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Individual tree diameter growth modeling system for Dalat pine (*Pinus dalatensis* Ferré) of the upland mixed tropical forests

Bao Huy[a,b], Le Canh Nam[c,1], Krishna P. Poudel[d], Hailemariam Temesgen[e,*]

[a] *Consultancy for Forest Resources and Environment Management (frem), No. 06 Nguyen Hong, Buon Ma Thuot, Dak Lak, Viet Nam*
[b] *Visiting Scholar of Department of Forest Engineering, Resources and Management, Oregon State University (OSU), Corvallis, OR 97333, USA*
[c] *Department of Silviculture, Forest Science Institute of Central Highlands and South of Central Viet Nam, 09 Hung Vuong, Dalat, Lam Dong, Viet Nam*
[d] *Department of Forestry, Mississippi State University, PO Box 9681, Mississippi State, MS 39762, USA*
[e] *Department of Forest Engineering, Resources and Management, Oregon State University (OSU), Corvallis, OR 97333, USA*

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ABSTRACT

Pinus dalatensis Ferré (Dalat pine, or five-needle pine, locally) is an endemic large tree species of Vietnam that has both high timber and non-timber values. It is also a rare tree species listed in the Red List of the International Union for Conservation of Nature (IUCN). The objective of this study was to develop an individual tree diameter growth modeling system to facilitate the sustainable management and conservation of this species. We used Haglöf Sweden ® increment borers to collect tree ring samples from a total of 56 trees resulting in a dataset of 4566 diameter at breast height (*dbh*, cm) measurements at age (*t*, year) and obtained the associated ecological environmental factors in three different sites in the Central Highlands, Vietnam. A subset of this dataset (n = 1264) also had the climate data collected over the period of past 32–38 years (from 1980 to 2011 and from 1979 to 2016). Weighted mixed-effects models were used to model Dalat pine trees growth and account for autocorrelation and heteroscedasticity of the *dbh* measurements. Cross validation over 200 realizations were used to select the best equation form of *dbh* growth and incorporate the environmental effects and climatic factors that help improve reliability of the models. Under the mixed-effects modeling paradigm, the Mitscherlich equation fitted with random effects of ecological environmental factors (eco-subregions and altitude) and climatic factors (temperature, humidity, and temperature in dry and in rainy seasons) produced the best results. Whereas, under the fixed-effect modeling paradigm, the models that used the exponential function of environmental or climatic factors as the modifiers of an average diameter growth performed the best (Bias = −5.9% and RMSE = 10.0 cm). The models developed in this study will be useful for forecasting growth and for silvicultural planning under shifting environment and climate and are expected to contribute to the sustainable management of this endemic species.

1. Introduction

Pinus dalatensis Ferré (Dalat pine, or five-needles pine, locally) is an endemic tree species that grows in the mountains of Vietnam at altitudes from 600 to 2,600 m (Farjon, 2002; Zonneveld et al., 2009; Hai, 2018; Phong et al., 2016). Dalat pine usually grows alongside other conifer and broadleaf trees in the mixed broad-leaved and coniferous forests in the uplands (Hiep et al., 2004; Trang, 2011). It is a large tree, growing up to 30–40 m in height (*h*, m) and 250 cm or greater in diameter at breast height (*dbh*, cm) (Businsky, 2004; Loc et al., 2017). Globally, the species is now distributed in fewer than 10 locations because of the declining habitat and the number of individuals in these locations is usually limited to less than 100 mature trees (Hiep et al., 2004).

Like other pine species, Dalat pine has a high use and major economic value, supplying large timber, pulp, nuts, resin, and other non-timber products (Richardson and Rundel, 1998). Decades of excessive logging has damaged its habitat and reduced the number of individuals of this species, threatening its long-term survival. Dalat pine is currently listed as Near-Threatened (NT) in the Red List of the International Union for Conservation of Nature (IUCN, 2019). Therefore, there is a critical need for this species to be managed and conserved in Vietnam (Trang, 2011; Hai, 2018; Phong et al., 2016).

Dendrochronology is the study and reconstruction of past changes

* Corresponding author.
E-mail addresses: Krishna.Poudel@msstate.edu (K.P. Poudel), Temesgen.Hailemariam@oregonstate.edu (H. Temesgen).
[1] The same first author.

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that affected plant growth. It has been used as a tool for forest growth modeling and sustainable management as it provides data and the basis for development of biological models based on annual tree growth and its relationship with ecological environment and climate variables (Biondi, 2020; Vaganov et al., 2006; Baillie, 2012; Fritts, 1976, 1987; Fritts and Swetnam, 1989; Cook et al., 1987; Wosber et al., 2003; Buckley et al., 2017; Dymond et al., 2016).

Tree growth equations based on tree rings describe changes in individual tree size with age (Zeide, 1993). The resulted growth models support managers and researchers in a variety of ways by providing accurate growth information for selecting appropriate management practice (Hilt, 1983). These models also help in predicting future yields, identifying suitable silvicultural solutions for the production and conservation of individual trees and forest populations (Timilsina and Staudhammer, 2013).

There is a large amount of literature on growth modeling for pure even-aged forest stands, especially for planted forests; however, these ecosystems are quite simple, and many of the modeling approaches for these forests do not apply to stands with multiple tree species and age groups (Vanclay, 1994; Zeide, 1993). Mixed tropical forests present a special challenge because of species diversity and a great variety of sizes and ages. Given the complexity of mixed-species uneven-aged forests, especially tropical moist rain forests, many modeling techniques for pure plantations are not appropriate (Vanclay, 1994).

One of the important tree variables commonly used in management decision-making is *dbh*. This variable has many benefits, including ease of measurement and a strong relationship with other tree attributes such as height, volume, biomass, and carbon. The growth model of individual tree diameter is the most basic and essential component of forest growth modeling, and it is an invaluable tool for forest management planning at any level (Uzoh and Oliver, 2008). It allows predicting the state of plants at future times (Bueno and Bevilacqua, 2009). Therefore, developing and validating diameter growth models is critical to provide better knowledge of causes and mechanisms of tree growth and increment, as well as to help implement appropriate silvicultural treatments (Sedmak and Scheer, 2012; Ma and Lei, 2015).

Despite the importance of Dalat pine, there has been almost no research on developing the best growth models for this species. Therefore, the objective of this study was to develop and cross-validate an individual tree diameter growth modeling system that can be used to facilitate the sustainable management and conservation of this large, endemic, high-value tree species. We hypothesized that there is an effect of the ecological environment and climate on tree growth and inclusion of these factors in *dbh* growth modeling system improves the reliability growth estimates.

2. Materials and methods

2.1. Study sites

The study was conducted in the Central Highlands, one of eight ecological regions of Vietnam. Study sites were chosen in three ecological sub-regions (eco-subregion) with Dalat pine distribution (Photos of the stem, five-needle bundles, and cones of the species are shown in Fig. 1) and located in three mountains of Bi Dup Nui Ba (BD), Chu Yang Sin (CYS), and Kon Ka Kinh (3 K), as shown on the map in Fig. 2. The characteristics of the study sites are indicated in Table 1. The three eco-subregions differed in climatic and topographic factors, such as precipitation (P, mm year^{-1}), temperature (T, °C year^{-1} averaged), humidity (% year^{-1} averaged), altitude (m, averaged), and slope (degree, averaged). However, all three eco-subregions had the Yellow-Red Ferralsols soil (Table 1).

Dalat pine is distributed in mixed broad-leaved and coniferous forests. Fig. 3 shows the diameter distributions of the studied stands from 17 sample plots (6 plots in BD, 6 plots in CYS, and 5 plots in 3 K) of 2500 m^2 (50 m × 50 m). The stand-level diameter distribution patterns showed the reduced number of trees as the diameter increased, indicating that the mixed species and uneven-aged forests have continuous regeneration and growth. However, the diameter distributions of Dalat pine within those stands had apical forms focusing from left to right (Fig. 3), showing that Dalat pine had no continuous regeneration process on a given stand. It is only able to regenerate when light is present under the canopy, which is provided when old trees fall. Thus, it is often not possible to find regenerated Dalat pine under a mature canopy; instead, the regeneration appears in gaps in the forest canopy or at the edge of the forest.

Stand density ranged from 1069 to 1605 trees ha^{-1} with *dbh* ≥ 6 cm, and the density of Dalat pine in the stands was 1–62 tree ha^{-1}, accounting for 1–4% of the tree population of the stands. Other species in the stands included *Pinus krempfii* Lecomte, *Syzygium zeylanicum* (L.) DC., *Castanopsis indica* (Roxb. ex Lindl.) A.DC., *Rhodoleia championii* Hook. f., *Quercus augustini* Skan, *Schima wallichii* Choisy, *Elaeocarpus* spp., and *Mimusops elengi* L.


a b c

Fig. 1. Photos of (a) the stem, (b) five-needle bundles and flowers, and (c) cones of *Pinus dalatensis* Ferré. (Photos: Le Canh Nam, 2019).

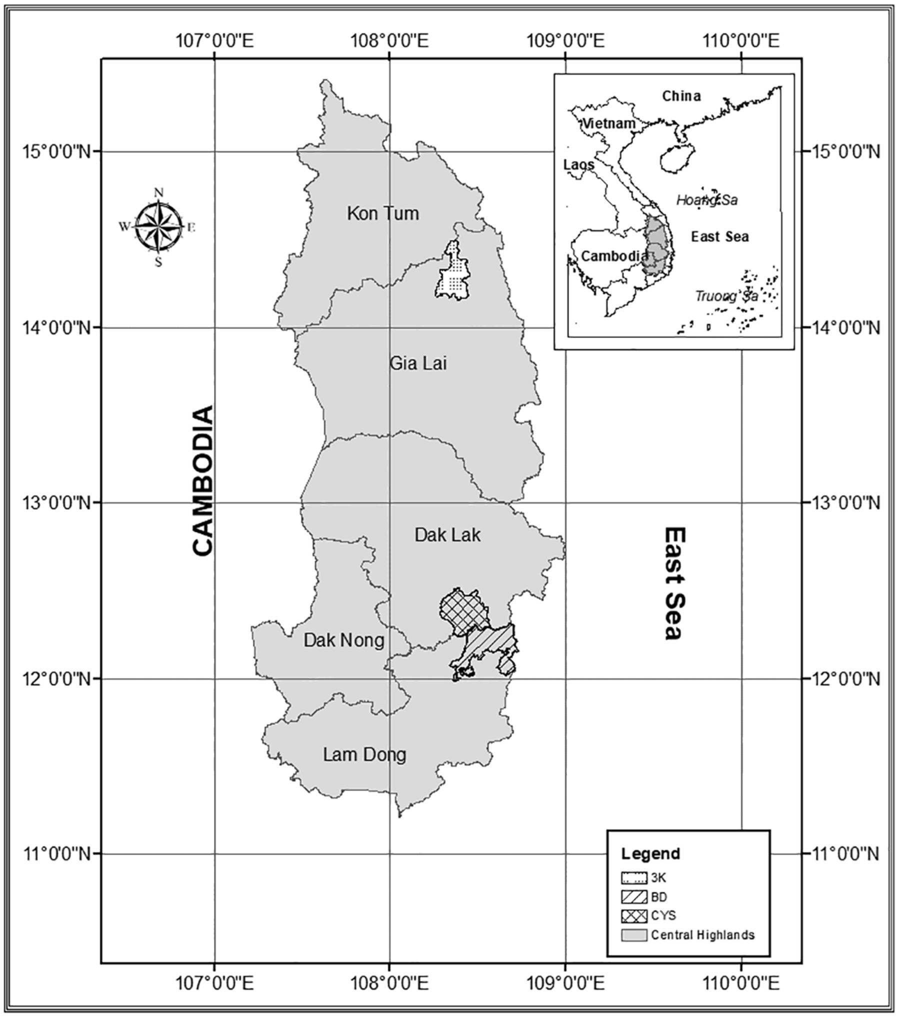


Fig. 2. Map of the study sites in three ecological sub-regions in the Central Highlands of Vietnam: 3 K: Kon Ka Kinh; BD: Bi Dup Nui Ba; and CYS: Chu Yang Sin mountains.

2.2. Measurement of diameter growth

Trees were sampled along topographic gradients (Dymond et al., 2016) in three ecological sub-regions to assess tree-ring growth responses to changes in environmental and climatic factors. The selection of trees from which to collect increment cores was proportional to the diameter distribution of Dalat pine (Fig. 3). Of the total 56 trees sampled, 26 trees came from the BD, 14 trees from the CYS, and 16 trees from the 3 K ecological sub-region. All three ecological sub-regions are located in three national parks, and the forest is strictly protected and no silvicultural or other treatments have been applied.

Diameter at breast height (*dbh*, cm; 1.3 m above the ground) and total height (*h*, m) were measured for each sampled tree. Haglöf Sweden ® increment borers of 70 cm in length and 5 mm in width were used to extract tree cores to the chronological center of the tree. We collected at least two cores and normally four cores per sampled tree, in the four cardinal directions at breast height. All tree cores were placed into labeled plastic straw tubes for transport to the laboratory. Core samples were air-dried, glued to wooden mounts, and then sanded to obtain a polished surface.

To determine the age of individual trees, we used standard dendrochronological methods (Stokes and Smiley, 1996). The surface of each tree core was crossdated by examining tree rings under the microcope at 7–40× magnification (Fig. 4). The series of tree ring widths were checked for missing and false tree rings (Bebber et al., 2004), and all tree cores were cross dated (Fritts, 1976) within trees and then among trees from each site. Tree ring widths were measured to the nearest 0.001 mm with a Velmex Measuring System and the Measure J2X computer software program (Speer, 2010; Speer et al., 2010; Dymond et al., 2016), then using COFECHA software (Holmes, 1983) to ensure that annual tree ring widths were correctly allocated to the proper year and age.

Tree ring widths at the same age and year were averaged over two to four of the directions of measurement to obtain the diameter at breast height (*dbh,* cm) at that age (*t*, year). A dataset totaling 4566 measures of *dbh* vs. *t* was collected from all sampled cored trees. The statistical summary of these variables is shown in Table 2.

2.3. Environmental and climatic factors

For each tree core sampled, percent canopy cover obtained using line intersect sampling and calculated as a ratio of the length of the transect covered by canopy and the full length of the transect (Korhonen et al., 2006), slope, and altitude variables were measured and recorded. Climatic variables including precipitation (P, mm year^{-1}), temperature (T, °C year^{-1} averaged), and humidity (H, % year^{-1} averaged) were collected at three local meteorological stations in BD for 38 years (1979–2016) and at CYS and 3 K for 32 years (1980–2011). In addition, the Central Highlands has two seasons, the dry and rainy seasons; so this study also assessesed the effects of

Table 1
The site characteristics in three studied ecological sub-regions.

Factors	BD	CYS	3 K
Precipitation (P, mm year^{-1})	1340–2356	1347–2598	1451–3175
Temperature (T, °C year^{-1})	17.5–19.0	23.4–24.7	21.4–23.0
Humidity (% year^{-1})	84.0–87.8	77.6–85.0	79.9–88.0
Number of drought months	2–3	2–3	2–3
Drought months	12, 1, 2	1, 2, 3	12, 1, 2
Soil type	Yellow-Red Ferralsols		
Altitude (m)	1458–1870	1504–1687	976–1200
Slope (degree)	5–20	18–24	16–25

Note: Climatic data were collected at three local meteorological stations: Bi Dup Nui Ba (BD) for 38 years (1979–2016); and Chu Yang Sin (CYS) and Kon Ka Kinh (3 K) for 32 years (1980–2011). Soil and topographic factors were collected at the sites of sampled cored trees.

seasonal climatic factors on the seasonal growth of forest trees. That are rainfall, temperature, and humidity in dry and rainy seasons including Pdry (mm), Prain (mm), Tdry (°C, averaged), Train (°C, averaged), Hdry (%, averaged) and Hrain (%, averaged) respectively, in which the dry season in BD and 3 K is in December, January and February and CYS is in January, February, and March.

A dataset of 4566 tree ring width measurements was used to obtain diameter at breast height (*dbh*, cm) at the age (*t*, year) and associated ecological environmental factors collected at each sample tree. A restricted dataset (n = 1264) for *dbh* vs. *t* was incorporated the past 32–38 years (from 1980 –to 2011 and from 1979 to 2016) of climatic dataset collected. The statistical summary of the environmental and climatic factors are also presented in Table 2.

In order to identify the variables accounting for the hightest variability in the diameter growth, the Principal Component Analysis (PCA; Abdi and Williams, 2010) was conducted. Two sets of PCA, one based on 4566 dataset of *dbh* vs t and ecological environmental factors such as eco-subregions, forest canopy, slope and altitude; and another based on 1264 dataset *dbh* vs t and climatic factors such as P, T, Humidity and seasonal climatic factors of Pdry, Prain, Tdry, Train, Hdry and Hrain were conducted. The values of the variables were standardized by subtracting their means and dividing by their standard deviations.

2.4. Selection of diameter growth model

A large number of models were proposed and developed to describe plant growth (Zeide, 1993; Vanclay, 1994; Sedmak and Scheer, 2012; Martins et al., 2014). Below are the main equation forms for diameter growth that have been studied (Zeide, 1989, 1993; Vanclay, 1994; Luo et al. 2018):

$$\text{Bertalanffy: } dbh = d_m \times (1 - a \times exp(-b \times t))^3 \quad (1)$$

$$\text{Chapman} - \text{Richards: } dbh = d_m \times (1 - exp(-a \times t))^b \quad (2)$$

$$\text{Gompertz: } dbh = d_m \times exp(-a \times exp(-b \times t)) \quad (3)$$

$$\text{Korf:} dbh = d_m \times exp(-a/t^b) \quad (4)$$

$$\text{Logistic}\backslash;(\text{Autocatalytic}): dbh = d_m/(1 + a \times exp(-b \times t)) \quad (5)$$

$$\text{Mitscherlich}\backslash;(\text{Monomolecular}): dbh = d_m \times (1 - exp(-a \times t)) \quad (6)$$

$$\text{Power}\backslash;\text{Decline:} dbh = d_m \times exp(a/(b-1)) \times t^{-(b-1)} \quad (7)$$

$$\text{Weibull:} dbh = d_m \times (1 - exp(-a \times t^b)) \quad (8)$$

where *dbh* is diameter at breast height in cm at *t* age in years and d_m is the limit of the diameter (asymptotic diameter) and was set at 300 cm as an approximate maximum *dbh* value for this species (Businsky, 2004; Loc et al., 2017); a and b are parameters of the models.

Preliminary analysis showed heteroscedasticity in the model residuals. This is systematically linked to tree age (Yang et al., 2012; Fowler, 2018) and was accounted for by using weighted regression (Ma and Lei, 2015; Huy et al., 2019; Davidian and Giltinan, 1995; Picard et al. 2012; Xu et al, 2014).

The Furnival index (Furnival, 1961; Jayaraman, 1999) was used to compare the performance of log-linear and weighted non-linear models to predict. As a results of that comparison, nonlinear models were selected; this is consistent with Huy et al. (2016c). Additionally, to account for autocorrelation in the repeated-measure data, weighted nonlinear mixed effects models (nlme) including first order autoregressive correlation structure to describe the within-group correlation structure was used (Xu et al, 2014).

In this study, the eight nonlinear equation forms above were fit by maximum likelihood (Bates, 2010; Pinheiro et al., 2014) using nlme package in R (R Core Team, 2019). A weighted nonlinear fixed effects model can be written in a general form as (Huy et al., 2016a, b, c, 2019; Timilsina and Staudhammer, 2013):

$$y_i = f(x_i, \alpha) + \varepsilon_i \quad (9)$$

where y_i is a vector of growth measurements of the i^{th} diameter (*dbh*, cm), x_i is the age (*t*, year) associated with the i^{th} diameter, α is a vector of fixed parameters, and ε_i is the random error associated with the i^{th} diameter measurement.

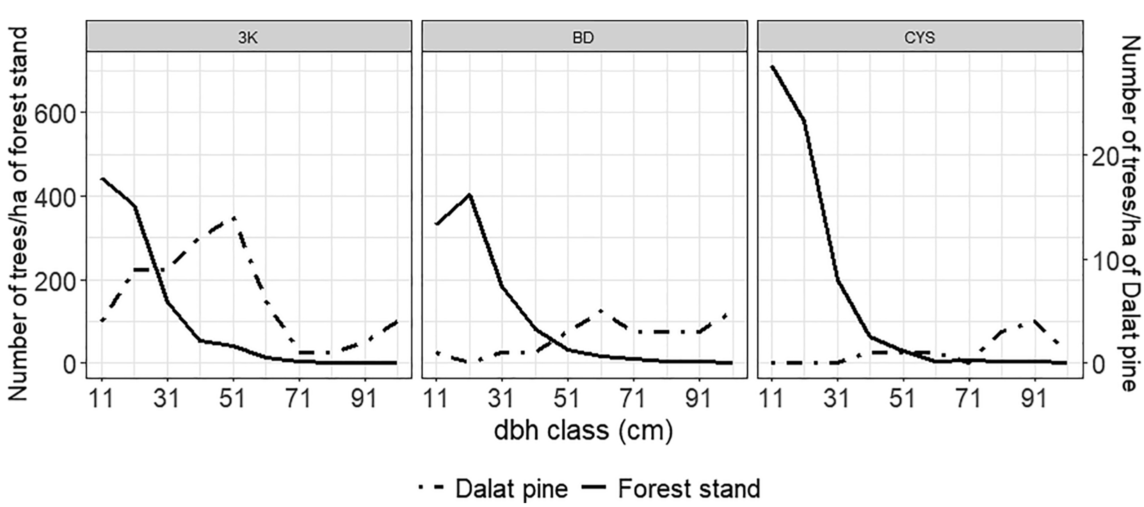


Fig. 3. Diameter distributions of *Pinus dalatensis* Ferré and the upland mixed tropical forests in three ecological subregions: 3 K: Kon Ka Kinh; BD: Bi Dup Nui Ba; and CYS: Chu Yang Sin mountains.

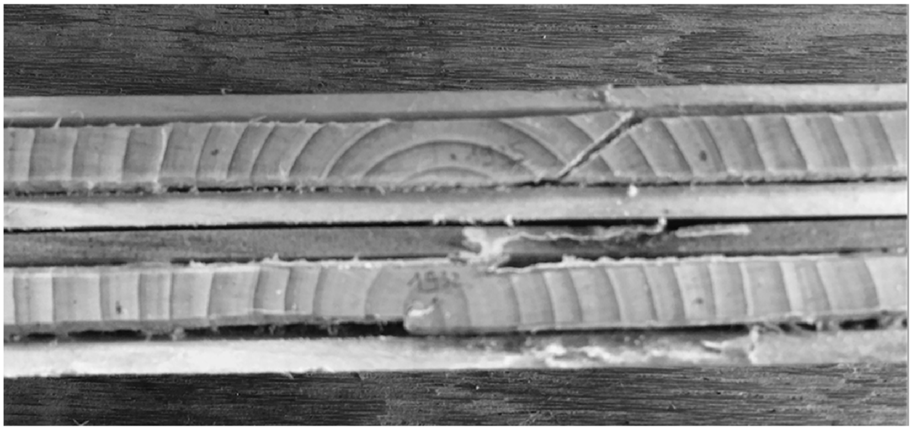


Fig. 4. Tree cores under microscope (Photo: Le Canh Nam, 2019).

Table 2
Statistical summary of variables used in modeling system.

Variables	n	Min	Mean	Max	Std.
dbh (cm)	4566	0.313	31.1776	80.846	18.974
t (year)	4566	1.0	101.7	322.0	76.016
Forest canopy (1/10)	4566	0.40	0.62	0.70	0.085
Slope (degree)	4566	5.0	13.9	25.0	5.205
Altitude (m)	4566	976	1541	1870	211.187
P (mm year^{-1})	1264	1340	1941	3175	335.220
T (°C year^{-1} averaged)	1264	17.5	20.7	24.7	2.579
Humidity (% year^{-1} averaged)	1264	77.6	83.8	88.0	2.362
Pdry (mm)	1264	68	78	84	3.727
Prain (mm)	1264	80	86	90	2.061
Tdry (^{0}C, averaged)	1264	15.5	19.2	24.8	2.895
Train (^{0}C, averaged)	1264	17.9	21.3	24.7	2.496
Hdry (%, averaged)	1264	68.0	78.1	84.3	3.727
Hrain (%, averaged)	1264	80.0	85.3	89.9	2.062

Note: *dbh:* Diameter at breast height; *t*: Age of the tree in year. P: Precipitation; T: Temperature. Pdry, Prain, Tdry, Train, Hdry and Hrain are rainfall, temperature, and humidity in dry and rainy seasons respectively. Data of climate variables collected at three local meteorological stations: Bi Dup Nui Ba (BD) for 38 years (1979 –2016); and Chu Yang Sin (CYS) and Kon Ka Kinh (3 K) for 32 years (1980–2011). Topographic and forest factors were collected at the sites of sampled cored trees.

$$\varepsilon_i \ iidN(0, \sigma^2) \tag{10}$$

The variance function was as follows (Huy et al., 2016a, b, c, 2019):

$$Var(\varepsilon_i)=\widehat{\sigma^2}(\nu_i)^{2\delta} \tag{11}$$

where $\widehat{\sigma^2}$ is the estimated error sum of squares; ν_i is the weighting variable (*t:* the age of the tree) associated the i^{th} diameter; and δ is the variance function coefficient to be estimated.

2.5. Development of the diameter growth modeling system with random effects

After selecting the best model for diameter growth, weighted non-linear mixed effects models (Xu et al, 2014) were fit by maximum likelihood and the random effects were incorporated to account for the variability due to environmental and climate factors (Vonesh and Chinchilli, 1997; Pinheiro and Bates, 2000; Bates, 2010; Pinheiro et al., 2014; Timilsina and Staudhammer, 2013). The mixed effects model was fit using nlme package in statistical software R (R Core Team, 2019) and had the following general form (Huy et al., 2016a, b, c, 2019; Timilsina and Staudhammer, 2013):

$$y_{i,j} = f(x_{i,j}, \alpha, \beta_j) + \varepsilon_{i,j} \tag{12}$$

where f is the selected equation form; $y_{i,j}$ is a vector of i^{th} diameter growth measurements from the j^{th} class of a factor; $x_{i,j}$ is the age of the diameter i^{th} in j^{th} of class of a factor; α is a vector of fixed-effects parameters; β_j is a vector of random-effects parameters associated with j^{th} class of a factor; and $\varepsilon_{i,j}$ is the random error associated with the i^{th} diameter and j^{th} class of a factor.

$$\varepsilon_{i,j} \ iidN(0, \sigma^2) \tag{13}$$

The variance function was as follows (Huy et al., 2016a, b, c):

$$Var(\varepsilon_{i,j})=\widehat{\sigma^2}(\nu_{i,j})^{2\delta} \tag{14}$$

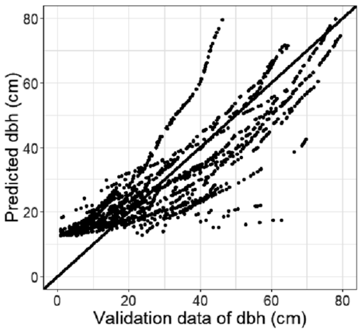
where $\widehat{\sigma^2}$ is the estimated error sum of squares; $\nu_{i,j}$ is the weighting variable (*t, year*) associated the i^{th} diameter from the j^{th} class of the random effect factor; and δ is the variance function coefficient to be estimated.

The following factors for random effects were examined: (i) ecological sub-regions in three sites at BD, CYS, and 3 K; (ii) classes of

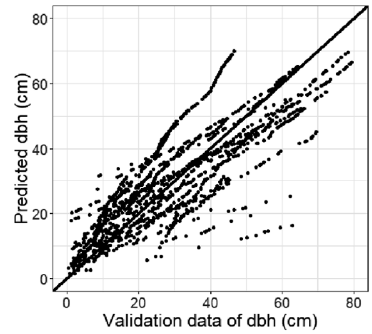
Table 3
Cross validation for comparison and selection of equation form for diameter growth.

Id	Model forms	Weight variable	AIC	$R^2_{adj.}$	Bias (%)	RMSE (cm)	MAPE (%)
	Bertalanffy: $dbh = d_m \times (1 - a \times \exp(-b \times t))^3$	$1/t^\delta$	24113.0	0.687	−38.41	10.6	58.94
	Chapman-Richards: $dbh = d_m \times (1 - \exp(-a \times t))^b$	$1/t^\delta$	23717.5	0.718	−21.77	10.0	41.66
	Gompertz: $dbh = d_m \times \exp(-a \times \exp(-b \times t))$	$1/t^\delta$	24254.4	0.675	−42.41	10.8	63.01
	Korf: $dbh = d_m \times \exp(-a/t^b)$	$1/t^\delta$	23857.8	0.708	−15.88	10.2	39.62
	Logistic (Autocatalytic): $dbh = d_m/(1 + a \times \exp(-b \times t))$	$1/t^\delta$	24530.2	0.648	−49.42	11.3	69.92
	Mitscherlich (Monomolecular): $dbh = d_m \times (1 - \exp(-a \times t))$	**$1/t^\delta$**	**24508.0**	**0.646**	**3.70**	**11.3**	**33.68**
	Power Decline: $dbh = d_m \times \exp(a/(b - 1)) \times t^{(b-1)}$	$1/t^\delta$	23718.1	0.719	−22.06	10.1	41.87
	Weibull: $dbh = d_m \times (1 - \exp(-a \times t^b))$	$1/t^\delta$	23718.9	0.719	−20.86	10.1	41.05

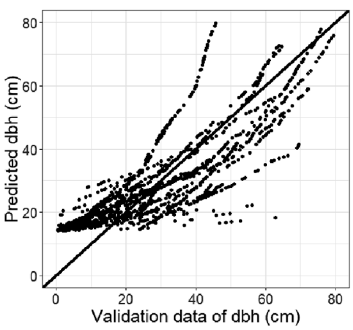
Note: *dbh*: Diameter at breast height in cm at age *t* in year; d_m is the limit of the diameter (asymptotic diameter); n = 4566. Splitting the dataset randomly into 70% data for equation development and 30% for validation over 200 realizations, statistics for comparison and validation of the models were averaged over 200 realizations; δ: the variance function coefficient; Bold: Selected model based on cross-validation statistics and diagnostic plots. Sources of equation forms (Zeide, 1989, 1993; Vanclay, 1994; Luo et al. 2018).



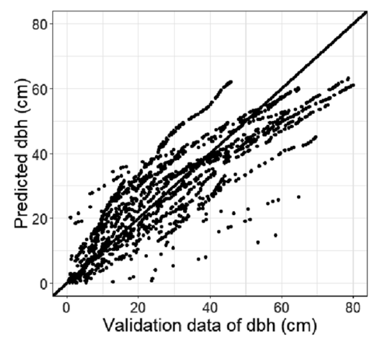
Bertalanffy: $dbh = d_m \times (1- a\times exp(-b\times t))^3$



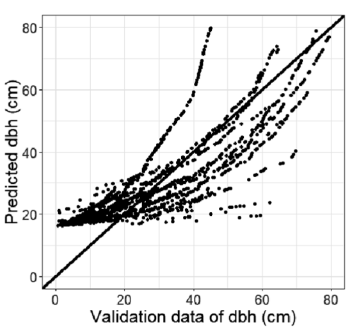
Chapman-Richards: $dbh = d_m \times (1- exp(-a\times t))^b$



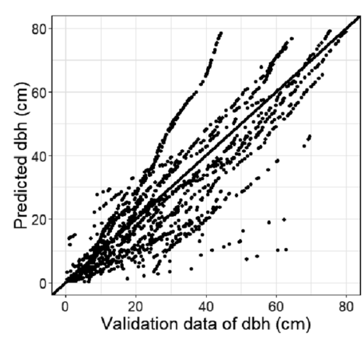
Gompertz: $dbh = d_m\times exp(-a\times exp(-b\times t))$



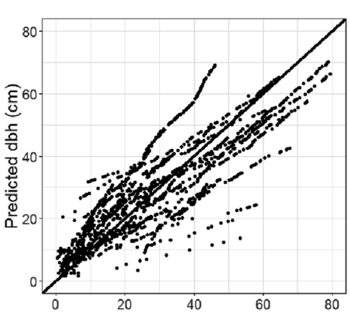
Korf: $dbh = d_m\times exp(-a/t^b)$



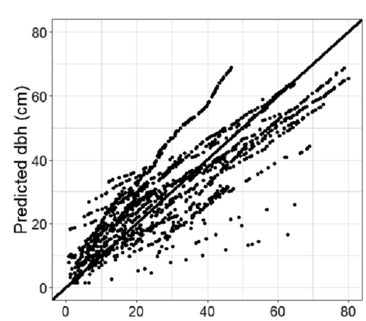
Logistic: $dbh = d_m/(1+a\times exp(-b\times t))$



Mitscherlich: $dbh = d_m\times(1- exp(- a\times t))$



Power Decline: $dbh = d_m\times exp(a/(b-1))\times t^{-(b-1)}$



Weibull: $dbh = d_m\times(1- exp(-a\times t^b))$

Fig. 5. Validation data of *dbh* from randomly splitting 30% of the dataset over 200 realizations vs. predicted *dbh at age t* by different equation forms. Bold: Selected model based on cross-validation statistics and diagnostic plots. d_m is the limit of the diameter (asymptotic diameter).

Table 4
Selected diameter growth models with random effects of ecological environmental factors.

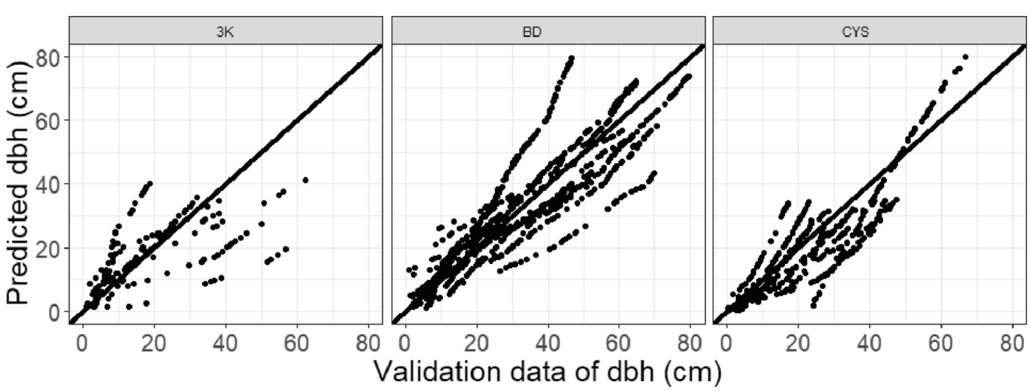
Id	Model form	Random effect	Weight variable	AIC	$R^2_{adj.}$	Bias (%)	RMSE (cm)	MAPE (%)
1	Mitscherlich: $dbh = d_m \times (1 - \exp(-a \times t))$	None	$1/t^{\delta}$	24508.0	0.646	3.70	11.3	33.68
2		**Ecological Sub-Regions**	$1/t^{\delta}$	**23737.9**	**0.708**	**−4.77**	**10.3**	**33.17**
3		Canopy Classes	$1/t^{\delta}$	24499.4	0.645	3.65	11.3	33.71
4		Slope Classes	$1/t^{\delta}$	24505.0	0.644	3.78	11.3	33.58
5		**Altitude Classes**	$1/t^{\delta}$	**23912.7**	**0.712**	**1.60**	**10.1**	**32.40**

Note: *dbh:* Diameter at breast height in cm; *t*: Age of the tree in year; d_m is the limit of the diameter (asymptotic diameter); n = 4566; Cross validation by splitting the dataset randomly into 70% data for equation development and 30% for validation over 200 realizations, statistics for comparison and validation of the models were averaged over 200 realizations; δ: the variance function coefficient; Bold: Selected model based on cross-validation statistics and diagnostic plots.

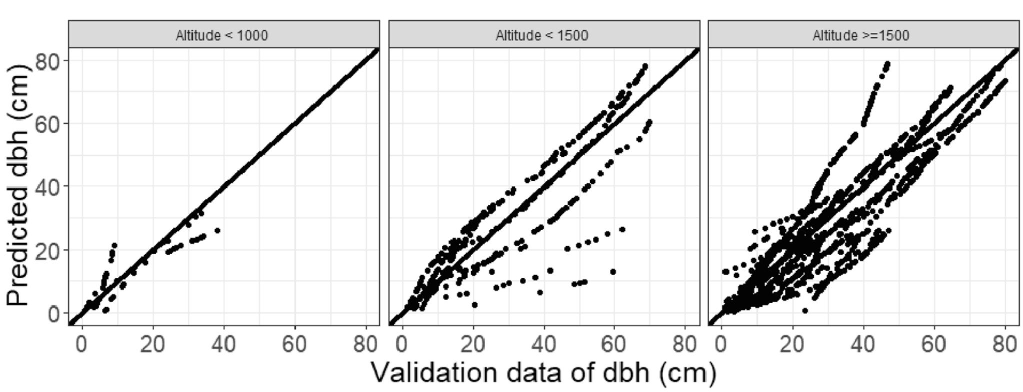
Table 5
Selected diameter growth models with random effects of climate factors.

Id	Model form	Random effect	Weight variable	AIC	$R^2_{adj.}$	Bias (%)	RMSE (cm)	MAPE (%)
1	Mitscherlich: $dbh = d_m \times (1 - \exp(-a \times t))$	None	$1/t^{\delta}$	7165.0	0.497	13.28	13.9	31.31
2		**T Classes**	$1/t^{\delta}$	**7011.0**	**0.581**	**−1.75**	**12.7**	**30.26**
3		**Humidity Classes**	$1/t^{\delta}$	**7119.6**	**0.527**	**8.85**	**13.5**	**30.20**
4		Pdry classes	$1/t^{\delta}$	7165.5	0.497	13.02	13.9	31.16
5		**Tdry classes**	$1/t^{\delta}$	**7102.7**	**0.538**	**8.40**	**13.2**	**30.38**
6		**Train classes**	$1/t^{\delta}$	**7057.2**	**0.557**	**4.11**	**13.0**	**29.69**
7		Hdry classes	$1/t^{\delta}$	7137.1	0.516	10.25	13.6	30.49
8		Hrain classes	$1/t^{\delta}$	7129.1	0.521	9.81	13.6	30.50

Note: *dbh*: Diameter at breast height in cm; *t*: Age of the tree in year; d_m is the limit of the diameter (asymptotic diameter); n = 1264; Cross validation by splitting the dataset randomly into 70% data for equation development and 30% for validation over 200 realizations, statistics for comparison and validation of the models were averaged over 200 realizations; δ: the variance function coefficient; Pdry, Tdry, Train, Hdry and Hrain are rainfall, temperature, and humidity in dry and rainy seasons respectively. Bold: Selected model based on cross-validation statistics and diagnostic plots. P: Precipitation; T: Temperature



a)



b)

Fig. 6. Validation data of *dbh* from randomly splitting 30% of the dataset over 200 realizations vs. prediction of *dbh* through selected equation Mitscherlich: $dbh = d_m \times (1 - \exp(-a \times t))$ with random effects of ecological environment factors (a) ecological subregions: 3 K: Kon Ka Kinh BD: Bi Dup Nui Ba; and CYS: Chu Yang Sin mountains; and (b) random effect of altitude (in m) classes.

Table 6
Parameters of selected model: $dbh = 300 \times (1 - \exp(-a \times t))$ along with random effects of environmental factors.

Random effect factors	Classes	n	Parameter a ± Approx. Std Error
All	None	4566	0.001508 ± 0.000725
Ecological Sub-Regions	BD	2780	0.001017 ± 2.380826e−05
	CYS	1297	0.001096 ± 3.485620e−05
	3 K	489	0.002412 ± 5.676696e−05
Altitude Classes (m)	< 1000	153	0.001286 ± 3.828229e−05
	1000 to < 1500	1042	0.001601 ± 1.466931e−05
	≥1500	3371	0.001020 ± 8.155756e−06

Note: *dbh*: Diameter at breast height in cm; d_m is the limit of the diameter (asymptotic diameter) and was set at 300 cm as an approximate maximum *dbh* value for this species (Businsky, 2004; Loc et al., 2017); *t*: Age of the tree in year; n = 4566 (entire dataset); Bi Dup Nui Ba (BD), Chu Yang Sin (CYS), and Kon Ka Kinh (3 K) mountains.

ecological environmental factors: forest canopy (< 0.6 and ≥ 0.6), slope (< 10°, 10° to < 20°, and ≥ 20°), and altitude (< 1000 m, 1000 m to < 1500 m, and ≥ 1500 m); (iii) classes of climatic factors: P (< 2000 mm, 2000 mm to < 2400 mm, and ≥ 2400 mm year^{-1}), T (< 20 °C, 20 °C to < 22 °C, and ≥ 22 °C year^{-1}, averaged) and humidity (< 82%, 82% to < 85%, and ≥ 85% year^{-1} averaged); and seasonal climatic factors: Pdry (< 100 mm, and ≥ 100 mm), Prain (< 2000 mm, 2000 mm to < 2400 mm, and ≥ 2400 m), Tdry (< 20 °C, 20 °C to < 22 °C, and ≥ 22 °C, averaged), Train (< 20 °C, and ≥ 22 °C, averaged), Hdry (< 80%, and ≥ 80%, averaged) and Hrain (< 85%, and ≥ 85% year-1 averaged).

2.6. Development of fixed-effects diameter growth model with combination of factors

Mixed-effects diameter growth model with random effects of environmental and climatic variables sets up a single model with each environmental and climatic factor. Meanwhile, these factors interact and have synergistic effects on diameter growth. Therefore, we examined a fixed-effects model that incorporates a combination of environmental and climatic factors.

In this case, the form of the diameter growth model consists of two components, an average diameter growth model and a modifier (Lessard et al. 2001) as follows:

$$\text{DIAMETER\;GROWTH} = \text{AVERAGE} \times \text{MODIFIER} \quad (15)$$

where $\text{AVERAGE} = f(x_i, \alpha)$, the selected fixed diameter growth (16)

and $\text{MODIFIER} = exp(factor\ \ j - average\ \ value\ \ of\ \ factor\ \ j)$ (17)

where DIAMETER GROWTH is a vector of growth measurements of the i^{th} diameter (*dbh*, cm), x_i is the age (*t*, year) associated with the i^{th} diameter, α is a vector of fixed parameter of the selected average diameter growth model, *j* values within the modifier are the average values of the *j* factors (presented in Table 2), and ε is the random error of the model.

The modifier is an exponential equation involving environmental and climatic factors as additional covariates. The modifier adjusts diameter growth based on the combined effects of these factors. In this study, factors consisted of ecological sub-regions (*Eco-subregion*) coded in the data set as 1, 2 and 3 corresponding with BD, CYS and 3 K respectively and factors presented in Table 2 were examined. Average values of the variables were incorporated into the modifier, so that the higher the observed variable's value than the average value, the greater the effect on the diameter prediction.

To obtain the model in (15), weighted non-linear fixed-effects models were fit using maximum likelihood (Davidian and Giltinan, 1995; Lessard et al. 2001; Bates, 2010; Pinheiro et al., 2014) in nlme package in R (R Core Team, 2019).

2.7. Cross validation

The models, including both fixed and mixed with random effects, were cross-validated to compare and select the best model. The dataset was randomly split into two parts, with 70% for model development and 30% for validation. The cross-validation process was repeated 200 times, and statistics and errors of the model were averaged over 200 realizations (Temesgen et al., 2014; Huy et al., 2016a, b).

The goodness-of-fit statistic used to validate, compare, and select models was Akaike's Information Criteria (Akaike, 1973; Bueno and Bevilacqua, 2009). The model that had smallest AIC value was preferred, along with adj. R^2 (the larger the better). The diagnostic plots of the trend of validation data vs. prediction were also used to assess model performance.

Validation and prediction data were then used to calculate model fit statistics that included percent bias, root mean squared error (RMSE, cm), and mean absolute percent error (MAPE, %) (Temesgen et al., 2014; Swanson et al., 2011; Huy et al., 2016a, b, c, 2019) to determine the accuracy of model estimations. Models that had smaller values of cross-validation errors were preferred.

$$Bias(\%) = \frac{1}{R}\sum_{r=1}^{R}\frac{100}{n}\sum_{i=1}^{n}\frac{y_i - \hat{y}_i}{y_i} \quad (18)$$

$$RMSE\,(cm) = \frac{1}{R}\sum_{R=1}^{R}\sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2} \quad (19)$$

$$MAPE\,(\%) = \frac{1}{R}\sum_{r=1}^{R}\frac{100}{n}\sum_{i=1}^{n}\frac{|y_i - \hat{y}_i|}{y_i} \quad (20)$$

where R is the number of realizations (200); n is the number of samples per realization R; and y_i and $\hat{y}_i$ are the observed and predicted *d* for the i^{th} realization R, respectively.

Where the AIC and $R^2_{adj.}$ values of the models were quite similar, the selected form was the one in which the errors (such as bias, RMSE, MAPE) were the smallest. Final parameter estimates for all of the selected modeling systems were obtained by fitting models with the entire dataset.

3. Results

3.1. Diameter growth model

We collected 1297, 2780, and 489 ring width measurements spanning from 1698 to 2017 (320 years), 1697–2018 (322 years) and 1945–2017 (73 years) from CYS, BD and 3 K sites respectively. The average age of the trees was 75 years in CYS, 126 years in BD and 28 years in 3 K. From here we obtained the dataset of 4566 *dbh* vs *t* for growth modeling.

The Mitscherlich (Monomolecular) function was the best fit model compared to other models, based on statistical criteria and errors (Table 3). Comparison of the observed vs. predicted diameters in the validation dataset (Fig. 5) also supported the selection of the Mitscherlich function.

3.2. Ecological environmental and climatic factors that affect the diameter growth

As the results of PCAs, in case of 5 variables analysis from 4566 dataset of *dbh* and four environmental factors eco-subregion, forest canopy, slope and altitude, two principal components were extracted, since 2 components had eigenvalues greater than or equal to 1.0. Together they account for 66.85% of the variability in the original data.

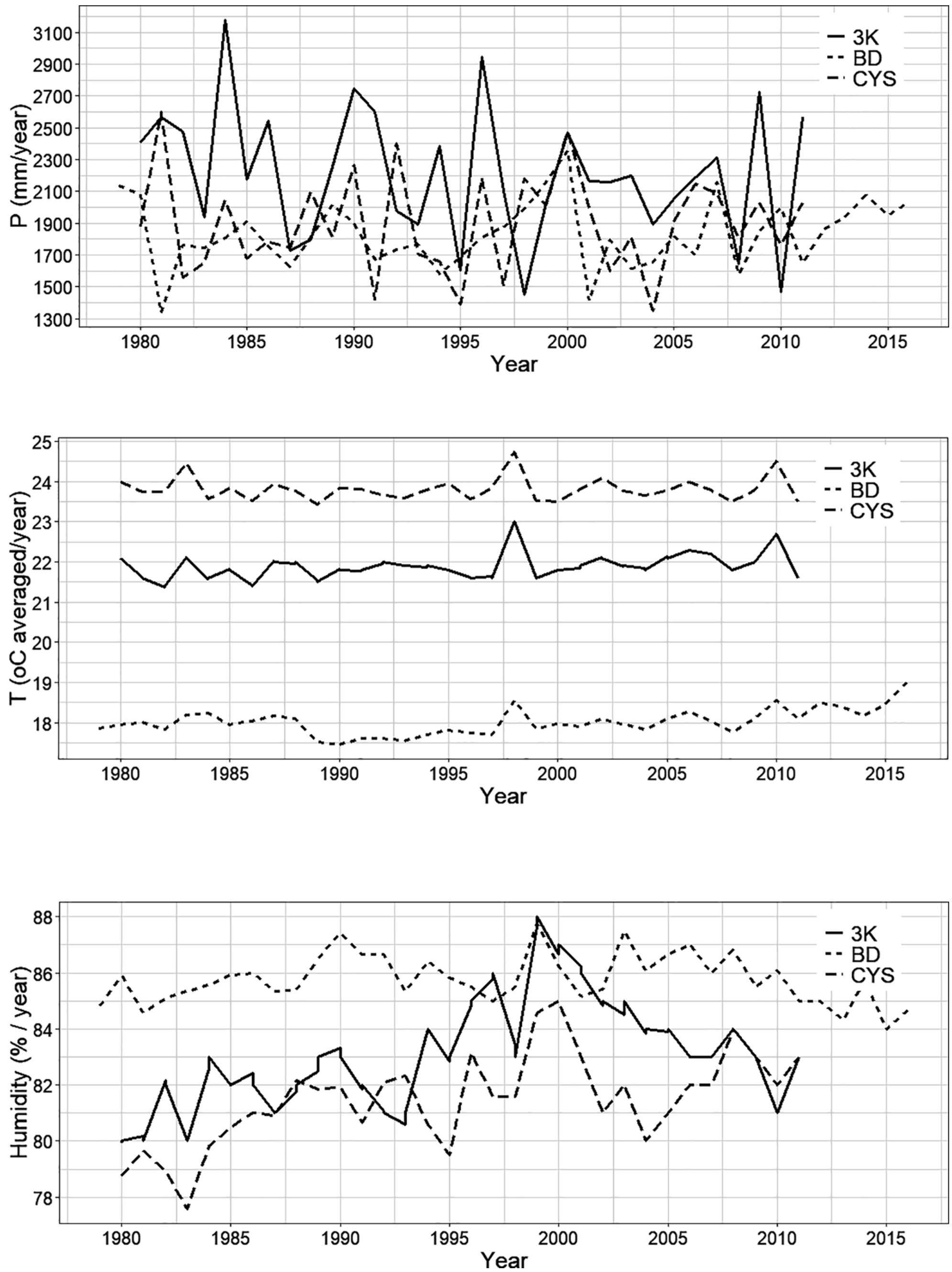


Fig. 7. Changes of precipitation (P, mm year[1]), temperature (T, °C year[1] averaged), and humidity (% year[1] averaged) during 1979–2016 in three ecological sub-regions: 3 K: Kon Ka Kinh; BD: Bi Dup Nui Ba; and CYS: Chu Yang Sin.

The first principal component (PC1) had the equation as follow:

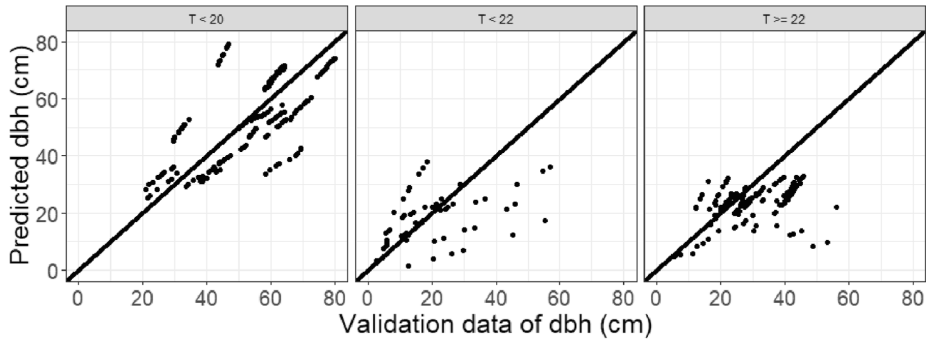
$$PC1 = 0.323152 \times dbh - 0.608388 \times Eco - subregion + 0.355542 \times Forest\;canopy - 0.457655 \times Slope + 0.435407 \times Altitude \quad (21)$$

In above equation, all four environmental factors had significant weight values and correlation with *dbh* growth; so, these factors as Eco-subregion, Forest canopy, Slope and Altitude were considered in *dbh* growth modeling.

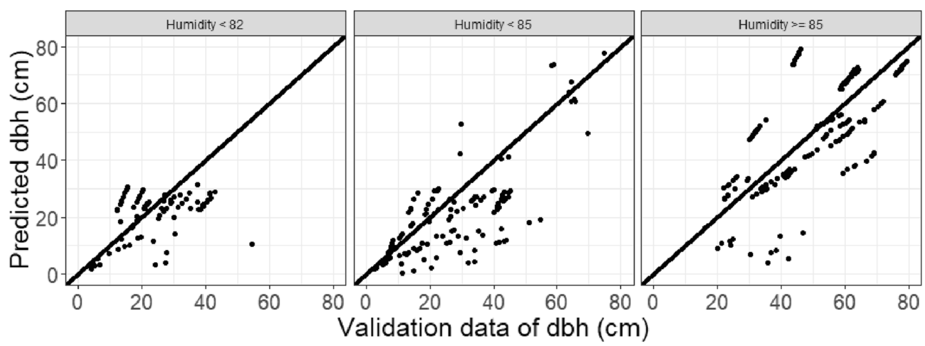
From the PCA of 10 variables analysis from 1244 dataset of *dbh* and nine climatic factors of P, T, Humidity, Pdry, Prain, Tdry, Train, Hdry and Hrain, two principal components were extracted, since 2 components had eigenvalues greater than or equal to 1.0. Together they account for 77.90% of the variability in the original data. The first principal component had the equation as follow:

$$PC1 = 0.241702 \times dbh - 0.385943 \times Tdry - 0.39855 \times Train + 0.183058 \times Pdry - 0.112234 \times Prain + 0.382196 \times Hdry + 0.356722 \times Hrain - 0.0899805 \times P - 0.398033 \times T + 0.384484 \times Humidity \quad (22)$$

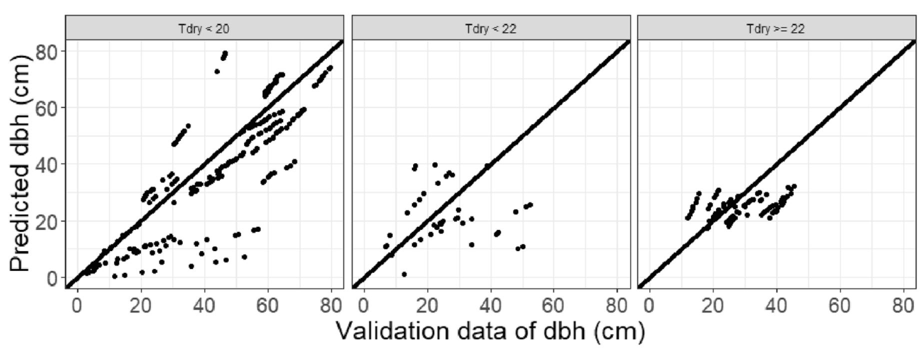
In above equation, two climatic factors of Prain and P had low weight values and weak correlation with *dbh* growth; so, these two variables were excluded in the *dbh* growth modeling. Other variables of climatic factors such as Tdry, Train, Pdry, Hdry, Hrain, T and Humidity were considered when developing *dbh* growth model.



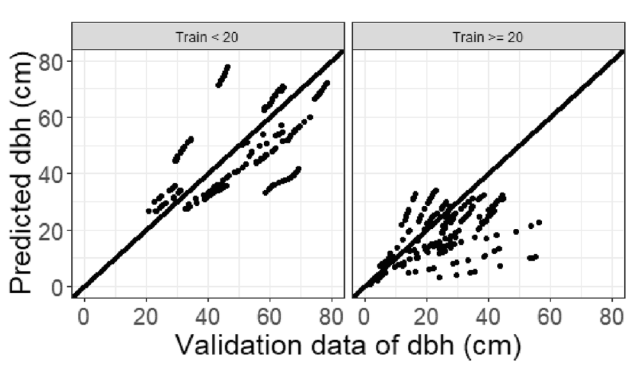
a) Random effect of T Classes



b) Random effect of Humidity Classes



c) Random effect of Tdry Classes



d) Random effect of Train Classes

Fig. 8. Validation data of *dbh* from randomly splitting 30% of the dataset over 200 realizations vs. prediction of *dbh* through selected equation Mitscherlich: $dbh = d_m \times (1 - \exp(-a \times t))$ with random effects of climate factors. T: Temperature (°C year^{-1} averaged), humidity (% year^{-1} averaged). Tdry and Train are temperature (^{0}C, averaged) in dry and rainy seasons respectively.

Table 7
Parameters of selected model: $dbh = 300 \times (1 - \exp(-a \times t))$ along with random effects of climatic factors.

Random effect factors	Classes	n	Parameter a ± Approx. Std Error
T Classes (°C year^{-1} averaged)	< 20	570	0.000717 ± 6.594039e−05
	< 22	210	0.002553 ± 1.086374e−04
	≥22	484	0.001042 ± 7.155933e−05
Humidity Classes (% year^{-1} averaged)	< 82	296	0.001085 ± 1.107754e−05
	< 85	415	0.000939 ± 9.355463e−06
	≥85	553	0.000865 ± 8.104510e−06
Tdry Classes (°C, averaged)	< 20	791	0.000837 ± 4.562669e−06
	< 22	113	0.000980 ± 1.207169e−05
	≥2	360	0.000942 ± 6.763258e−06
Train Classes (°C, averaged)	< 20	570	0.000705 ± 1.669870e−05
	≥20	694	0.001106 ± 1.513354e−05

Note: *dbh:* Diameter at breast height; d_m is the limit of the diameter (asymptotic diameter) and was set at 300 cm as an approximate maximum dbh value for this species (Businsky, 2004; Loc et al., 2017); t: Age of the tree in years; n = 1264 (entire dataset); T: Temperature. Tdry and Train are temperature (0C, averaged) in dry and rainy seasons respectively.

3.3. Random effects of environmental and climatic factors

Since the soil type was the same in the three studied ecological sub-regions (Table 1), it was excluded. Thus, as the results of PCAs we considered the random effects of each eco-subregion and environmental factors (forest canopy, slope, and altitude), as well as climatic factors (Tdry, Train, Pdry, Hdry, Hrain, T and Humidity). These factors are also the indicators that form the site index.

Of the four ecological environmental factors examined, two factors (eco-subregions and altitude) significantly affected the diameter growth model, with significant reductions in AIC values and increase in $R^2_{adj.}$ as well as significant reductions in some error statistics (Table 4). Meanwhile, the remaining factors, forest canopy and slope, had statistical indicators and errors that were not substantially different from the fixed model (Table 4). The fluctuation between observed *dbh* and predicted *dbh* value in the validation data for each class of eco-subregion and altitude was also narrower than that of the fixed model (Fig. 5 and Fig. 6). Therefore, we recommend setting the parameters for the diameter growth modeling system according to the classes of ecological

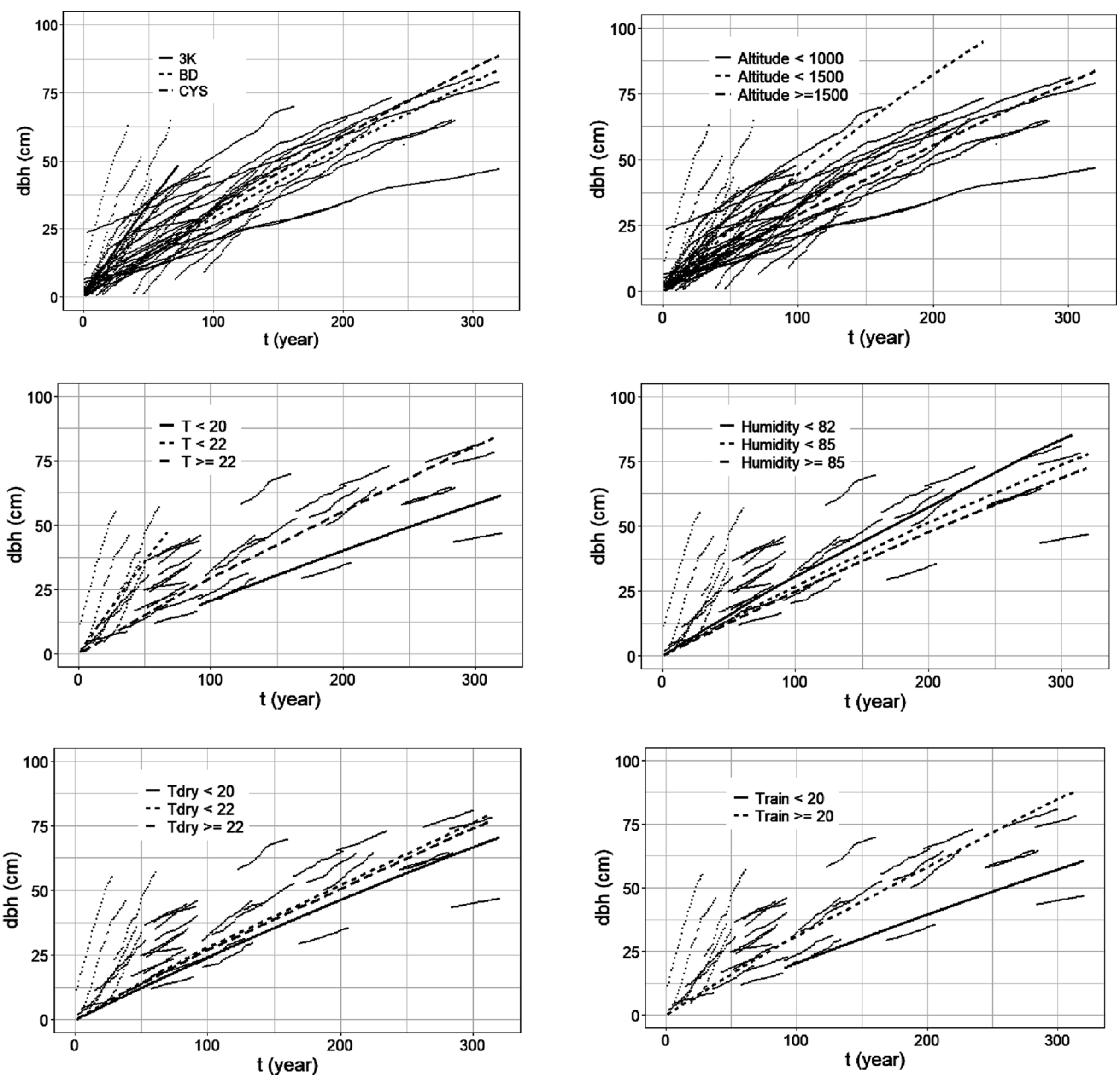


Fig. 9. The *dbh* growth curve from Mitscherlich: $dbh = d_m \times (1 - \exp(-a \times t))$ of Dalat pine was distinguished by classes of environment and climate factors. 3 K: Kon Ka Kinh, BD: Bi Dup Nui Ba, and CYS: Chu Yang Sin mountains. Altitude in m, T: Temperature (°C year^{-1} averaged), Humidity (% year^{-1} averaged). Tdry and Train are temperature (^{0}C, averaged) in dry and rainy seasons respectively. Scatter plots of observed *dbh* at *t* age.

Table 8
Cross validation for comparison and selection of equation form based on fixed effect model for diameter growth with environmental variables included. The general model: *dbh* = *AVERAGE* × *MODIFIER*. where *AVERAGE* = $d_m \times (1 - exp(-a \times t))$ *(Mitscherlich model selected)*, *MODIFIER* = $exp(b_1 \times (Eco\text{-}subregion - 2) + b_2 \times (Forest\ canopy - 0.62) + b_3 \times (Slope - 13.9) + b_4 \times (Altitude - 1541))$.

Id	Model forms	Weight variable	AIC	$R^2_{adj.}$	Bias (%)	RMSE (cm)	MAPE (%)
	$dbh = d_m \times (1 - \exp(-a \times t)) \times \exp(b_1 \times (Eco-subregion - 2) + b_2 \times (Forest\ canopy - 0.62) + b_3 \times (Slope - 13.9) + b_4^* \times (Altitude - 1541))$	$1/t^{0.1\delta}$	23561.8	0.724	−7.10	9.9	33.60
	$\mathbf{dbh = d_m \times (1 - \exp(-a \times t)) \times \exp(b_1 \times (Eco\text{-}subregion - 2) + b_2 \times (Forest\ canopy - 0.62) + b_3 \times (Slope - 13.9))}$	$\mathbf{1/t^{0.1\delta}}$	**23554.5**	**0.725**	**−6.98**	**9.9**	**33.54**
	$\mathbf{dbh = d_m \times (1 - \exp(-a \times t)) \times \exp(b_1 \times (Eco\text{-}subregion - 2)\ b_4 \times (Altitude - 1541))}$	$\mathbf{1/t^{0.1\delta}}$	**23623.1**	**0.719**	**−5.97**	**10.0**	**33.18**

Note: *dbh*: Diameter at breast height in cm at age t in year; d_m is the limit of the diameter (asymptotic diameter); Eco-subregion: Ecological sub-region coded; Forest canopy (1/10); Slope (degree); Altitude (m). n = 4566. Splitting the dataset randomly into 70% data for equation development and 30% for validation over 200 realizations, statistics for comparison and validation of the models were averaged over 200 realizations; δ: the variance function coefficient; *: Parameter with Pvalue > 0.05. Bold: Selected model based on cross-validation statistics and diagnostic plots.

Table 9
Cross validation for comparison and selection of equation form based on fixed effect model for diameter growth with climatic variables included. The general model: *dbh* = *AVERAGE* × *MODIFIER. where AVERAGE* = $d_m \times (1 - \exp(-a \times t))$ *(Mitscherlich model selected)*, *MODIFIER* = $\exp(b_5 \times (T - 20.7) + b_6 \times (Humidity - 83.8) + b_7 \times (Pdry - 78) + b_8 \times (Tdry - 19.2) + b_9 \times (Train - 21.3) + b_{10} \times (Hdry - 78.1) + b_{11} \times (Hrain - 85.3))$.

Id	Model forms	Weight variable	AIC	$R^2_{adj.}$	Bias (%)	RMSE (cm)	MAPE (%)
	$dbh = d_m \times (1 - \exp(-a \times t)) \times \exp(b_5 \times (T - 20.7) + b_6^* \times (Humidity - 83.8) + b_7^* \times (Pdry - 78) + b_8 \times (Tdry - 19.2) + b_9 \times (Train - 21.3) + b_{10}^* \times (Hdry - 78.1) + b_{11}^* \times (Hrain - 85.3))$	$1/t^{-0.1\delta}$	7112.4	0.563	2.54	13.0	29.79
	$dbh = d_m \times (1 - \exp(-a \times t)) \times \exp(b_5 \times (T - 20.7) + b_8^* \times (Tdry - 19.2) + b_9 \times (Train - 21.3))$	$1/t^{0.1\delta}$	7066.1	0.559	2.09	12.9	29.38
	$\mathbf{dbh = d_m \times (1 - \exp(-a \times t)) \times \exp(b_5 \times (T - 20.7) + b_9 \times (Train - 21.3))}$	$\mathbf{1/t^{-0.1\delta}}$	**7049.5**	**0.557**	**2.83**	**13.1**	**29.01**

Note: *dbh*: Diameter at breast height in cm at age *t* in year; d_m is the limit of the diameter (asymptotic diameter); T: Temperature (°C year^{-1} averaged); Humidity (% year^{-1} averaged). Pdry (mm), Tdry (^{0}C averaged), Train (^{0}C averaged), Hdry (%, averaged) and Hrain (%averaged (are rainfall, temperature, and humidity in dry and rainy seasons respectively n = 1264. Splitting the dataset randomly into 70% data for equation development and 30% for validation over 200 realizations, statistics for comparison and validation of the models were averaged over 200 realizations; δ: the variance function coefficient; *: Parameter with $P_{value} > 0.05$. Bold: Selected model based on cross-validation statistics and diagnostic plots.

subregions and elevation above the sea level to improve the reliability of estimation *dbh* via *t* (Table 6).

Because of the annual (Fig. 7) and seasonal variability in the climate in three ecological sub-regions, and based on PCA result we included seasonal factors (the dry and rainy seasons) to examine the effects of seven factors such as Tdry, Train, Pdry, Hdry, Hrain, T and Humidity on the *dbh* model. As a result, four climatic factors of T, humidity, Tdry and Train were reflected in their impact on the growth model *dbh*, with decreased AIC values and significantly increased R^2adj.; some errors of the model considering the effect of T, humidity, Tdry and Train were also improved (Table 5), compared to the fixed model. Fig. 8 also shows a reduction in the variation between validation data of observed *dbh* and *dbh* predicted by each class of the T, humidity, Tdry and Train factors, compared to the fixed model in Fig. 5. Therefore, establishing a class-based modeling system of climatic factors could improve the reliability of growth model *dbh* of Dalat pine (Table 7).

The *dbh* growth curve of Dalat pine was distinguished by classes of ecological sub-regions, altitude, T, humidity, Tdry and Train factors, indicating a clear separation between *dbh* fitted values, according to different classes in each factor (Fig. 9).

3.4. Diameter growth model with combination of environmental and climatic factors

Based on the results of PCAs to select the factors, our examination of the performance of diameter growth model under combined effect of two factor combinations consisted of ecological environment and climate factors (Table 8 and Table 9).

The result for combination of ecological enviromental factors (including four factors such as Eco-subregion, Forest canopy, Slope and Altitude) showed that Altitude had no significant effect ($P > 0.05$; Table 8). Therefore, we selected three factors of eco-subregion, forest canopy and slope which affected on *dbh* to develop the growth model (Table 8). In addition, we tried to include only two factors of eco-subregion and altitude that are important and easy to access into the *dbh* model. The resulting model showed a good fit for estimating *dbh* growth along with different eco-subregions and gradients of altitudes (Table 8).

The combination of climatic factors including seven factors such as T, Humidity, Pdry, Tdry, Train, Hdry, and Hrain indicated that factors of Humidity, Pdry, Hdry, Hrain and Tdry had no significant effect ($P > 0.05$; Table 9). So, we selected two factors T and Train which influenced *dbh* to develop the growth model (Table 9).

The two entire datasets (environment and climate) were used to estimate final set of parameters. The selected models has the following forms:

For *dbh* model with ecological environment factors:

$$dbh = 300 \times (1 - exp(-0.001475 \times t)) \times exp(0.483785 \times (Eco - subregion - 2) - 1.197256 \times (Forestcanopy - 0.62) - 0.027390 \times (Slope - 13.9)) \quad (23)$$

$$dbh = 300 \times (1 - exp(-0.001294 \times t)) \times exp(0.253774 \times (Eco - subregion - 2) - 0.000612 \times (Altitude - 1541)) \quad (24)$$

For *dbh* model with climatic factors:

$$dbh = 300 \times (1 - exp(-0.001190 \times t)) \times exp(-0.418898 \times (T - 20.7) + 0.481779 \times (Train - 21.3)) \quad (25)$$

4. Discussion

4.1. Variation of diameter growth at different sites: Fixed vs. Mixed models

The model of Mitscherlich (Monomolecular) chosen is simple and is parsimonious with only one parameter consistent with the recommendation of Sedmak and Scheer (2012), who pointed out that a simpler form, with fewer parameters, had better extrapolation than more complicated equations and also fitted better to the observed data.

The fixed-effects model had wide variation between observed *dbh* and predicted values and gave quite large errors. Meanwhile, including random effects in a nonlinear mixed-modeling approach improved the reliability of the dbh growth model, concurring with the previous study by Timilsina and Staudhammer (2013). Incorporating random effects into the growth model also increased the accuracy of fixed-effects prediction (Pinheiro and Bates 2000, Budhathoki et al. 2008). Therefore, the random effects are essential to account for the effects of different site formation factors on the growth model when the site index has not been established (Timilsina and Staudhammer, 2013). The random effects may be due to soil (fertility, drainage), topography (elevation, aspect), climate (temperature and rainfall patterns), and other factors, that reflect the fluctuation of growth in diameter of a certain tree species (Vanclay, 1994). Meaningful growth and yield forecasts require some validation of these site differences which is a composite function of slope, aspect, and altitude (Ma and Lei, 2015; Trasobares et al., 2004).

Consistent with those assumptions, this study has shown that mixed models under random effects of a number of forest ecological environmental and climatic factors, such as ecological sub-regions, altitude, T, humidity and two seasonal climatic factors of Tdry and Train improved the reliability of *dbh* predictions. The predicted *dbh* values for each class of random effect factors were closer to the observed *dbh* values than for the fixed-effects only model (Figs. 6 and 8, compared to Fig. 5); and mixed models produced higher precision than did fixed models, such as lower AIC value, larger $R^2_{adj.}$, lower bias, and lower MAPE (Tables 4 and Table 5).

Based on $R^2_{adj.}$, Bias, RMSE, MAPE, fixed *dbh* growth model that combined environmental and climatic factors, in many cases outperformed the mixed-effects *dbh* growth models with random effect of each factor. When using the combination of environmental and climatic factors in the fixed *dbh* growth model, the factors were related to each other, e.g., eco-subregion already accounts for some ecological and environmental factors, so other factors that did not reflect their influence.

4.2. Ecological environmental and climatic factors affected the diameter growth of Dalat pine

The site characteristics significantly influence the growth and increment of forest trees (Timilsina and Staudhammer, 2013). In the Central Highlands of Vietnam, the highest dbh growth for Dalat pine was in the ecological sub-region 3 K, which received the highest annual precipitation levels ranging from 1451 mm $year^{-1}$ to 3175 mm $year^{-1}$, the annual average temperature around the 21 °C − 23 °C, and also extending at the lower altitudes range between 1000 m and 1200 m. This was followed by the CYS sub-region and the lowest dbh growth was observed in BD sub-region (Table 6, Fig. 9).

Topographic factors can be used for modeling site effects on forest tree growth in tropical mixed uneven-aged forests. For example, the parameters for *Pinus resinosa* Aiton (red pine) models for classes of altitude and slope factors were significantly different, with the results showing that trees grew better in lower and flatter areas (Lee et al., 2004). In this study, the slope factor varied highly (from 5° to 25°), and it is consistent with comments of Lee et al. 2004, this factor affected the *dbh* growth of Dalat pine through equation (23), the increase in the slope degree over 14^0 decreased the diameter growth of Dalat pine trees. Meanwhile, similar to findings for red pine (Lee et al., 2004), *dbh* growth of Dalat pine changed significantly under different altitudes. Growth was best at altitudes of 1000–1500 m and then decreased with altitudes over 1,500 m (Table 6, Fig. 9, Equation (24)). Dalat pine trees also don't regenerate in closed canopy forests (Trang, 2011; Hai, 2018). This was also reflected through the negative coefficient for canopy cover (Equation (23)) suggesting that the dbh growth in Dalat pine decreased for forests with higher than 62% canopy cover.

The dendrochronology field has had many studies on the relationship between climate and tree growth (Fritts et al., 1979; Cook et al., 1987; Dymond et al., 2016). Studies on the impact of climate change on tree growth have extensively shown that changes in important climatic factors such as annual rainfall and temperature affect tree ring widths. The climate data used in this study show the annual variability of P, T and humidity for the last 40 years, with a positive trend in temperature specially in the BD ecological sub-region, by 1 °C, while in 3 K and CYS ecological sub-regions the humidity increased by 3–4%. This observation further emphasizes the need for examining the growth in response to climatic variables (Dymond et al., 2016). Conifers are influenced by climate, especially temperature; they exist in a wide range of climates, and the coldness affects the distribution and growth of different conifers (Bannister and Neuner. 2001). In addition, climate change has the potential to create additional threats and affect the growth and the regeneration of pine forests (Zonneveld, et al. 2009.

The average annual temperature (T), Tdry and Train for optimal dbh growth of Dalat pine were between 20 °C and 22 °C, and $< 82\%$ humidity (Table 7 and Fig. 9). An increase of T or Tdry over 22 °C reduced the growth of dbh (Fig. 9). In fact, the temperature, humidity, and hours of sunlight are correlated. Usually in tropical areas when trees correlate positively with temperature it could be because of some physiological behavior related to the need for sunlight to photosynthesize. Additionally, when temperature increases, humidity is reduced which is reflected in the growth curves under three classes of humidity. Generally, the drier the better but when the temperature exceeds the optimal threshold, it will reduce the growth of trees.

Following the same recommendation as Bueno and Bevilacqua (2009) for *Pinus occidentalis*, the *dbh* growth modeling system developed and validated in this study should be used to estimate both future diameter (yield) and periodic diameter increment (growth), with site as the random effects. Using the selected model $dbh = dm \times (1 - \exp(-a \times t))$ and the parameters for each ecological sub-region (Table 6) estimates the fitted *dbh* vs. *t* for Dalat pine shows at the age of 100 years, the respective *dbh* growth and increment measures of trees from the different sites were 29.01 cm and 0.29 cm year^{-1} for BD, 31.14 cm and 0.31 cm year^{-1} for CYS, and 64.29 cm and 0.64 cm year^1 for 3 K. The *dbh* increments of Dalat pine at the age of 40 years on an optimal site, such as 3 K, reached 0.690 cm year^{-1}, double that of other conifers such as *Pinus strobus* L., with an average annual *dbh* increment of 0.308 cm at the same age (Bebber et al. 2004).

Research on the relationship between climate and forest tree growth is a broad topic and has many achievements that contribute to sustainable forest management (Dymond et al., 2016; Buckley et al., 2017; Cook et al., 1987; Fritts, 1987, 1976; Fritts and Swetnam, 1989). This study indicated a close relationship between climate and dbh growth of Dalat pine, in particular the annual mean temperature and average temperature during the rainy season as the growing season has a significant effect on the trees growth of this species, which is one of the bases for silvicultural management and species conservation. The system of growth models developed in this study account for the influence of ecological and climate factors and will contribute to identify the most suitable areas for conservation and expansion and optimize planning systems of Dalat pine for forest management under climate change.

5. Conclusion

The developed modeling system for diameter growth of Dalat pine consists of Mitscherlich equation: $dbh = d_m \times (1 - \exp(-a_j \times t))$ selected for dbh model with random effects of ecological environmental factors (Eco-subregion includes three ecological sub-regions in the Central Highlands of Vietnam, Altitude), and climatic factors (T), Humidity, and temperature in dry (Tdry) and in rainy (Train) seasons produced the best results.

Whereas, the systems of the fixed-effects *dbh* growth models that used the exponential function of environmental or climatic factors as the modifiers of an average diameter growth model performed the best:

$$\begin{aligned} dbh = 300 &\times (1 - exp(-0.001475 \times t)) \\ &\times exp(0.483785 \times (Eco - subregion - 2) - 1.197256 \\ &\times (Forestcanopy - 0.62) - 0.027390 \times (Slope - 13.9)) \end{aligned}$$

$$\begin{aligned} dbh = 300 &\times (1 - exp(-0.001294 \times t)) \\ &\times exp(0.253774 \times (Eco - subregion - 2) - 0.000612 \\ &\times (Altitude - 1541)) \end{aligned}$$

$$\begin{aligned} dbh = 300 &\times (1 - exp(-0.001190 \times t)) \\ &\times exp(-0.418898 \times (T - 20.7) + 0.481779 \times (Train - 21.3)) \end{aligned}$$

Improved predictions were observed when environmental and climatic factors were incorporated as fixed-effects to the growth model.

Establishment of the *dbh* growth models under the influence of environment and climate are expected to contribute to site definition for conservation and development of this species, and to forecasting growth for silvicultural planning for population conservation of this endemic species.

CRediT authorship contribution statement

All authors do not have any financial and personal relationships with other people or organizations that could inappropriately influence (bias) their work. Bao Huy conceptualized the project, acquiring funding , conducted data analysis, developed methods and wrote the original draft manuscript. Le Canh Nam administered the project, helped in acquiring funding, collected data, and provided supervision. Krishna P. Poudel – reviewed the manuscript and contributed methods for analysis. Hailemariam Temesgen critically reviewed the manuscript, edited draft, and handled correspondence among authors and editors.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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