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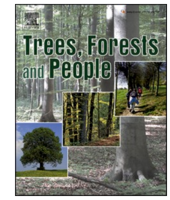

Stand growth modeling system for planted teak (*Tectona grandis* L.f.) in tropical highlands

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ABSTRACT

We developed a system for modeling the growth and yield of planted teak (*Tectona grandis* L.f.) for small diameter products under varying management regimes in the tropical Central Highlands of Viet Nam. We compared an independent and simultaneous system of models to predict dominant height (*Ho*), quadratic mean diameter (*Dg)*, averaged tree height *(Hg)* with *Dg*, and mean tree volume (*V)* versus stand age (*A*). In addition, the model system performance with and without site index (*SI)* and stand density *(N)* as covariates were compared using K-fold cross-validation. The best modeling system was obtained with the simultaneously fit models that included *SI* and *N* and were in the form of: $Dg = D_m/(1 + a \times exp(-b \times A)) \times exp[e_1 \times (SI - 15) + e_2/1000 \times (N - 722)]$; $Hg = H_m \times exp(-a \times exp(-b \times A)) \times exp[e_1 \times (SI - 15) + e_2/1000 \times (N - 722)]$; and $V = \frac{\pi}{4 \times 10^4} Dg^2 \times Hg \times 0.45$; where D_m, H_m, *a, b*, e_1 and e_2 were the parameters to be estimated. These models will help predict the growth and yield of teak planted for different planting schemes, includings monoculture, agroforestry, and forest enrichment planting in this region.

Introduction

Teak (*Tectona grandis* L.f.) is a well-known commercial timber species (Palanisamy et al., 2009) distributed mainly in tropical or subtropical countries. It is a large deciduous tree that grows up to 250 cm in diameter at breast height and up to 50 m in height under favorable conditions (Orwa et al., 2009; Palanisamy et al., 2009). The natural distribution of teak extends to India, Myanmar, Thailand, and Laos (Kaosa-ard, 1989; White, 1991; Weaver, 1993; Ladrack, 2009; Palanisamy et al., 2009; and Huy et al., 2018), covering an area of 28 million hectares (Radio and Delgado, 2014).

Teak is a light-demanding species that grows naturally in tropical semi-evergreen forests dominated by *Lagerstroemia* sp., *Xylia xylocarpa* (Roxb.) Taub., in mixed deciduous forests, dipterocarp forests (Kollert and Cherubini, 2012; Hlaing and Teplyakov, 2013), and in bamboo forests (Huy et al., 2018). It grows in a wide range of climates, from arid regions with 500 mm annual rainfall to wet areas with up to 5000 mm of rainfall in a year. However, this species grows best in areas receiving around 1200 - 2500 mm $year^{-1}$ of rainfall with a dry season length of 3 to 5 months; temperature between 27 and 36°C (Kaosa-ard, 1998; Weaver, 1993); and in altitude lower than 1000 m (Huy et al., 2018). Similarly, it can grow in various soil types but grows well in soil with high Ca, P, and Mg content, gravel soil. It does not grow well in soils with high clay or sand and waterlogged soils (Seth and Yadav, 1958; Hlaing and Teplyakov, 2013; Huy et al., 2018).

Teak has been popular worldwide due to its high quality of wood (Radio and Delgado, 2014) and its high demand on the global market (Palanisamy et al., 2009; Radio and Delgado, 2014). Teak plantations have been established in 4.3 million hectares (Roshetko et al., 2013; Sabastian et al., 2014; Newby et al., 2012) in and out of the areas where it grows naturally (Kanninena et al., 2004; Ladrack, 2009). Although teak was once managed on 80 to 100 years cycle (Kollert và Cherubini, 2012), the current rotation age has been reduced to 20 or 25 years for both veneer and bar production. It is used in many countries to generate

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profits relatively quickly (Ladrack, 2009; Radio and Delgado, 2014; Huy et al., 2018).

Teak has been experimentally grown in Viet Nam since the 1950s and expanded to Viet Nam's tropical Central Highlands and Southeast ecoregions since the 1980s and 1990s. In the past two decades, teak plantation area in Viet Nam has been comparable with industrial crops of high economic value, such as coffee, rubber, and pepper. For this reason, many of the teak plantations have been replaced by these industrial crops. However, the unsustainable monoculture of industrial crops has led to soil degradation and reduced groundwater levels. Therefore, there is an increasing need for intercropping teak with short-term crops and cash crops (Mulia and Nguyen, 2021) or to use teak to enrich degraded dipterocarp forests (Huy et al., 2018).

Individual-tree and stand-level teak growth models have been developed in many teak-growing continents such as Asia, South America, and Africa. Diameter and height growth models (components of growth and yield models) have used functions such as Mitscherlich, Richards, Gompertz, and Korf (e.g., by Hlaing and Teplyakov (2013) in Myanmar and by Vongkhamho et al. (2022) in Laos). Volume growth is usually estimated as a function of diameter and height using the power function (Akossou et al., 2013; Canadas et al., 2018). The dominant tree height growth model is commonly used to determine the site index for teak plantations (Canadas et al., 2018).

Growth and yield studies for teak planted in agroforestry models or the teak plantation, in general, are scarce in Viet Nam. An established yield table was based on stand growth such as height, basal area, and volume (Huy, 1995). However, the growth equations have not been sufficiently developed or cross-validated to select the optimal equations from various forest growth models (Zeide, 1989, 1993; Vanclay, 1994; Luo et al., 2018; Huy et al., 2020). In addition, teak growth and yield models have not been based on the changes in the ecological, environmental, and stand characteristics. Therefore, developing a growth modeling system for planted teak stands is necessary based on-site indices representing different ecological and environmental conditions and stand variables for planning and managing teak plantations under different farming practices in the tropical Central Highlands of Vietnam.

The objectives of this study were to (i) develop a modeling system for planted teak stand growth; and (ii) predict the growth and yield of the planted teak for producing small wood products with a rotation period of fewer than 20 years under varying management regimes such as monoculture, agroforestry, and forest enrichment planting.

Materials and methods

Study sites and planted teak stand

The study sites are located in the Kon Tum and Dak Lak provinces of the tropical Central Highlands of Viet Nam (Fig. 1). The altitude ranges from 300 to 600 m; the average annual rainfall varies from 1200 mm to 2000 mm; the average annual temperature is approximately 22°C and varies from 18 to 30°C (Hydro-meteorological stations in the Central Highlands). The soil types include red-brown soil on basalt and gray-

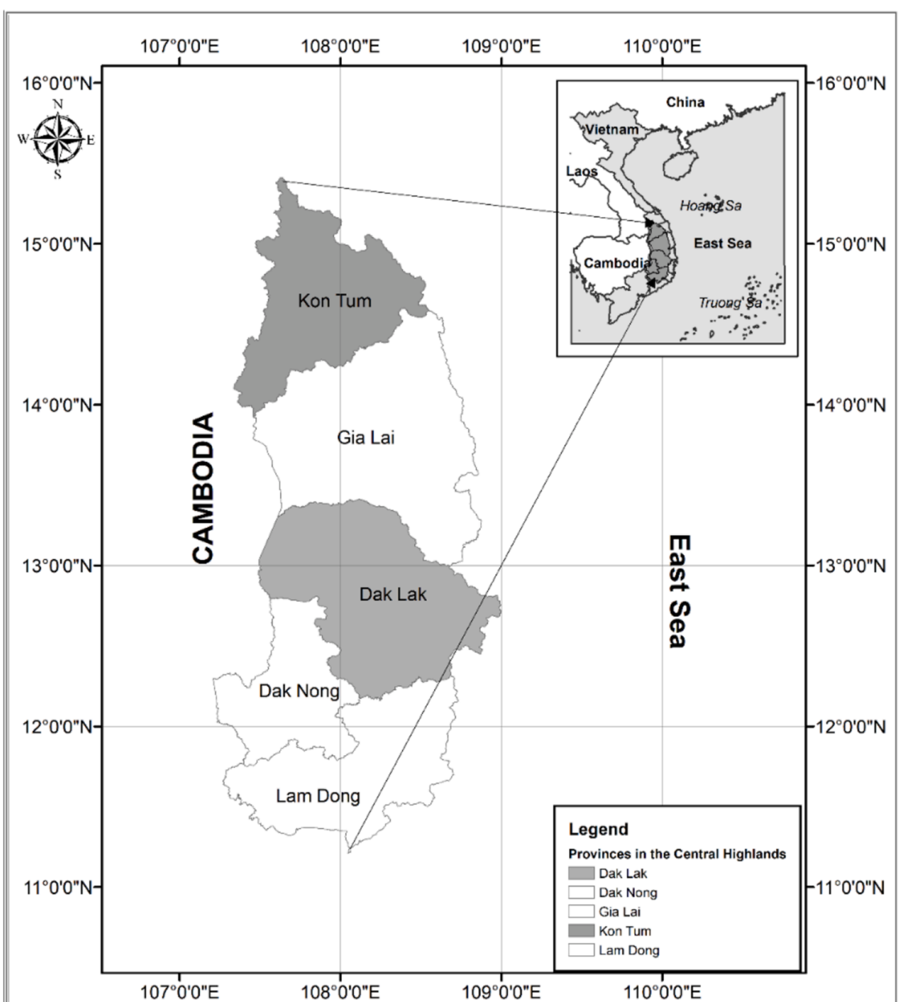

Fig. 1. Tropical Central Highlands of Viet Nam and two provinces Kon Tum and Dak Lak where the study was conducted.

yellow soil on magma acid.

The studied teak trees were planted in a monoculture or agroforestry models, in which teak is intercropped with short-term crops such as rice, maize, cassava, and beans. Stand age (A, year) ranged from 3 to 17 years, basal area (BA) of the stand was 1.6 - 34.0 m^2 ha^{-1}, stand density (N, tree ha^{-1}) ranged from 230 to 1400 trees ha^{-1} with an average of 722 trees ha^{-1} (Table 1). The plantation was established to provide small timber with an expectation of achieving 20–25 cm diameter under a 15–20 year rotation cycle.

Sampling design, data collection, and variable calculation

One hundred and ten 1000m^2 rectangular plots (20 × 50 m) of planted teak stands representing a range of ages and planting density were purposively sampled (Fig. 2). Diameter at breast height (D, cm) and tree height (H, m) were recorded for all planted teak trees in the sample plots. The quadratic mean diameter (Dg, cm) was calculated for each sample plot. The average height of the trees corresponding to Dg is denoted by Hg (m) obtained from the H - D regression model based on Dg in each sample plot. The average height of the dominant trees (Ho, m) was obtained as the average of 20% of the tallest trees in the sample plot. The mean volume (V, m^3) of the tree with Dg and Hg in each plot was calculated in the following form:

$$V = \frac{\pi}{4 \times 10^4} Dg^2.Hg.f \tag{1}$$

where f is the average form factor for teak and equals 0.45 (Hlaing and Teplyakov, 2013).

Table 1 shows the summary statistics for each variable of the studied stand.

Independent stand growth models

The commonly used model forms for growth of Ho, Dg, Hg, and V are listed below (Zeide, 1989, 1993; Vanclay, 1994; Sedmak and Scheer, 2012; Martins et al., 2014; Luo et al., 2018; Huy et al., 2020):

$$Bertalanffy: \ y = y_m \times (1 - a \times exp(-b \times x))^3 \tag{2}$$

$$Chapman - Richards: y = y_m \times (1 - exp(-a \times x))^b \tag{3}$$

$$Gompertz: y = y_m \times exp(-a \times exp(-b \times x)) \tag{4}$$

$$Korf: y = y_m \times exp(-a / x^b) \tag{5}$$

$$Logistic(Autocatalytic): y = (y_m / 1 + a \times exp(-b \times x)) \tag{6}$$

$$Mitscherlich(Monomolecular): y = y_m \times (1 - exp(-a \times x)) \tag{7}$$

$$Power\ Decline: y = y_m \times exp(a / (b - 1)) \times x^{-(b-1)} \tag{8}$$

$$Weibull: y = y_m \times (1 - exp(-a \times x^b)) \tag{9}$$

Table 1
Summary statistics of variables used in this study ($n = 110$ sample plots).

ID	Variables	Min	Mean	Max	Std.
1	*A (age of the stand, year)*	3	9.7	17	3.5
2	*Dg (cm)*	6.7	16.0	30.6	4.8
3	*Hg (m)*	3.5	11.6	19.7	3.8
4	*Ho (m)*	4.2	12.5	20.9	3.9
5	*V (m^3 $tree^{-1}$)*	0.006	0.133	0.635	0.124
6	*N (number of trees ha^{-1})*	230	722	1440	260

Note: Dg is the quadratic mean diameter and Hg is the height of the tree with diameter at breast height = Dg. Ho is the average height of 20% of the tallest trees in the sample plot. V is the volume of the tree with Dg and Hg.

where y represents Ho, Dg, Hg, or V, x is age (A), and y_m, a, and b are parameters to be estimated.

Analysis of the stand growth of Ho, Dg, Hg, and V versus A (Fig. 3) showed heteroscedasticity in the model residuals, which was accounted for by using weighted regression (Davidian and Giltinan, 1995; Picard et al., 2012; Ma and Lei, 2015; Huy et al., 2019, 2020). Additionally, preliminary analysis showed autocorrelation among Ho, Dg, Hg, and V model residuals. This was accounted for by including a first-order autoregressive correlation structure to describe the within-group correlation (Xu et al., 2014; Huy et al., 2020). Weighted nonlinear models were fitted by maximum likelihood (Timilsina and Staudhammer, 2013; Pinheiro et al., 2014) using nlme package in R (R Core Team, 2020).

Site index curves

The site index (SI) curves were based on the selected Ho versus A model (Weaver, 1993; Gomez and Ugalde, 2006; Kim et al., 2018). The standard (base) age (Ast) selected to determine SI values (Gomez and Ugalde, 2006) was 12 years, the age at which the teak trees in the study area had the greatest variability in height.

Simultaneous estimation modeling system

The seemingly unrelated regression (SUR) allows for simultaneous estimation of growth components and accounts for the cross-equation correlation (Parresol, 2001; Affleck and Dieguez-Aranda, 2016; Poudel and Temesgen, 2016; Gonzalez-Benecke et al., 2018; Huy et al., 2019; Trautenmüller et al., 2021). Therefore, the weighted nonlinear SUR (WNSUR) was used to fit the system of Dg, Hg, and V equations using the SAS procedure Proc Model (SAS Institute Inc. 2014). The general forms of the system components were as follows:

$$Dg = f_1(A) + \varepsilon_1 \tag{10}$$

$$Hg = f_2(A) + \varepsilon_2 \tag{11}$$

$$V = \frac{\pi}{4 \times 10^4} Dg^2.Hg.f = \frac{\pi}{4 \times 10^4} f_1(A)^2.f_2(A).0.45 + \varepsilon_3 \tag{12}$$

where f_1 and f_2 were functions selected from Eqs. Eqs. (2)–(9) and $\varepsilon_{1,2,3}$ are the random errors of the models.

WNSUR stand modeling system associated with SI and N

This study examined a WNSUR simultaneous growth modeling system that incorporates the combination of SI and N as predictor variables. Then, it was compared with the weighted nonlinear growth models fitted independently. In the WNSUR modeling, the form of the stand growth models consists of two parts, a selected average growth model and a modifier (Lessard et al., 2001; Huy et al., 2020) as follows:

$$Stand\ Growth = Average \times Modifier + \varepsilon \tag{13}$$

$$and\ Modifier = \exp[e_1(SI - \overline{SI}) + e_2(Ni - \overline{N})] \tag{14}$$

where Stand Growth is a vector of growth measurements of the i^{th} tree in terms of Dg, Hg, or V; Average is the selected fixed-effect growth model for Dg, Hg, or V; e_1 and e_2 are coefficients of the Modifier equation; SI, $\overline{SI}$ and Ni, $\overline{N}$ are the value of site index and density of the i^{th} plot and their averages, respectively, and ε is the random error of the model. The Modifier function helps to adjust the stand growth prediction values according to SI and N factors. When SI and N are equal to their means, Modifier = 1 and Stand growth are equal to the Average function. In other words, when SI or N for the stand is different from the means, the Stand Growth models are adjusted according to exponential function along with the parameters e_1 and e_2.

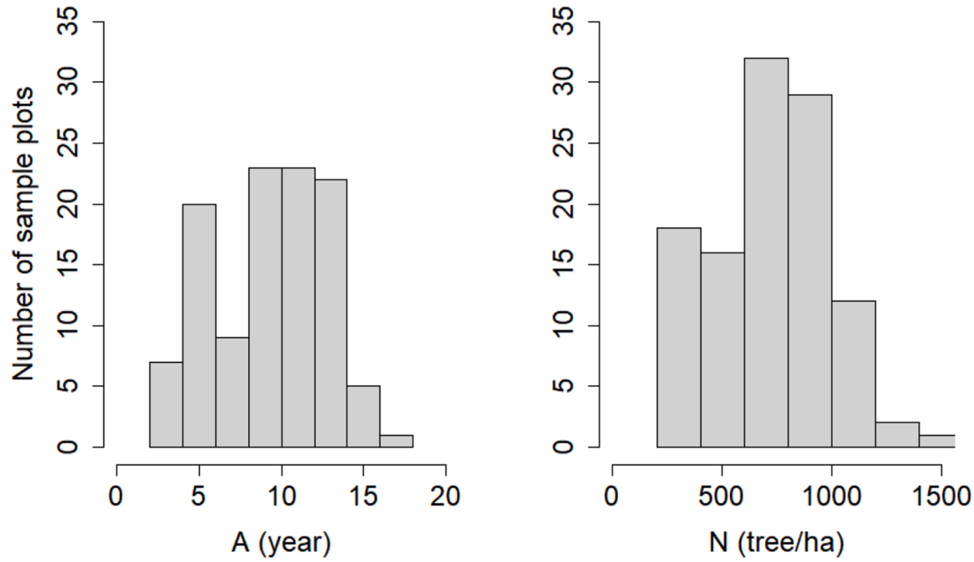

Fig. 2. Stand age (*A, year*) and density (*N*, tree ha^{-1}) distributions in the 1000 m^2 sample plots ($n = 110$).

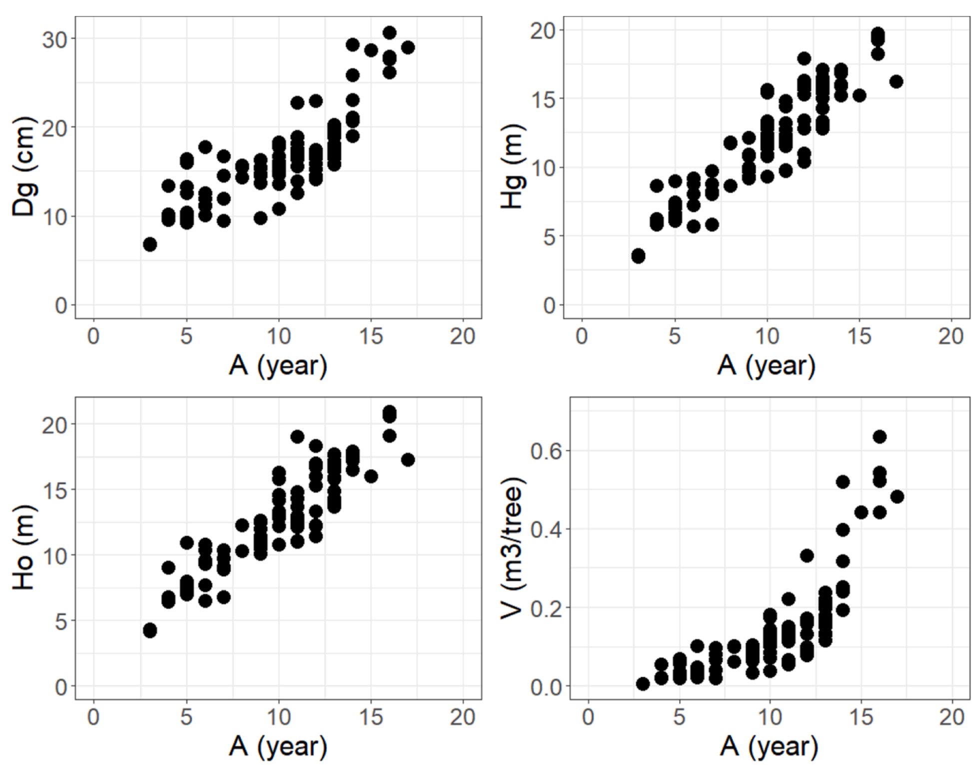

Fig. 3. Scatter plot of observed stand growth values vs. *A* (age of stand, year). *Dg* is the quadratic mean diameter at breast height and *Hg* is the height of the tree with *Dg*. *Ho* is the mean height of 20% of the tallest trees in the sample plot. *V* is the volume of the tree with *Dg* and *Hg*.

Cross-validation

K-fold cross-validation (Kohavi, 1995) was applied to compare and select the best teak stand growth modeling system. The dataset was randomly split into K folds subsamples ($K = 10$) of equal size, in which K - 1 subsamples were used to develop models and calculate AIC (Akaike, 1973) and adjusted R^2, and the remaining subsample was used to validate the models and estimate errors such as percent bias, root mean squared error (RMSE), and mean absolute percent error (MAPE,%). Finally, all those statistics were averaged over 10 times. The model with the smallest AIC value and high adjusted R^2 was preferred. Diagnostic plots of the trend of fitted vs. observed values and weighted residuals vs. fitted values were also used to assess model performance. Models that had smaller values of cross-validation errors were preferred.

$$Bias\ (\%) = \frac{1}{K}\sum_{1}^{10}\frac{100}{n}\sum_{i=1}^{n}\frac{y_i - \widehat{y}_i}{y_i} \tag{15}$$

$$RMSE = \frac{1}{K}\sum_{1}^{10}\sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \widehat{y}_i)^2} \tag{16}$$

$$MAPE\ (\%) = \frac{1}{K}\sum_{1}^{10}\frac{100}{n}\sum_{i=1}^{n}\frac{|y_i - \hat{y}_i|}{y_i} \tag{17}$$

where K is the number of folds (10); n is the number of samples in Kth fold; and y_i and $\hat{y}_i$ are observed and predicted values of the dependent variables for the *ith* sample, respectively.

Once the models have been cross-validated, final parameters for all of the selected modeling systems were estimated by fitting the models with the entire dataset.

Results

Models for Ho, Dg, Hg, and V developed indepedently

The results of K-fold cross-validation for independently developed *Ho, Dg, Hg,* and *V* models are presented in Table 2. Diagnostic plots associated with the *Ho* model fit are given in Fig. 4. Similar diagnostics plots were also evaluated for other dependent variables but not presented here. Based on statistical criteria, cross-validation errors, and diagnostic plots, the model forms selected for each stand growth variables are as follows.

$$Ho = H_m \times (1- a \times \exp(-b \times A))^3 \tag{18}$$

$$Dg = D_m/(1 + a \times \exp(-b \times A)) \tag{19}$$

$$Hg = H_m \times \exp(-a \times \exp(-b \times A)) \tag{20}$$

$$V = V_m/(1 + a \times \exp(-b \times A)) \tag{21}$$

Site index curves

The *SI* determined for teak plantations in the tropical Central Highlands was based on the Bertalanffy function with the estimated parameters as follows:

$$Ho = 48.84 \times (1- 0.5933 \times \exp(-0.04981 \times A))^3 \tag{22}$$

SI values correspond to the standard age or the base age ($A_{st} = 12$ years) according to the following equation:

$$SI = 48.84 \times (1- 0.5933 \times \exp(-0.04981 \times A_{st}))^3 \tag{23}$$

An average *SI* value at $Ast = 12$ years for the study area was 15 m using Eq. (23). Based on the observed variation of *Ho* at age $Ast = 12$ and practical applicability in this region, the planted teak was divided into 3 levels of site index: $SI = 12$ m (S12: poor site), $SI = 15$ m (S15: average site), and $SI = 18$ m (S18: good site). The *Ho* curves for three levels of the site index were determined by dividing Eq. (22) by (23) together with the values of the site index such as S12, S15, and S18 at $Ast = 12$ years as follows:

$$Poor\ site\ S12:\ Ho = 12\left[\frac{1 - 0.5933 \times exp(-0.04981 \times A)}{1 - 0.5933 \times exp(-0.04981 \times 12)}\right]^3 \tag{24}$$

$$Average\ site\ S15:\ Ho = 15\left[\frac{1 - 0.5933 \times \exp(-0.04981 \times A)}{1 - 0.5933 \times \exp(-0.04981 \times 12)}\right]^3 \tag{25}$$

$$Good\ site\ S18:\ Ho = 18\left[\frac{1 - 0.5933 \times exp(-0.04981 \times A)}{1 - 0.5933 \times exp(-0.04981 \times 12)}\right]^3 \tag{26}$$

Fig. 5 provides the *Ho* curves for the three site indexes S12, S15, and S18. The base age 12 *SI* for planted teak at any site and stand age this region can be estimated using Eq. (27).

$$SI = Ho_j\left[\frac{1 - 0.5933 \times exp(-0.04981 \times 12)}{1 - 0.5933 \times exp(-0.04981 \times A_j)}\right]^3 \tag{27}$$

where Ho_j is *Ho* at A_j of the stand that needs to define *SI*.

Eq. (27) determines the *SI* values at $Ast = 12$ years for 110 plots studied at different ages A_j. Then, the *SI* variable was incorporated into the growth modeling system.

Simultaneous modeling system for Dg, Hg, and V

A modeling system including *Dg, Hg* and *V* fit by WNSUR and cross-validated by K-Fold was performed to address the limitation of independent stand growth models. In the WNSUR modeling, the equation forms for *Dg* and *Hg* were selected from the cross-validation of independently developed models presented in Table 2. The Logistic function was selected as *Dg* model form and Gompertz function for *Hg* model form in WNSUR system. The results of the K-fold cross-validation for the fit of the *Dg, Hg,* and *V* modeling system developed simultaneously by WNSUR are presented in Table 3.

Effects of SI and N on stand growth

K-Fold cross-validation statistics for the selected WNSUR stand growth modeling system (*Dg, Hg,* and *V*) associated with *SI* and stand *N* are presented in Table 4. The estimated modeling system parameters are presented in Table 5. The estimated stand attributes of a 15 years old (which is the age near the end of the rotation cycle of a small diameter teak production system) teak plantation in three site classes (*S12, S15,* and *S18*) and under three common stand densities (300, 700 and 1100 tree ha^{-1}) are presented in Table 6. Stand densities of 300 - 700 tree ha^{-1} are common in agroforestry systems that combine teak with short-term crops or in enrichment planting of teak in the degraded dipterocarp forests. At the same time, $N = 1100$ tree ha^{-1} is exclusive.

Discussion

The need for site index curves for planted teak in tropical highlands

Planted teak growth and yield vary depending on ecological and environmental conditions (Palanisamy et al., 2009). In determining whether a site is good or poor for teak plantations, one needs to consider factors such as climate, geology, topography, and soil (Radio and Delgado, 2014). Because teak stands have been grown in the tropical Central Highlands of Viet Nam in different soils, topographies, and climates, teak has different growth. Therefore, the site index curves for different site classes representing various ecological and environmental conditions are critical. The division of teak plantations according to other SI in Eq. (27) will help improve the reliability in the estimate of stand growth and the management and prediction of yield according to the appropriate production cycle.

Independent vs. simultaneous stand growth modeling system fit

The simultaneous modeling system fit by WNSUR did not significantly improve the cross-validation statistics compared to the independent model fit (Table 3 vs. Table 2). However, the calculation of the *V* values through Eq. (1) based on the predicted *Dg* and *Hg* with independent fit differed from the estimates obtained from the independent *V* model. Additionally, separate stand models of *Dg, Hg,* and *V* produce biologically inconsistent estimates that scale up to a large area, affecting the final growth and yield estimated. In contrast, simultaneous fit provides greater efficiency than independent fit because the variance and covariance information of the stand components such as *Dg, Hg,* and *V* are included in the modeling system (Parresol, 2001; Poudel and Temesgen, 2016).

Table 2
Comparison and selection of the stand growth models of *Ho, Dg, Hg*, and *V* developed independently using K-Fold cross-validation.

Id	Model forms	AIC	$R^2_{adj.}$	Bias (%)	RMSE	MAPE (%)
Stand *Ho* growth models						
1	**Bertalanffy:** $\boldsymbol{Ho = H_m \times (1- a \times exp(-b \times A))^3}$	**372.3**	**0.844**	**−1.56**	**1.5**	**10.01**
2	Chapman-Richards: $Ho = H_m \times (1- exp(-a \times A))^b$	372.0	0.841	−1.60	1.5	10.11
3	Gompertz $Ho = H_m \times exp(-a \times exp(-b \times A))$	373.6	0.843	−1.73	1.6	10.09
4	Korf: $Ho = H_m \times exp(-a/A^b)$	376.7	0.832	−1.47	1.6	10.29
5	Logistic (Autocatalytic): $Ho = H_m/(1 + a \times exp(-b \times A))$	374.1	0.843	−1.66	1.5	10.14
6	Mitscherlich (Monomolecular): $Ho = H_m \times (1- exp(-a \times A))$	373.3	0.835	−1.17	1.6	10.16
7	Power Decline: $Ho = H_m \times exp(a/(b-1)) \times A^{-(b-1)}$	371.7	0.841	−1.58	1.5	10.07
8	Weibull: $Ho = H_m \times (1- exp(-a \times A^b))$	370.8	0.841	−1.59	1.5	10.19
Stand *Dg* growth models						
1	Bertalanffy: $Dg = D_m \times (1- a \times exp(-b \times A))^3$	478.6	0.695	−2.61	2.6	12.63
2	Chapman-Richards: $Dg = D_m \times (1- exp(-a \times A))^b$	484.2	0.650	−2.77	2.8	12.82
3	Gompertz: $Dg = D_m \times exp(-a \times exp(-b \times A))$	475.6	0.708	−2.61	2.6	12.70
4	Korf: $Dg = D_m \times exp(-a/A^b)$	488.0	0.633	−2.62	2.8	12.92
5	**Logistic (Autocatalytic):** $\boldsymbol{Dg = D_m/(1 + a \times exp(-b \times A))}$	**472.6**	**0.711**	**−2.66**	**2.5**	**12.70**
6	Mitscherlich (Monomolecular): $Dg = D_m \times (1- exp(-a \times A))$	494.7	0.603	−2.59	3.0	13.28
7	Power Decline: $Dg = D_m \times exp(a/(b-1)) \times A^{-(b-1)}$	485.9	0.650	−2.76	2.8	12.60
8	Weibull: $Dg = D_m \times (1- exp(-a \times A^b))$	485.0	0.650	−2.64	2.8	12.72
Stand *Hg* growth models						
1	Bertalanffy: $Hg = H_m \times (1- a \times exp(-b \times A))^3$	368.5	0.840	−2.08	1.5	11.22
2	Chapman-Richards: $Hg = H_m \times (1- exp(-a \times A))^b$	367.2	0.838	−1.83	1.5	11.03
3	**Gompertz:** $\boldsymbol{Hg = H_m \times exp(-a \times exp(-b \times A))}$	**366.9**	**0.840**	**−1.90**	**1.5**	**11.01**
4	Korf: $Hg = H_m \times exp(-a/A^b)$	372.5	0.827	−1.78	1.6	11.44
5	Logistic (Autocatalytic): $Hg = H_m/(1 + a \times exp(-b \times A))$	367.0	0.840	−1.96	1.5	11.12
6	Mitscherlich (Monomolecular): $Hg = H_m \times (1- exp(-a \times A))$	369.5	0.835	−1.58	1.5	11.12
7	Power Decline: $Hg = H_m \times exp(a/(b-1)) \times A^{-(b-1)}$	366.9	0.838	−1.81	1.5	11.06
8	Weibull: $Hg = H_m \times (1- exp(-a \times A^b))$	361.5	0.837	−1.62	1.5	11.03
Stand *V* growth models						
1	Bertalanffy: $V = V_m \times (1- a \times exp(-b \times A))^3$	−331.0	0.713	−20.00	0.063	38.42
2	Chapman-Richards: $V = V_m \times (1- exp(-a \times A))^b$	−316.1	0.655	−12.09	0.071	41.21
3	Gompertz: $V = V_m \times exp(-a \times exp(-b \times A))$	−342.0	0.784	−17.70	0.055	37.12
4	Korf: $V = V_m \times exp(-a/A^b)$	−319.1	0.612	−19.49	0.070	38.72
5	**Logistic (Autocatalytic):** $\boldsymbol{V = V_m/(1 + a \times exp(-b \times A))}$	**−344.3**	**0.807**	**−17.17**	**0.053**	**37.11**
6	Mitscherlich (Monomolecular): $V = V_m \times (1- exp(-a \times A))$	−311.0	0.859	−16.72	0.048	38.43
7	Power Decline: $V = V_m \times exp(a/(b-1)) \times A^{-(b-1)}$	−327.8	0.692	−18.52	0.064	38.17
8	Weibull: $V = V_m \times (1- exp(-a \times A^b))$	−328.1	0.693	−18.53	0.063	38.06

Note: *Ho* is a dominant tree height in m averaged by 20% of the tallest trees in the sample plot. *Dg* is the quadratic mean diameter at breast height in cm. *Hg* in m is the height of the tree with a *Dg*. *V* (m^3 $tree^{-1}$) is the volume of the tree with *Dg* and *Hg*. *A* is the age of the stand in year.
In K-fold cross-validation, the dataset is randomly split into equal-sized subsamples K ($K = 10$ folds), K - 1 subsamples used to develop models, calculate AIC, Adj. R^2; and K remaining subsample used for validation, calculation of Bias, RMSE, MAPE; finally, all those statistics averaged over 10 realizations.
Number size $n = 110$ sample plots. Weight variable: $1/A^{\delta}$, δ: the variance function coefficient; **Bold**: Selected models based on K-Fold cross-validation statistics and diagnostic plots.
Sources of equation forms (Zeide, 1989, 1993; Vanclay, 1994; Luo et al., 2018; Huy et al., 2020).

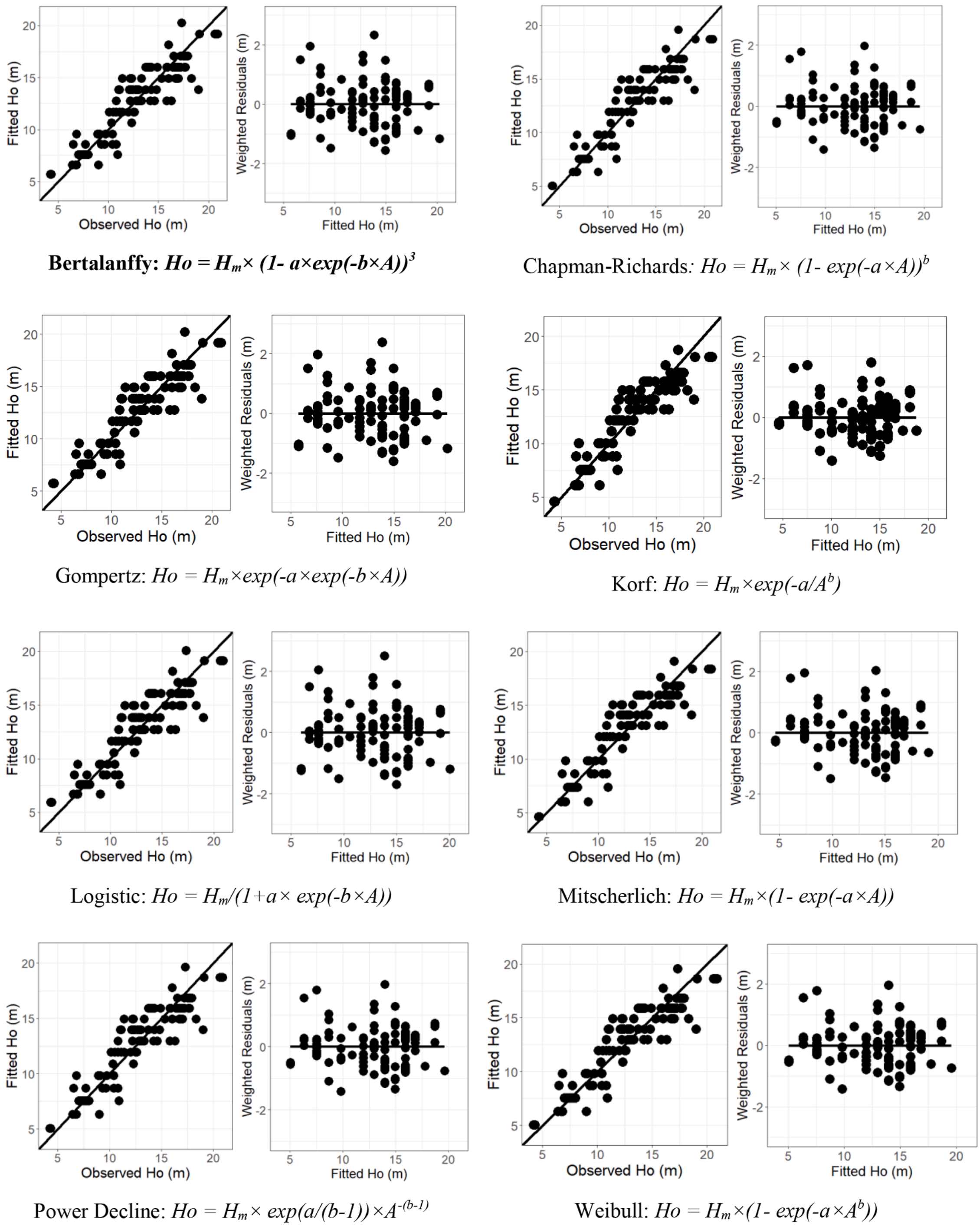

Fig. 4. Fitted vs. observed (left) and residuals vs. fitted (right) values for different *Ho* growth models evaluated in this study. Bold: A selected model based on K-Fold cross-validation statistics and diagnostic plots.

Effects of SI and N on teak stand models

Incorporating the *SI* and *N* variables into a simultaneous modeling system significantly improved the prediction of *Dg, Hg,* and *V*, compared to models that fit independently and without these variables (Table 4 vs. Table 2). The Bias% models to predict *Dg, Hg, V* were from −2.66%, −1.90%, and −17.17% (Table 2) to −0.10%, −1.32%, and −6.36% (Table 4), reduced by 2.56%, 0.58% and 10.81% in absolute value, respectively. The MAPEs of *Dg, Hg, V* models decreased from 12.70%, 11.01%, and 37.11% (Table 2) to 11.81%, 4.69%, and 26.88% (Table 4), reduced by 0.89%, 6.32%, and 10.23%, respectively. These results are also clearly seen in the plots comparing the performance of the three model systems presented in Fig. 6. The Bias and MAPE statistics used in this study are like average systematic error (ASE) and mean percent standard error (MPSE) (Zeng et al., 2017), respectively. The only difference is the denominator, and this study used the observed value, whereas Zeng et al. (2017) used the estimated value.

The site index affects the growth of *Dg, Hg,* and *V*, whereas *N* affects *Dg* and *V* more strongly than *Hg* (Table 5, Table 6). At sites with *SI* greater than the average of 15 m at $A_{st} = 12$ years, *Dg, Hg,* and *V* growth increased (Table 5 and Table 6). This result is consistent with Tanaka et al. (1995), Kaosa-ard (1998), and Huy et al. (2018), suggesting that

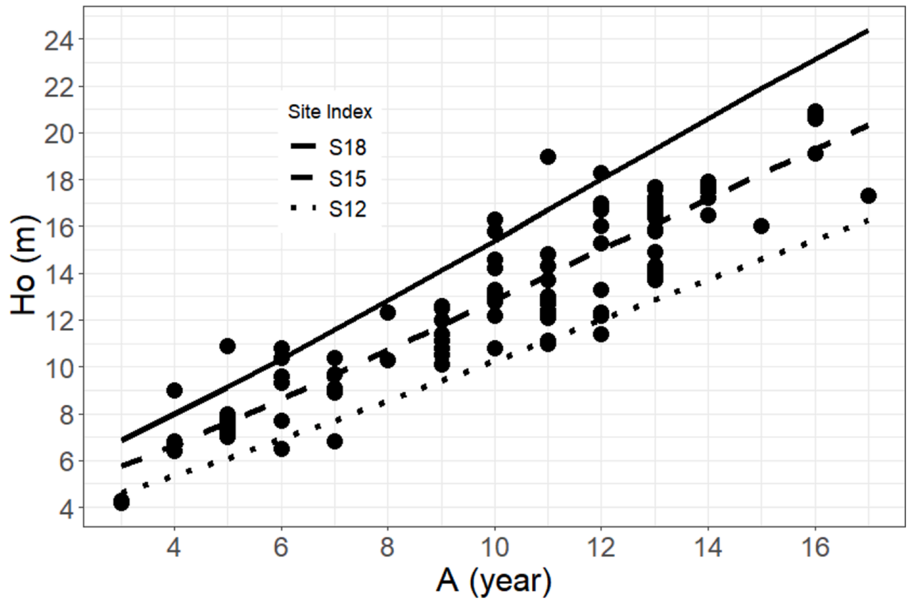

Fig. 5. Fitted *Ho* vs. stand age *(A)* curves demonstrate three site indexes S_{12}, S_{15}, and S_{18} along with a scatter plot of observed *Ho* vs. *A*.

Table 3
Simultaneous models for stand growth (*Dg, Hg, V*) versus stand age (*A*) fit by the WNSUR method and K-Fold cross-validation statistics.

Selected equation system	Bias (%)	RMSE	MAPE (%)
Logistic: $Dg = D_m/(1 + a \times exp(-b \times A))$	−4.07	2.6	14.86
Gompertz: $Hg = H_m \times exp(-a \times exp(-b \times A))$	−5.20	1.6	13.49
$V = \frac{\pi}{4 \times 10^4} Dg^2.Hg.0.45$	−15.63	0.048	40.96

Note: *Dg* is the quadratic mean diameter at breast height in cm. *Hg* in m is the height of the tree with a *Dg*. *V* (m^3 $tree^{-1}$) is the volume of the tree with *Dg* and *Hg*. *A* is the age of the stand in year.
In K-fold cross-validation, the dataset is randomly split into equal-sized subsamples K ($K = 10$ folds), K - 1 subsamples used to develop models, and K remaining subsample used for validation, calculation of Bias, RMSE, MAPE; finally, all those statistics averaged over 10 realizations. Number size $n = 110$ sample plots. Weight variable: $1/A^{\delta}$, δ: the variance function coefficient.

Table 4
Simultaneous models for stand growth (*Dg, Hg, V*) versus stand age (*A*) associated with variable combination site index (*SI*) and stand density (*N*) fit by the WNSUR method and cross-validated by K-Fold cross-validation statistics.

Equation system	Bias (%)	RMSE	MAPE (%)
$Dg = D_m/(1 + a \times exp(-b \times A)) \times exp[e_1 \times (Si - 15) + e_2 \times (N - 722)]$	−0.10	2.2	11.81
$Hg = H_m \times exp(-a \times exp(-b \times A)) \times exp[e_1 \times (Si - 15) + e_2 \times (N - 722)]$	−1.32	0.6	4.69
$V = \frac{\pi}{4 \times 10^4} Dg^2 \times Hg \times 0.45$	−6.36	0.037	26.88

Note: *Dg* is the quadratic mean diameter at breast height in cm. *Hg* in m is the height of the tree with a *Dg*. *V* (m^3 $tree^{-1}$) is the volume of the tree with *Dg* and *Hg*. *A* is the age of the stand in year.
In K-fold cross-validation, the dataset is randomly split into equal-sized subsamples K ($K = 10$ folds), K - 1 subsamples used to develop models, and K remaining subsample used for validation, calculation of Bias, RMSE, MAPE; finally, all those statistics averaged over 10 realizations. Number size $n = 110$ sample plots. Weight variable: $1/A^{\delta}$, δ: the variance function coefficient. All of the parameters had Pvalue < 0.05 except parameter e_2 in *Hg* model (Pvalue $= 0.14$).
The general model: *Stand Growth* = *Average* × *Modifier*.
where *Average* = Stand growth models selected by K-Fold cross-validation.
and *Modifier* = $exp[e_1 \times (Si - 15) + e_2 \times (N - 722)]$.

Table 5
Estimated parameters of the modeling system for simultaneous estimations of stand *Dg, Hg* and *V* associated with variable combination site index (*SI*) and stand density (*N*) using the WNSUR method (based on the entire dataset).

Model form	Parameter	Estimate ± Approx. Std Error	RMSE	Adj. R^2
$Dg = D_m/(1 + a \times exp(-b \times A)) \times exp[e_1 \times (SI - 15) + e_2 /1000 \times (N - 722)]$	D_m	113.4 ± 4.8	2.2	0.799
	a	14.70 ± 0.15		
	b	0.08750 ± 0.00407		
	e_1	0.03150 ± 0.00500		
	e_2	−0.2595 ± 0.0347		
$Hg = H_m \times exp(-a \times exp(-b \times A)) \times exp[e_1 \times (SI - 15) + e_2/1000 \times (N - 722)]$	H_m	38.65 ± 5.55	0.6	0.979
	a	2.586 ± 0.087		
	b	0.07740 ± 0.00942		
	e_1	0.06324 ± 0.00219		
	e_2	0.02764 ± 0.01880		
$V = \frac{\pi}{4 \times 10^4} Dg^2 \times Hg \times 0.45$	idem	idem	0.042	0.886

Note: *Dg* is the quadratic mean diameter at breast height in cm. *Hg* in m is the height of the tree with a *Dg*. *V* (m^3 $tree^{-1}$) is the volume of the tree with *Dg* and *Hg*. *A* is the age of the stand in year.
All of the parameters had Pvalue < 0.05 except parameter e_2 in *Hg* model (Pvalue $= 0.14$).

teak growth is sensitive to climate change and soil fertility, which are key ecological factors of the site index.

Meanwhile, *N* larger than the average of 722 tree ha^{-1} reduced the growth of *Dg* and *V* and slightly increased the growth of *Hg* (Tables 5 and 6), suggesting that the teak planted in low-density agroforestry models would result in faster growth. Additionally, if teak is planted at high *N*, a selective thinning is recommended because teak is an obligate light-demanding species throughout its life cycle (Gomez and Ugalde, 2006; Radio and Delgado, 2014; Huy et al., 2018). Thinning does not yield any commercial timber, but it is necessary to eliminate competing, malformed trees (FAO 2002; Huy et al., 2018).

Table 6
Prediction of the planted teak growth and yield of the stand at 15-years old.

A (year)	SI (m)	N (tree ha^{-1})	Dg (cm)	Hg (m)	V (m^3 $tree^{-1}$)	M (m^3 ha^{-1})	MAI of Dg (cm $year^{-1}$)	MAI of Hg (m $year^{-1}$)	MAI of M m^3 ha^{-1} $year^{-1}$
15	12	300	23.2	14.1	0.268	80	1.5	0.9	5.4
15	12	700	20.9	14.2	0.220	154	1.4	0.9	10.3
15	12	1100	18.9	14.4	0.181	199	1.3	1.0	13.3
15	15	300	25.5	17.0	0.392	117	1.7	1.1	7.8
15	15	700	23.0	17.2	0.322	225	1.5	1.1	15.0
15	15	1100	20.7	17.4	0.264	291	1.4	1.2	19.4
15	18	300	28.1	20.5	0.572	172	1.9	1.4	11.4

Note:.
A: The age of the planted teak stand.
SI: Site index.
N: The density of teak planted.
Dg is the quadratic mean diameter at breast height and *Hg* is the height of the tree with a *Dg*. *V* is the volume of the tree with *Dg* and *Hg*. These stand growth attributes are predicted by the WNSUR modeling system of *Dg*, *Hg* and *V* associated with variable combination of *SI* and *N* presented in Table 5.
M: The volume of the stand, $M = V \times N$.
MAI: The mean annual increment. MAI = Stand growth values (*Dg, Hg, M) / A*.

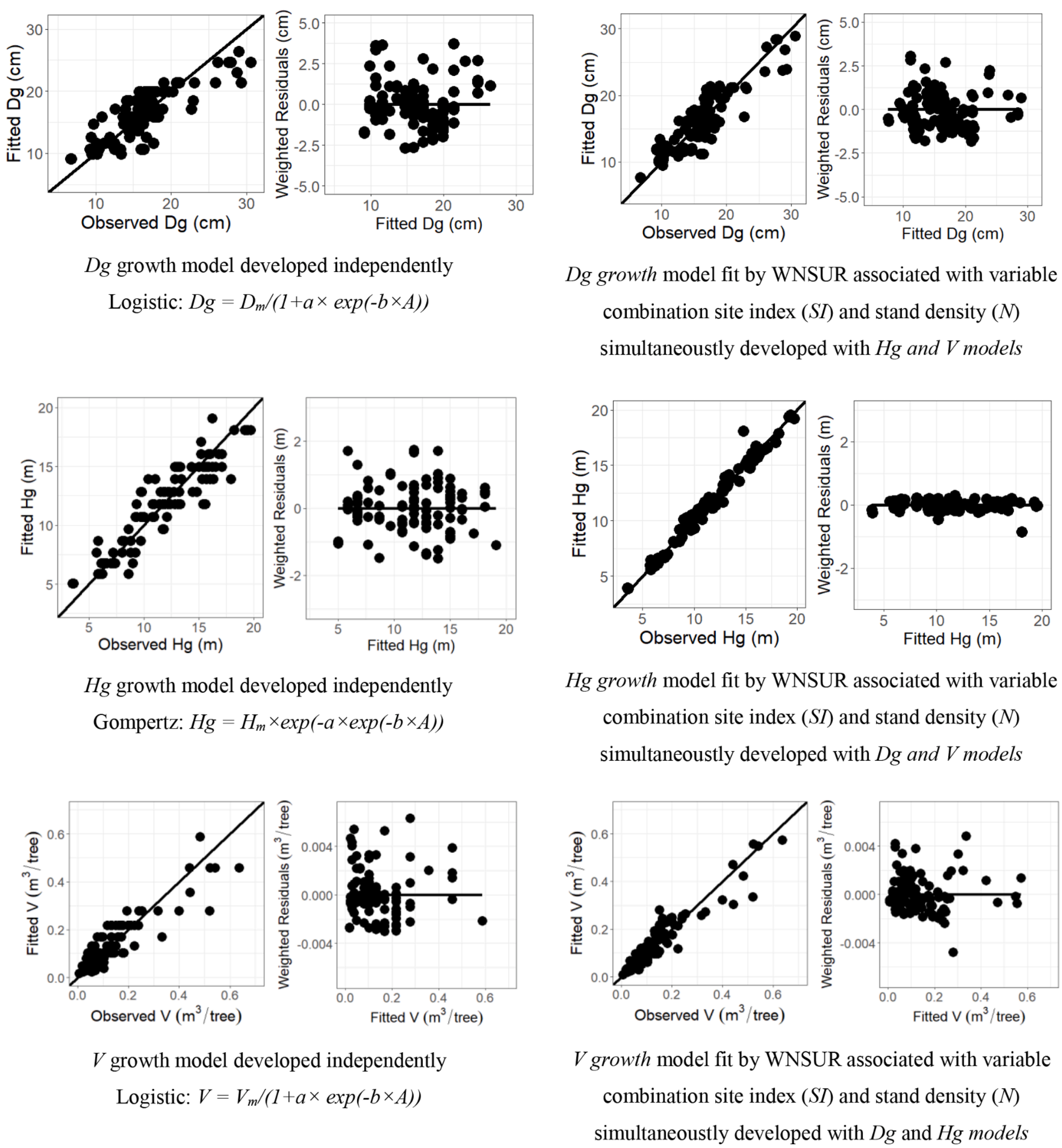

Fig. 6. Comparison of the performance of stand *Dg, Hg, V* growth models developed independently and simultaneously. Left: Fitted vs. Observed growth values; Right: Weighted residuals vs. Fitted growth values.

Growth and yield of teak planted in the region

At the age of $A = 15$ years, on three site indexes (*S12, S15*, and *S18*) and three levels of *N* (300, 700, and 1100 tree ha^{-1}), *Dg* ranged from 18.9 to 28.1 cm, *Hg* were from 14.1 to 20.5 m, and the stand volume (*M*) reached in the range of 80–291 m^3 ha^{-1} (Table 6). The mean annual increment (MAI) of *Dg, Hg,* and *M* were 1.3 - 1.9 cm $year^{-1}$, 0.9 - 1.4 m $year^{-1}$, and 5.4 – 19.4 m^3 ha^{-1} $year^{-1}$, respectively (Table 6). This result shows that *M* varied greatly with *SI* and *N*. At the average *SI (S15)* with a 15-year cycle, the teak monoculture had the highest *M* at $N = 1100$ tree ha^{-1} corresponding to *M* was 291 m^3 ha^{-1}. While applying agroforestry, $N = 300$ - 700 teak tree ha^{-1}, corresponding to *M* was 117 – 225 m^3 ha^{-1} (Table 6). This result in Table 6 also shows that it is possible to produce small teak wood ($D = 20$ - 25 cm) in 15–20 years using pure planting or agroforestry of teak with short-term crops. Meanwhile, teak planting to enrich degraded dipterocarp forests usually has a low density, $N = 300$ tree ha^{-1} (Huy et al., 2018), on average *SI* of *S15* with a 15-year cycle, *Dg* reached 25.5 cm, *Hg* reached 17.0 m, and *M* reached 117 m^3 ha^{-1}, corresponding to MAI = 7.8 m^3 ha^{-1} $year^{-1}$ (Table 6).

The MAI predictions for the planted teak in the tropical Central Highlands of Viet Nam are different from other teak growing areas in India with an MAI of 2 m^3 ha^{-1} $year^{-1}$ and in Nigeria with an MAI of 27 m^3 ha^{-1} $year^{-1}$ (Radio and Delgado, 2014) or approximate to MAI in Indonesia, Trinidad, and Tobago above 20 m^3 ha^{-1} $year^{-1}$ (Bhat and Ma, 2004). However, MAI of teak planted in the tropical highland region of Viet Nam is higher than that of Central America, which has an MAI of 10.2 – 13.3 m^3 ha^{-1} $year^{-1}$ for teak plantation with a rotation cycle of 25 – 28 years (Bhat and Ma, 2004; Radio and Delgado, 2014). In Myanmar, at 15 years of age, the average diameter of the plantations reached 15.5 cm, and the average height reached 11.8 m (Hlaing and Teplyakov, 2013), which is lower than the tropical highlands of Viet Nam on all three site indexes. Meanwhile, in Malaysia, teak has an increment in diameter of 1.5 to 2.0 cm $year^{-1}$ and 25 to 35 cm of *D* at 15 years (Radio and Delgado, 2014), showing that teak in Viet Nam's tropical region has growth and productivity similar to Malaysia's.

Conclusions

Incorporating site index and stand density information improved the reliability of the growth and yield prediction models for planted teak. WNSUR simultaneous modeling system based on *SI* and *N* provided the highest reliability compared to independent models without incorporating *SI* and *N* variables. The best modeling system developed simultaneously by incorporating *SI* and *N* for predicting teak stand growth in tropical highlands is as follows.

$$\mathrm{Dg} = \mathrm{D_m}/(1 + a \times \exp(-b \times \mathrm{A})) \times \exp[e_1 \times (\mathrm{SI}-15) + e_2/1000 \times (\mathrm{N}-722)]$$

$$\mathrm{Hg} = \mathrm{H_m} \times \exp(-a \times \exp(-b \times \mathrm{A})) \times \exp[e_1 \times (\mathrm{SI}-15) + e_2/1000 \times (\mathrm{N}-722)]$$

$$V = \frac{\pi}{4 \times 10^4} Dg^2 \times Hg \times 0.45$$

These models will help predict the growth and yield of teak planted for different planting schemes such as monoculture, agroforestry, and forest enrichment planting in this region.

Credit authorship contribution statement

All authors have no financial or personal relationships with other people or organizations that could inappropriately influence (bias) their work. Bao Huy conceptualized the project, acquired funding, developed methodology, collected the dataset, performed data analysis, wrote the original draft, and revised the manuscript. Nguyen Quy Truong administered the project, developed the methods, performed data analysis, and edited the first draft manuscript. Nguyen Quy Khiem developed the methods, performed data analysis, and edited the first draft manuscript. Krishna P. Poudel reviewed the manuscript, contributed analysis methods, and edited and revised the manuscript. Hailemariam Temesgen critically reviewed the manuscript, advised the methodology, edited and revised the final manuscript, provided supervision, 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 influenced the work reported in this paper.

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