MODELLING DIAMETER INCREMENT OF NATURAL FOREST STATE III IN FOUR PROVINCES IN THE CENTRAL REGION, VIETNAM

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SUMMARY

The data from 12 permanent sample plots (PSPs) were collected in 2005, 2012 and 2013 in four provinces Ha Tinh, Thua Thien Hue, Binh Dinh and Khanh Hoa. Each plot has an area of one ha (100 m x 100 m). All trees equal to or larger than 6 cm diameter at breast height ($DBH \geq 6$ cm) were identified by species, their diameter was measured at 1.3 m. The data from 12 plots were used to model the periodic annual diameter increment for individual important tree species in each province and four important tree species which occurred in all or at least in three provinces. The response variable was the periodic annual diameter increment. The results illustrate that only one predictor, $lnDBH_{2005}$, to be a significant regression model for about 47.1% to 75% important species in each province. With the remaining important species, a simple, namely constant growth model $ADI_k = \exp(\beta_0 + \varepsilon_k)$ was sufficient. The most frequently negative logarithmic relationship between initial diameter (DBH_{2005}) and the periodic annual diameter increment implies that data are from stands, where the maximum growth rates occur for trees of lower diameter classes. Linear mixed effects models with plots as random effects on intercepts and slopes were chosen for the four important species *S. wightianum*, *G. subaequelis*, *D. sylvatica*, and *N. melliferum*, which occurred in at least three of the four provinces. The explained variance by the random plot effects varied from 85.09% to 90.02%.

Keywords: Diameter increment, fixed-effects model, linear mixed effects models, species group, tropical rainforests.

I. INTRODUCTION

Forest models play a crucial role in forest management and as such are an essential key to developing long-term strategies for management and ensuring resource sustainability. They assist forest managers in planning forests, evaluating silvicultural options for sustainable timber yield, and reducing damage. Many diverse forest models have been developed by researchers in order to account for uneven and even-aged trees and stand tables; each model has its own unique technique to accommodate specific locations and tree species. Forest models are produced by a combination of several models, e.g., diameter or basal area increment, recruitment, and mortality; furthermore, they are developed by different techniques. For example, Vanclay (1989) used non-linear regression techniques to present a growth model for uneven -aged

monospecific stands of *Cypress Pine*. The model is implemented as a cohort model comprising stand basal area increment, diameter increment, mortality, and regeneration. He also described techniques for modeling tropical forest growth (1995). Additionally, Palahi et al. (2002) developed stand density, stand basal area, and volume models by using a non-linear three-stage least square technique as the estimation procedure to predict the stand growth and yield of Scots pine stands in Northeast Spain.

According to Monserud (2003), there are six different kinds of forest vegetation simulation models: (1) Forest growth and yield models, (2) Ecological gap models, (3) Ecological compartment models, (4) Process/mechanistic models, (5) Vegetation distribution models, and (6) Hybrid models. Of these, forest growth and yield models are the

Silviculture

oldest and most expansive class; as such, they are the most widely used in forest management. The most significant benefits of those models are their ability to provide an efficient way to forecast resources and predict tree/stand characteristics in detail.

These days, modeling diameter increment in natural forests within the tropics is a subject that has been widely developed. Despite the significant progress made, there has been relatively little study illustrating the growth model of tree species in tropical forests, especially in the tropical forests of Southeast Asia. The purpose of this study is thus to construct the diameter increment model in tropical rainforests state III in four provinces in the central region, Vietnam.

II. RESEARCH METHODOLOGY

2.1. Study area

Measurements were taken in a tropical rainforest, in four different provinces of Central region of Vietnam: Ha Tinh Province, Thua Thien Hue Province, Binh Dinh Province, and Khanh Hoa Province. There were three plots in each of the 1 four provinces.

2.2. Data collection

In this research, 12 PSPs in four provinces were selected from the network of PSPs which was established by the Forest Inventory and Planning Institute (FIPI) of Vietnam. Data from 2005 inherited, and re-measurement of these plots was done by the author in 2012, 2013.

Each plot has a square shape (100 m x 100 m^2) and is divided into twenty five 20 m x 20 m quadrats. It was aligned according to a magnetic-north direction and has four major corner posts made of concrete. All trees equal to or larger than 6 cm diameter at breast height ($DBH \geq 6$ cm) were identified by species and permanently marked using a white metal tag.

2.2.1. Field methods in 2005

On each plot, all trees in each plot with a diameter at breast height from 6 cm ($DBH \geq 6$ cm) were marked and, identified by species; their diameter was measured at 1.3 m from the ground. Trees with multiple stems above the ground were recorded as a single tree. Total tree height was measured at all trees in the 13 odd quadrats only. The data within the plot were assigned to their 20 m x 20 m quadrat.

2.2.2. Field methods in 2012 and 2013

Measurements were repeated on all 12 plots, either in 2012 (plot 1, plot 2 in Ha Tinh; plot 1, plot 3 in Thua Thien Hue; plot 1, plot 2 in Binh Dinh; plot 1, plot 2 in Khanh Hoa) or in 2013 (plot 3 in Ha Tinh, plot 2 in Thua Thien Hue, plot 3 in Binh Dinh, plot 3 in Khanh Hoa).

The coordinates of trees on the plot allow several types of competition indexes to be calculated, including overtopping basal area, and overtopping diameter. Because of the immense working time for measuring single tree coordinates, only one of the three plots in each province was randomly selected to have its tree coordinates recorded (plot 2 in Ha Tinh, plot 3 in Thua Thien Hue, plot 2 in Binh Dinh, plot 1 in Khanh Hoa).

2.3. Data analysis

2.3.1. Species group

There are a huge number of tree species in natural tropical rainforests. Several species appear more frequently, some occur with only low frequency. Moreover, some may have similar growth rates, and some may have definitely different growing patterns. For that reason, species might be aggregated into some groups to reduce the number of growth models and to avoid the need for adding data for species with insufficient number of

observations. For our study, simply the importance value index (IVI) was used to determine a group of most important species.

Important tree species having IVI $\geq$ 5% in pooled data from three plots in each province were utilized to model periodic annual diameter increment.

2.3.2. Local growth equations

a) Response variable

In this study, periodic annual diameter increment (ADI) was used as a dependent variable, because 8 of the 12 plots were remeasured in 2012 and the 4 others in 2013. It was calculated as:

$$ADI = \frac{DBH_1 - DBH_0}{t_1 - t_0} \qquad (1)$$

Where:

ADI is periodic annual diameter increment (cm);

DBH_1 and t_1 are diameter at breast height and time at the end of the growth period, respectively;

DBH_0 and t_0 are are diameter at breast height and time at the beginning of the growth period, respectively.

b) Explanatory variables

Independent variables include diameter at breast height in 2005, subplot basal area, stand basal area, ratio of basal area of kth tree to subplot basal area, overtopping basal area and overtopping diameter.

In this study, there were four plots having coordinates of each tree, therefore, overtopping basal area and overtopping diameter corresponding to circular plots with a 2 m, 5 m, 7 m and 10 m radius around the subject tree were calculated.

A typical function is usually used to model diameter increment comprising size, competition and site (Wykoff, 1990).

However, in tropical forests, site quality is unavailable. Therefore, the periodic annual diameter increment model was built as follows:

$$lnADI_k = \beta_0 + \beta_1 tree\ size + \beta_2 competition\ indices + \varepsilon_k \qquad (2)$$

Where:

$lnADI_k$ is the logarithm of periodic annual diameter increment for the kth tree;

β_0, β_1, β_2 are the intercept and slopes;

tree size presents the logarithm of diameter at breast height in 2005 for the kth tree ($lnDBH_{2005k}$);

competition indices expresses the log-transformation of subplot basal area, stand basal area, ratio of basal area of kth tree to subplot basal area, overtopping basal area and overtopping diameter; ε_k is the residual, $\varepsilon_k \sim N(0,\sigma^2)$.

The ordinary least squares estimation was applied to fit the growth model by using SPSS 20.0.

2.3.3. Linear mixed effects model approach

Since one important species occurred on all plots in four locations, and three others appeared on all plots in three provinces, a model using plot and province as random effects was used in order to study the between plot and between province variation of diameter increment.

To evaluate whether linear mixed effects models improved model fit, a pure fixed-effects model based on the least squares method was compared with different mixed effects models. The models were compared by using fit criteria following the Akaike Information Criterion (AIC) and the Bayesian Information Criterion (BIC). The model with the lowest AIC and BIC was preferred.

Nine linear mixed effects models were employed in this chapter as follows:

$$lnADI_{jk} = (\beta_0 + \beta_j) + \beta_1 lnDBH_{2005jk} + \varepsilon_{jk} \qquad (3)$$

$$lnADI_{jk} = \beta_0 + (\beta_1 + \beta_j)lnDBH_{2005jk} + \varepsilon_{jk} \qquad (4)$$

$$lnADI_{ik} = \beta_0 + (\beta_1 + \beta_i)lnDBH_{2005ik} + \varepsilon_{ik} \qquad (5)$$

$$lnADI_{jk} = (\beta_0 + \beta_j) + (\beta_1 + \beta_j)lnDBH_{2005jk} + \varepsilon_{jk} \qquad (6)$$

$$lnADI_{ijk} = (\beta_0 + \beta_i + \beta_{ij}) + \beta_1 lnDBH_{2005ijk} + \varepsilon_{ijk} \qquad (7)$$

$$lnADI_{ijk} = \beta_0 + (\beta_1 + \beta_i + \beta_{ij})lnDBH_{2005ijk} + \varepsilon_{ijk} \qquad (8)$$

$$lnADI_{ijk} = (\beta_0 + \beta_i + \beta_{ij}) + (\beta_1 + \beta_j)lnDBH_{2005ijk} + \varepsilon_{ijk} \qquad (9)$$

$$lnADI_{ijk} = (\beta_0 + \beta_j) + (\beta_1 + \beta_i + \beta_{ij})lnDBH_{2005ijk} + \varepsilon_{ijk} \qquad (10)$$

$$lnADI_{ijk} = (\beta_0 + \beta_i + \beta_{ij}) + (\beta_1 + \beta_i + \beta_{ij})lnDBH_{2005ijk} + \varepsilon_{ijk} \qquad (11)$$

Where: $lnADI_{jk}$, $lnADI_{ik}$, $lnADI_{ijk}$ presents the logarithm of periodic annual diameter increment for the kth tree from the jth plot, the kth tree from the ith province, and the kth tree from the jth plot within the ith province; β_i, β_j, β_{ij} represent the random effect variables of ith province, j^{th} plot and j^{th} plot within i^{th} province, respectively. $\beta_i \sim N(0, \sigma^2_{province})$, $\beta_j \sim N(0, \sigma^2_{plot})$, and $\beta_{ij} \sim N(0, \sigma^2_{plot\ within\ province})$; ε_{jk}, ε_{ik}, ε_{ijk} account for residual errors. $\varepsilon_{jk} \sim N(0, \sigma^2_\varepsilon)$, $\varepsilon_{ik} \sim N(0, \sigma^2_\varepsilon)$, $\varepsilon_{ijk} \sim N(0, \sigma^2_\varepsilon)$.

The linear mixed effects models were fitted in R utilizing functions from both "nlme" and "lme4" packages (Bates, 2010).

III. RESULTS

3.1. Species group

10,291 individuals on 12 plots in four locations belonged to 291 species, of which 52 species had an *IVI* equal or greater than 5%. The total number of trees of those important species was 6,588. In Ha Tinh, 17 out of 104 species were important species according to our definition, in Thua Thien Hue, Binh Dinh and Khanh Hoa 21 of 105, 17 of 127, and 12 of 81, respectively, were important species.

3.2. Local growth equations

Based on the backward selection procedure, non-significant predictor variables were dropped from the growth model (2). With the 8 plots remeasured in 2012, the explanatory variables consisted of the logarithm of initial diameter (*lnDBH*$_{2005}$) as tree size, and three competition indices (log-transformation of the subplot basal area, stand basal area and ratio of basal area of kth tree to subplot basal area). With the four other plots, where coordinates of each tree in the plot were available, log-transformation of the overtopping basal area and overtopping diameter were also examined. When fitting different forms of growth equations, the competition indices did not represent obvious trends in most cases. Specifically, they were sometimes positive, sometimes negative and mostly non-significant in the growth model, whereas a clear negative effect was expected.

Because of the indistinct and often nonsignificant competition effects, the function of the periodic annual diameter increment resulted in the reduced model (12), consisting of only one (mostly significant) predictor.

$$lnADI_k = \beta_0 + \beta_1 lnDBH_{2005k} + \varepsilon_k \quad (12)$$

Where:

$lnADI_k$ is the logarithm of periodic annual diameter increment for the kth tree;

β_0, β_1 are the intercept and the slope;

ε_k is the residual, $\varepsilon_k \sim N(0, \sigma^2)$.

Each important species, all important species and all others in each province were fitted by the final equation (12). The summary of the intercept and significant slope parameters, related *p*-value and standard error of each important species from the pooled data in each province are listed in table 1.

Table 1. Number of trees, intercept (β_0) and significant slope (β_1), including *p*-values, and standard error of estimate from equation (12) for important species in four provinces

Province	Species	*n*	β_0	p-value	β_1	p-value	σ_{res}
Ha Tinh	*Gironniera subaequalis*	115	-0.572	0.000	-0.104	0.022	0.220
	Vatica odorata	88	-0.459	0.000	-0.117	0.008	0.197
	Calophyllum calaba	99	-0.358	0.033	-0.170	0.003	0.261
	Nephelium melliferum	58	-0.450	0.006	-0.134	0.014	0.195
	Lithocarpus annamensis	24	-0.447	0.018	-0.125	0.031	0.145
	Wrightia annamensis	30	-0.391	0.023	-0.158	0.010	0.151
	Hydnocarpus annamensis	22	-0.124	0.596	-0.238	0.006	0.184
	Engelhardtia roxburghiana Wall	10	-0.154	0.704	-0.252	0.047	0.198
Thua Thien Hue	*Canarium album*	169	-0.264	0.002	-0.160	0.000	0.251
	Syzygium zeylancium	173	-0.130	0.140	-0.198	0.000	0.235
	Syzygium wightianum	173	-0.281	0.002	-0.155	0.000	0.193
	Gyrocarpus americanus	72	0.129	0.569	-0.277	0.000	0.319
	Ormosia pinnata	107	-0.372	0.001	-0.122	0.003	0.211
	Syzygium chanlos	99	-0.383	0.000	-0.110	0.008	0.192
	Shorea roxburghii	76	-0.108	0.562	-0.207	0.001	0.310
	Machilus platycarpa	101	-0.385	0.000	-0.121	0.003	0.190
	Cassine glauca	90	-0.409	0.001	-0.112	0.022	0.199
	Cinnamomum parthenoxylum	68	-0.366	0.006	-0.103	0.034	0.225
	Paranephelium spirei	57	-0.013	0.955	-0.251	0.003	0.319
Binh Dinh	*Parashorea chinensis* Wang Hsie	424	-0.269	0.000	-0.159	0.000	0.273
	Diospyros sylvatica	140	-0.182	0.118	-0.212	0.000	0.230
	Scaphium macropodum	111	-0.353	0.004	-0.150	0.001	0.223
	Quercus dealbatus	86	-0.275	0.114	-0.163	0.009	0.261
	Lithocarpus ducampii Hickel et A. camus	82	0.052	0.701	-0.278	0.000	0.229
	Nephelium melliferum	84	-0.233	0.080	-0.183	0.000	0.216
	Intsia bijuga	35	-0.270	0.262	-0.169	0.017	0.274
	Dillenia scabrella Roxb	51	-0.218	0.384	-0.186	0.026	0.329
	Melanorrhoea laccifera	52	0.028	0.859	-0.261	0.000	0.227
	Gironniera subaequalis	67	-0.359	0.049	-0.146	0.042	0.204
	Artocarpus rigidus	46	0.313	0.195	-0.372	0.000	0.267
Khanh Hoa	*Syzygium wightianum*	433	-0.573	0.000	-0.071	0.000	0.203
	Diospyros sylvatica	435	-0.489	0.000	-0.100	0.000	0.205
	Enicosanthellum sp.	390	-0.321	0.000	-0.152	0.000	0.223
	Saraca dives	201	-0.053	0.574	-0.251	0.000	0.244
	Nephelium melliferum	99	-0.454	0.000	-0.110	0.010	0.212
	Polyalthia nemoralis DC	76	-0.556	0.000	-0.073	0.036	0.169
	Ormosia balansae Drake	69	-0.370	0.002	-0.139	0.002	0.185
	Aphanamixis polystachya	55	-0.065	0.773	-0.254	0.004	0.292
	Lucua mamona Gaerten	42	-0.409	0.025	-0.130	0.044	0.210

The slope parameter β_1 of almost all individual important species in each province had the expected sign - a negative regression coefficient (Table 1), suggesting the periodic annual diameter increment decreases with increasing tree diameter. However, the slope parameter was not significant for 28 of 67 individual important species, and none of the positive slope parameters was significant. Zero slope, which might be assumed for species having non-significant slopes, means that the periodic annual diameter increment of these species is constant over the entire range of diameters from 6 cm to 100 cm, and a simple growth model $lnADI_k = \beta_0 + \varepsilon_k$ or, equivalently, $ADI_k = \exp(\beta_0 + \varepsilon_k)$ holds.

3.2. Linear mixed effects models

In order to analyze the variation among growth models of the four provinces, we selected important tree species which occurred in all or at least in three provinces. *Syzygium wightianum* was the sole important species that occurred on all plots in all locations, whereas there were three others appearing in three different provinces including *Diospyros sylvatica*, *Gironniera subaequalis* and *Nephelium melliferum*.

Because of unreasonable and mostly non-significant trends of the competition effects, the simple linear mixed effects models from equations (3) to (11) were used, which only use $lnDBH_{2005}$ as a covariate.

The comparison of model fit statistics (AIC, BIC) using generalized least squares and nine linear mixed effects models as well as the pure fixed effect model (12) is given in Table 2. The results showed that the linear mixed effects model substantially improved model fit for the four tree species *S. wightianum*, *D. sylvatica*, *G. subaequalis* and *N. melliferum* compared to the simple (fixed effects) linear regression (12) proving that there is significant variation of growth functions among the plots.

Table 2. A comparison of AIC and BIC between the fixed effects model and the mixed effects models

Species	*n*	Model	Model specification	AIC	BIC	Test	p-value
S. wightianum	750	1	Fixed effects model (FM)	-245.62	-231.76	1 vs 5	< .0001
		2	FM + plot intercept	-305.41	-286.93	2 vs 5	3.73e-09 [***]
		3	FM + plot slope	-294.93	-276.45	3 vs 5	1.98e-11 [***]
		4	FM + prov. slope	-262.65	-244.17	4 vs 5	< 2.2e-16 [***]
		5	FM + plot intercept + plot slope	-340.23	-312.51		
		6	FM + plots within prov. intercept	-304.12	-281.02	6 vs 5	6.69e-10 [***]
		7	FM + plots within prov. slope	-293.47	-270.37	7 vs 5	2.89e-12 [***]
		8	FM + plots within prov. intercept + plot slope	-311.02	-283.30	8 vs 5	< 2.2e-16 [***]
		9	FM + plots within prov. slope + plot intercept	-311.02	-283.30	9 vs 5	< 2.2e-16 [***]
		10	FM + plots within prov. intercept + plots within prov. slope	-335.23	-312.50	10 vs 5	0.7739

Species	*n*	Model	Model specification	AIC	BIC	Test	p-value
D. sylvatica	600	1	Fixed effects model (FM)	-163.28	-150.09	1 vs 5	< .0001
		2	FM + plot intercept	-174.72	-157.13	2 vs 5	1.49e-09***
		3	FM + plot slope	-169.86	-152.27	3 vs 5	1.32e-10***
		4	FM + prov. slope	-161.28	-143.69	4 vs 5	1.81e-12***
		5	FM + plot intercept + plot slope	-211.36	-184.98		
		6	FM + plots within prov. intercept	-172.72	-150.73	6 vs 5	1.82e-10***
		7	FM + plots within prov. slope	-167.86	-145.88	7 vs 5	1.32e-10***
		8	FM + plots within prov. intercept + plot slope	-186.83	-160.44	8 vs 5	< 2.2e-16***
		9	FM + plots within prov. slope + plot intercept	-186.83	-160.44	9 vs 5	< 2.2e-16***
		10	FM + plots within prov. intercept + plots within prov. slope	-205.36	-165.79	10 vs 5	1
G. subaequalis	299	1	Fixed effects model (FM)	-48.80	-37.70	1 vs 5	< .0001
		2	FM + plot intercept	-76.73	-61.92	2 vs 5	2.02e-05***
		3	FM + plot slope	-73.22	-58.42	3 vs 5	3.49e-06***
		4	FM + prov. slope	-64.34	-49.54	4 vs 5	4.12e-08***
		5	FM + plot intercept + plot slope	-94.35	-72.15		
		6	FM + plots within prov. intercept	-75.19	-56.69	6 vs 5	4.23e-06***
		7	FM + plots within prov. slope	-71.73	-53.23	7 vs 5	7.00e-07***
		8	FM + plots within prov. intercept + plot slope	-73.19	-50.99	8 vs 5	< 2.2e-16***
		9	FM + plots within prov. slope + plot intercept	-73.23	-51.02	9 vs 5	< 2.2e-16***
		10	FM + plots within prov. intercept + plots within prov. slope	-91.67	-58.36	10 vs 5	0.3451
N. melliferum	241	1	Fixed effects model (FM)	-68.83	-58.38	1 vs 5	0.0271
		2	FM + plot intercept	-66.83	-52.89	2 vs 5	0.0102*
		3	FM + plot slope	-66.83	-52.89	3 vs 5	0.0102*
		4	FM + prov. slope	-67.00	-53.06	4 vs 5	0.0111*
		5	FM + plot intercept + plot slope	-72.00	-51.10		
		6	FM + plots within prov. intercept	-65.09	-47.66	6 vs 5	0.0028**
		7	FM + plots within prov. slope	-65.00	-47.58	7 vs 5	0.0027**
		8	FM + plots within prov. intercept + plot slope	-63.09	-42.18	8 vs 5	< 2.2e-16***
		9	FM + plots within prov. slope + plot intercept	-63.00	-42.09	9 vs 5	< 2.2e-16***
		10	FM + plots within prov. intercept + plots within prov. slope	-66.90	-35.54	10 vs 5	0.8268

Model 1: Fixed effects model using equation (12); model 2: equation (3) with the plots designated as random intercepts; model 3: equation (4) with the plots designated as random slopes; model 4: equation (5) with the provinces designated as random slopes; model 5: equation (6) with the plots designated as random intercepts and slopes; model 6: equation (7) with the plots within a province designated as nested random intercepts; model 7: equation (8) with the plots within a province designated as nested random slopes; model 8: equation (9) with the plots within a province designated as nested random intercepts and plots designated as random slopes; model 9: equation (10) with the plots within a province designated as nested random slopes and plots designated as random intercepts; model 10: equation (11) with the plots within a province designated as nested random intercepts and slopes.

*Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1.*

For three of the four species considered (*S. wightianum*, *D. sylvatica*, and *G. subaequalis*), all nine types of linear mixed effects models had usually (except model 4 for *D. sylvatica*) lower AIC and BIC values than the fixed effects model (Table 2). Only for N. *melliferum*, only the mixed effects model with plots as random effects on intercepts and slopes (model 6) had a slightly lower AIC value compared with the fixed effects model. Thus, the best model in terms of AIC for all four species was, model 6. The BIC also led to model 6 as the best one, with the only *exception N. melliferum*, where the BIC of the fixed effects model was lowest. Moreover, there was no significant difference (p-value > 0.05) between model 6 and model 10, the most

complex mixed effects model, for all four important species. Therefore, model 6 was selected as the final, most appropriate model for these species because it was simpler. The main result of this analysis is that it is unnecessary to include a province effect into the model if only plot effects on intercept and slope are considered. Thus the variation among plots is very large compared to the variation among provinces, despite the small distances between plots within a province and the comparably large distances between the provinces.

Model coefficients of the linear mixed effects model (model 6) by species are presented in table 3.

Table 3. Parameter estimates based on REML estimation for the periodic annual diameter increment by species

Species	Parameters (Fixed effects)				Variance components			
	β_0	Std. error	β_1	Standard error	$\sigma^2_{\text{ran-in}}$	$\sigma^2_{\text{ran-slo}}$	σ^2	% variation explained by the plot
S. wightianum	-0.549	0.138	-0.065	0.049	0.175	0.021	0.034	85.09
D. sylvatica	-0.449	0.151	-0.111	0.055	0.144	0.018	0.039	80.79
G. subaequalis	-0.419	0.199	-0.124	0.067	0.299	0.033	0.037	90.02
N. melliferum	-0.266	0.169	-0.179	0.058	0.199	0.023	0.039	85.12

$\sigma^2_{\text{ran-in}}$ is the variance component for the random intercepts, and $\sigma^2_{\text{ran-slo}}$ the variance component for the random slopes at the plot level, σ^2 is the residual variance. The variation explained by the plot was calculated as the ratio of variances for random effects to the sum of the variances for random effects and residuals.

After fitting the mixed effects model (Table 3), the fixed effect parameter (β_1) was significant ($p < 0.05$) for *D. sylvatica* and *N. melliferum* and non-significant ($p > 0.05$) for *S. wightianum* and *G. subaequalis*. The sign of parameter β_1 was mostly negative, reflecting the decrease in ADI with increasing

diameter. The plot accounted for a large amount of unexplained variation in ADI for the four species, ranging from 85.09% to 90.02% (Table 3).

IV. DISCUSSION

Diameter growth models are one of the most basic and crucial components of forest growth models. They allow to describe the state of a tree at a future time and to estimate growth of an average tree of a given size (Bueno-López and Bevilacqua, 2013). This study represents the first set of models for diameter increment of lowland evergreen rainforests in Vietnam. In this paper, modeling the periodic annual diameter increment for

individual important tree species was employed. The explanatory variable logarithm of initial diameter ($lnDBH_{2005}$) had mostly an effect on diameter growth. The present study addressed a minor part of growth modeling for natural forests.

4.1. Model structure

The total number of important species on 12 plots in four provinces was 52 species, and 6,588 trees. 17 important species were in Ha Tinh, whereas in Thua Thien Hue, Binh Dinh, and Khanh Hoa were 21, 17, and 12 important species, respectively. We found that the equation of the periodic annual diameter increment (4.14) comprising only one predictor, $lnDBH_{2005}$, to be a significant regression model for about 47.1% to 75% important species in each province. With the remaining important species, a simple, namely constant growth model $ADI_k = \exp(\beta_0 + \varepsilon_k)$ was sufficient. The most frequently negative logarithmic relationship between initial diameter (DBH_{2005}) and the periodic annual diameter increment (ADI) implies that data are from stands, where the maximum growth rates occur for trees of lower diameter classes. This contrasts to a finding of Adame et al. (2014), who worked on plots in Puerto Rican secondary tropical forests, where a positive logarithmic relation between diameter and diameter growth was found. He explained that by young stand ages where trees have not reached yet the maximum growth rate. These results were contrary to the findings for North Queensland rainforests in a study of Vanclay (1989), where tree diameter increment got its maximum at a younger age and then decreased slowly, as also observed in most cases of our study.

On the reduced data set of one plot per province we had also studied the influence of competition indices in the growth model, such as stand or subplot basal area, overtopping diameter, and overtopping basal area. For instance, stand basal area accounts for competition among reference trees and their neighbours, and overtopping basal area is considered as an indicator of the relative competitive position of a subject tree among its neighbours having greater diameter in a plot due to their one-sided competition for light (Wykoff, 1990). These competition indices mostly turned out to be non-significant in our study, whereas they were often found to be significant predictors of diameter increment in other tropical and subtropical rainforests (Vanclay, 1995; Kariuki, 2005, Adame et al., 2014).

Site variables, such as elevation, aspect, precipitation, and soil fertility class were not included into the growth model, because they were either unavailable or did not vary enough between the three plots in a province, although they have been shown to affect stand-level growth responses in other studies (Kariuki, 2005). Other variables, such as moisture stress, saturated soil, and reduced solar radiation, can be effective at explaining variation in diameter increment; Puerto Rican forest trees are an illustration (Weaver, 1979). On the other hand, Adame et al. (2014) pointed out that the relationship between diameter increment and site characteristics (including precipitation, elevation, aspect, and soil fertility class) was insignificant. Similarly, Gourlet-Fleury and Houllier (2000), working in a lowland evergreen rain forest in French Guiana, showed that their attempt to include site information by the use of soil and topographical data in a diameter increment model was unsuccessful.

4.2. Linear mixed effects model

Linear mixed effects models with plots as random effects on intercepts and slopes (equation 6) were chosen for the four important species *S. wightianum*, *G.*

subaequelis, D. sylvatica, and *N. melliferum,* which occurred in at least three of the four provinces. As expected, the linear mixed effects model could in almost all cases account for random variation in intercepts and slopes of the periodic annual diameter increment models for four ubiquitous important species. Through the mixed effects model, the spatial correlation among trees on the same plot could be considered by fitting random effects for plot-to-plot variation (Pukkala et al., 2009). The explained variance by the random plot effects varied from 85.09% to 90.02%. These results are consistent with other studies modeling diameter, or basal area increment using the mixed effects model, which also found that the random effects associated with the sampling unit (for instance, plot) improved model fit (Pukkala et al., 2009; Pokharel and Dech, 2012; Adame et al., 2014). The variation of the plot-level random effects is possibly related to the effects of both microsite and individual genetic variability (Pokharel and Dech, 2012). Furthermore, sources of unexplained variation possibly arose from a pure error which no model can explain (Draper and Smith, 1998), and failure to include variables that affect tree growth in the model such as more appropriate competition indices or environmental factors which were not attempted to be measured in the inventory data. Because the plots in each province are neighbouring plots, located on the same commune, they are very close to each other. Moreover, climate data are typically assembled at the nearest meteorological station to the plot, therefore, environmental variation does not differ remarkably from plot to plot. The large variation in annual diameter increment may be explained, at least partially, by the fact that height of DBH measurement (1.3 m) was not marked on sample plot trees.

The limitations of the present findings are notable. Perfectly, species groups of similar growth dynamics should be based on growth rate, growth pattern and regeneration strategy (Vanclay, 1989), or on the dynamic process strategy (based upon recruitment, growth and mortality) (Gourlet-Fleury et al., 2005). However, tree species grouping was tackled here only by using *IVI*, because we did not find other clear and reasonable species groupings by clustering growth model parameters. Therefore, we developed growth models for each individual important tree species, as well as for that entire group and for the other "non-important" species.

The current findings are the first endeavor to model diameter increment of the individual important tree species of natural forests in Vietnam, which can be further improved in the future as additional data become available. Considering random plot effects turned out to be a necessary modelling requirement for single tree growth models based, as usual, on trees from sample plots having non-negligibly correlated tree characteristics. Further attempts are necessary to improve measurement precision.

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XÂY DỰNG MÔ HÌNH TĂNG TRƯỞNG ĐƯỜNG KÍNH RỪNG TỰ NHIÊN TRẠNG THÁI III Ở 4 TỈNH MIỀN TRUNG VIỆT NAM

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[1,2]*Trường Đại học Lâm nghiệp*

TÓM TẮT

Số liệu được thu thập từ 12 ô đo đếm trong các năm 2005, 2012 và 2013 ở bốn tỉnh là Hà Tĩnh, Thừa Thiên Huế, Bình Định và Khánh Hòa. Mỗi ô có diện tích 1 ha (100 m x 100 m). Tất cả các cây có đường kính từ 6 cm trở lên được xác định tên loài và đo đường kính. Số liệu từ 12 ô được dùng để xây dựng mô hình tăng trưởng đường kính cho các loài cây có chỉ số IVI% ≥ 5% và cho 4 loài cây cùng xuất hiện ở 3 hoặc 4 tỉnh. Biến phụ thuộc là tăng trưởng đường kính định kỳ hàng năm. Kết quả cho thấy, chỉ có biến $\ln(DBH_{2005})$ là có ảnh hưởng tới mô hình tăng trưởng đường kính từ 47,1% đến 75% loài quan trọng ở mỗi tỉnh. Với các loài quan trọng còn lại, chỉ cần dùng phương trình $ADI_k = \exp(\beta_0 + \varepsilon_k)$ là đủ. Biến $\ln(DBH_{2005})$ có mối quan hệ nghịch với tăng trưởng đường kính, điều này có nghĩa là tăng trưởng đường kính lớn nhất là ở cỡ đường kính nhỏ. Mô hình tuyến tính hỗn hợp với hiệu ứng ngẫu nhiên là hệ số tự do và hệ số hồi quy được chọn để xây dựng mô hình tăng trưởng đường kính cho 4 loài cây quan trọng là *S. wightianum*, *G. subaequelis*, *D. sylvatica* và *N. melliferum*. Mô hình tuyến tính hỗn hợp có thể giải thích được từ 85,09% đến 90,02% biến động ngẫu nhiên cho tăng trưởng đường kính.

Từ khóa: Hiệu ứng cố định, nhóm loài cây, phương trình tuyến tính tổng quát, rừng mưa nhiệt đới, tăng trưởng đường kính.