26).

Tree quality classification

In each species, average values of four examined variables were not significantly different between training and testing sets (Supplementary Table S2). The LDA model showed that the first linear discriminant function (LD1) explained much percentage

Table 4. Linear discriminant functions

Predictor	Coefficient estimates of linear discriminants			
	D. alatus		*H. odorata*	
	LD1	LD2	LD1	LD2
DBH (cm)	0.165	0.303	0.17	0.28
Tree height (m)	0.009	0.518	0.50	−0.15
Crown diameter (m)	1.252	−1.682	1.51	−1.47
Crown length (m)	0.121	−0.312	−0.01	0.64
Percent of separation explained	97.7%	2.3%	98.5%	1.5%

LD1 and LD2 are the first and second linear discriminants in LDA model.

Table 3. Comparison of tree growth and volume variables among quality classes using pooled data of both species

Quality classes	Growth variables										
	DBH (cm)	H (m)	Hb (m)	V (m³)	CD (m)	CPA (m²)	CR	CSR	CTI	LCI	CL (m)
1st (n = 189)	28.3a	14.6a	7.5a	0.45a	6.5a	33.2a	0.48a	0.44a	1.0a	0.23b	7.1a
2nd (n = 441)	22.1b	13.7b	7.2b	0.27b	5.7b	25.4b	0.47a	0.41b	0.9b	0.26a	6.5b
3rd (n = 195)	16.8c	13.0c	6.7b	0.16c	4.3c	14.5c	0.48a	0.33c	0.7c	0.26a	6.2c

Different letters indicate statistical significance among quality classes. Tukey's HSD was used as post-hoc test. The 1st, 2nd and 3rd correspond to good, medium and bad quality classes, respectively.

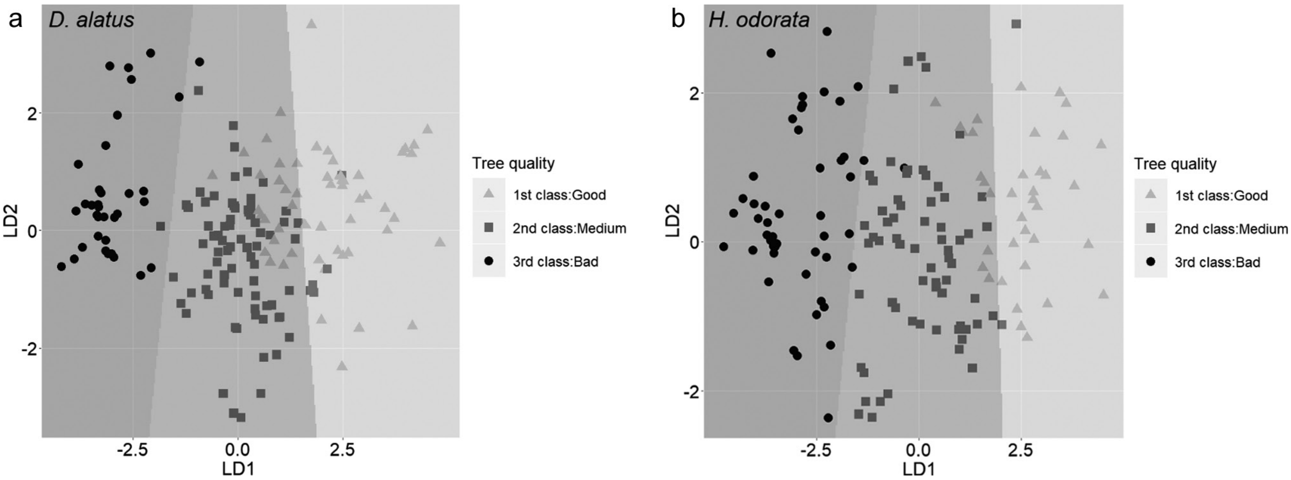

Fig. 1. Linear discrimination functions for tree quality classification in (a) *D. alatus,* and (b) *H. odorata*. Point shapes and shade regions indicate tree quality classes. Points show tree individuals in testing set

separation between tree quality classes in both *D. alatus* (97.7%) and *H. odorata* (98.5%). In *D. alatus*, the crown diameter, DBH and crown length had the highest contributions as indicated by their coefficients in LD1 for discriminating between quality classes (Table 4; Figure 1). In *H. odorata*, however, the most important variables in LD1 were crown diameter and tree height. Using four predictor variables, the LDA model of *D. alatus* performed relatively well with prediction accuracy of 87 and 85% in training and testing sets, respectively. Meanwhile, these accuracy numbers in LDA model of *H. odorata* were respectively 94 and 91%.

Discussions

Selection of the suitable species is necessary for successfully restoring degraded forests (Yousefi et al., 2013). On the contrary to the argument that dipterocarp species may not be suitable for rehabilitation of severely degraded lands (Appanah & Tumbull, 1998; Tolentino, 2008), our results demonstrated that *D. alatus* and *H. odorata* can be used for restoration of degraded forest land because they could have high proportion of good and medium quality trees (Table 3).

We compared our obtained results with previous work that studied *D. alatus* and *H. odorata* under different stand densities, ages, and planting techniques (Supplementary Table S3). Our result is consistent with the finding of Nghia (2003) who showed that *D. alatus* exhibited greater DBH and tree height than *H. odorata* in pure plantation (416 trees per ha) in Southern Vietnam. Furthermore, we found that *D. alatus* had higher values in other tree growth variables (i.e., Hb, CD, CL, CPA and CR), aboveground biomass and tree volume. Thus, our data provided evidence that in pure stand, *D. alatus* may outperform *H. odorata* in tree growth.

Several studies have shown that tree growth could be affected by stand density in dipterocarp (Rahman et al., 2016) and other species (Navarro et al., 2010; Jaouadi et al., 2018; Nguyen et al., 2019). In accordance with previous work, we observed that stand density negatively affected DBH in both *D. alatus* and *H. odorata* (Nghia, 2003; Hong et al., 2012). In Southern Vietnam, for instance, Nghia (2003) showed that DBH of *D. alatus* at age 17 years was about 22.4 and 17.2 cm in stand density of 416 and 1000 trees per ha, respectively. Meanwhile, DBH of *H. odorata* at age 18 years was 18.7 and 14.6 cm in stand density of 1100 and 2500 trees per ha, respectively (Table S3).

The effect of stand density on tree height is often modest (Nguyen et al., 2019; Jiang et al., 2007). For instance, Hong et al. (2012) found no significant effect of stand density on tree height in *D. alatus* and *H. odorata* in 9-year old stand. In our study, however, tree height tended to slightly decrease with increasing stand density in both species in 28-year old stands. This inconsistency in the obtained result between our study and Hong et al. (2012) could be attributed to the difference in age and environmental conditions. Our finding is supported by Nghia (2003) who observed a slightly greater height of *H. odorata* in stand density of 1100 trees per ha, compared with that in density of 2500 trees per ha. Noticeably, tree height at the first branch (Hb) was positively affected by stand density. Branches may greatly compete for light under high density condition, whereby increasing natural branch pruning and thus increasing tree height at the first branch.

We found that stem occupied the highest proportion of biomass in *H. odorata* (76.01%; equivalent to 256 kg per tree) and *D. alatus* (79.61%; 346 kg per tree). The biomass contributions of branches and leaves in *H. odorata* were 15.74 and 8.25%, respectively. Meanwhile, these numbers in *D. alatus* were

12.14 and 8.25%, respectively. Our obtained results were in accordance with other work indicating the greatest contribution of stem biomass to above ground biomass. For instance, in 19-year old *D. alatus* stand with density of 2425 trees per ha, Peawsa-ad and Viriyabuncha (2002) showed that biomass in stem, branches and leaves was 47.01, 8.94 and 2.35 kg, respectively. Kusno et al. (2012) reported that in *H. odorata* stand of 1350 trees per ha at age 11 years, biomass of stem, branches and leaves was 82.69, 6.12, 2.95 kg, respectively. In our study, a greater individual tree biomass was observed in lower density stand for both *D. alatus* and *H. odorata*. This result may be owing to severe competition for nutrient and light in high density stand.

It has been argued that tree biosocial position could be highly correlated with tree traits and can affect tree growth and development (Tomczak, 2013). Previous studies have attempted to classify tree biosocial position (Kaźmierczak & Zawieja, 2016). In our study, we focused on tree quality classification using LDA analysis with four tree variables including DBH, tree height, crown diameter and crown length. Our LDA models indicated that crown diameter was the most important variable in the first linear discriminant function (LD1) for determining tree quality class in both *D. alatus* and *H. odorata*. This result supported the finding of Kaźmierczak and Zawieja (2016) who showed that tree crown size highly influenced tree biosocial and quality. Crown size may affect light capture capacity and photosynthesis process (Choi et al., 2001; Kaźmierczak & Zawieja, 2016), by which influencing tree growth and quality. The LDA model had a high classification accuracy for testing set in both *D. alatus* (85%) and *H. odorata* (91%), suggesting that the model can be used to determine tree quality of these species.

Conclusions

The present study provides evidence that both species, *D. alatus* and *H. odorata*, planted with density equal or less than 500 trees per ha could yield high proportion of good and medium quality trees at age of 28 years in Southern Vietnam. Tree growth variables and biomass can vary with species and stand density. Our study suggests that controlling crown development is important for shaping individual tree quality.

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