Online ISSN: 2588-3526

Journal of Wildlife and Biodiversity

Volume 9(2): 18-31 (2025) (http://www.wildlife-biodiversity.com/)

Research Article

Dominant diameter growth model and Site Index Curves for certified Acacia forests in Thua Thien Hue province, Vietnam

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Received: 01 January 2025 / Revised: 10 February 2025 / Accepted: 15 February 2025/ Published online: 15 February 2025.

How to cite: Ha, H.T, Thuong, N.T, Hoi, N., Hieu, K., Nhat, TV. (2025). Dominant diameter growth model and Site Index Curves for certified Acacia forests in Thua Thien Hue province, Vietnam, Journal of Wildlife and Biodiversity, 9(2), 18-31. DOI: https://doi.org/10.5281/zenodo.15510916

Abstract

Site quality evaluation is considered an important aspect of forest management, whereby forest managers can assess potential forest stand timber production for a particular species or forest type. The dominant diameter growth models and site index curves were developed to assess the site quality of certified Acacia forests in Thua Thien Hue province, Vietnam. In this study, the correlation between dominant diameter (Dgo) and diameter at breast height (DBH) was selected from four common correlation function forms: linear, power, exponential, and parabolic function. In addition, Schumacher and Korf growth functions were used to select and develop the most suitable site index curves. to evaluate the developed models, the coefficient of determination (R^2) and root mean square error (RMSE) were used as statistical criteria. The study investigated 50 sample plots of certified acacia forests from age 2 to age 10 in Thua Thien Hue to develop the models and other 20 sample plots were used to evaluate the developed models. The results showed that the dominant diameter had the best correlation with diameter at breast height in the form of a logarithmic function(Dgo = 8.8446*ln(DBH) – 7.0985). Meanwhile, the Schumacher function with equation Dgo = 24.366. e^(-4.193/A^1.2) is best describes the relationship between dominant diameter and forest age. Certified Acacia plantations in Thua Thien Hue province can be divided into three soil classes based on the diameter of dominant trees at age 5. The site index (according to dominant diameter) for good soil class (I), average soil class (II), and poor soil class (III) at age 5 are 14 cm, 12 cm, and 10 cm, respectively.

Keywords: Acacia plantations, dominant diameter, Schumacher function, Site index curves

Introduction

Vietnam has 14.86 million hectares of forest, of which 4.73 million hectares are planted forest (MARD, 2024). However, the area of certified forests is very small, with 434,725 hectares of FSC-certified forests and 172,009 hectares of PEFC-certified forests (FSC, 2024; PEFC, 2024). The main species grown in plantation forests is Acacia hybrid (Acacia mangium x Acacia auriculiformis). The fast-growing Acacia hybrid has been planted extensively in central Vietnam and has become one of the main commercial species planted by smallholders (Frey et al. 2018). Smallholders grow Acacia hybrid plantations to supply pulpwood to chipping mills. However, growing Acacia hybrid for logwood in longer rotations turns out to be a much more profitable investment (Arvola et al., 2021). Smallholder farmers are generally highly dependent on their plantations, which generate 40% to 50% of household cash incomes, and Acacia plantations generate an annual income of on average 10.9 million VND per hectare, with a positive cost-benefit ratio and high internal rates of return of between 45 and 50% (Ho T.H. et al., 2024). Thua Thien Hue province has a planted forest area of 100,845 ha, accounting for 32.9% of the total forest area of the province. Acacia hybrid is the main tree species of the planted forests, accounting for about 85 to 90% of the total planted forest area (PPC TTH, 2024). The certified forest area of the province is 11,925 ha (TTH FPD, 2023).

Site quality evaluation is considered an important aspect in forest management, whereby forest managers can assess potential forest stand timber production for a particular species or forest type (Vu Tien Hinh, 2012). Site index is considered one of the better measures to evaluate site quality and is the most direct and most widely used in forestry (Fonweban et al. 1995; Onyekwelu 2005; Dieguez-Aranda et al. 2006). It is used to develop the growth and yield modeling for pure, even-aged forest stands (Corral-Rivas et al. 2004; Dieguez-Aranda et al. 2006). Various studies have been conducted to develop site index equations for plantation forests. Most authors use dominant height as the main indicator to classify site indexes (Aguirre-Bravo and C, Smith FW. 1986; Haywood A. 2009; Vu Tien Hinh,2012; Hyun-Jun Kim, 2018; Roscinto 2018; Tran Thi Ngoan, 2019) Most authors assert that height at a given age is a good indicator of forest productivity. However, measurement of the height in general and dominant height in particular to get accurate results is very difficult in practice. Meanwhile, the dominant diameter is easy to determine with high accuracy. Diameter in general and dominant diameter, in particular, are closely related to volume, thus reflecting well the productivity of the forest stand. In addition, dominant diameter growth is influenced by site conditions but is less affected by thinning. Therefore, this study was conducted to study the relationship between dominant diameter and diameter at breast height as well as to develop site index curves based on the dominant diameter of certified Acacia forests in Thua Thien Hue, Vietnam.

Materials and methods

Study site

Thua Thien Hue Province is located on the Central Coast of Vietnam, with an approximate total area of 5025.30 km2. Its boundaries lie between $15^0$59'30" to $16^0$44'30" North latitude and $107^0$00'56" to $108^0$12'57" East longitude. The total forested land area is 306,432.65 ha, of which natural forest is 205,587.40 ha and planted forest is 100.845 ha, accounting for 32.9% of the total forest area of the province (PPC TTH, 2024). Acacia hybrid is the main tree species of the planted forests, accounting for 85 to 90% of the total planted forest area. The certified forest area of the province is 11,925 ha (TTH FPD, 2023).

Data collection

A total of 50 temporary sample plots with an area of 500 m^2 (20m x 25m) of certified Acacia hybrid plantations from 2 to 10 years old were investigated to develop correlation models as well as develop the site index curves. The sample plots were selected to ensure the representativeness of the site conditions of each area. The evaluation of the developed site index was conducted using 20 other sample plots (not involved in the development of the site index models). Thus, a total of 70 sample plots with forest ages from 2 to 10 years old of certified Acacia hybrid plantations forest in Thua Thien Hue were investigated and analyzed.

+ Planting year (forest age) collected from forest planting records or interviews with forest owners;

+ Diameter at breast height (DBH) is determined by measuring the diameter or using a measuring tape to measure the circumference and then calculating the diameter.

+ Dominant diameter (Dgo) is the average diameter of the 20% biggest DBH in the sample plot.

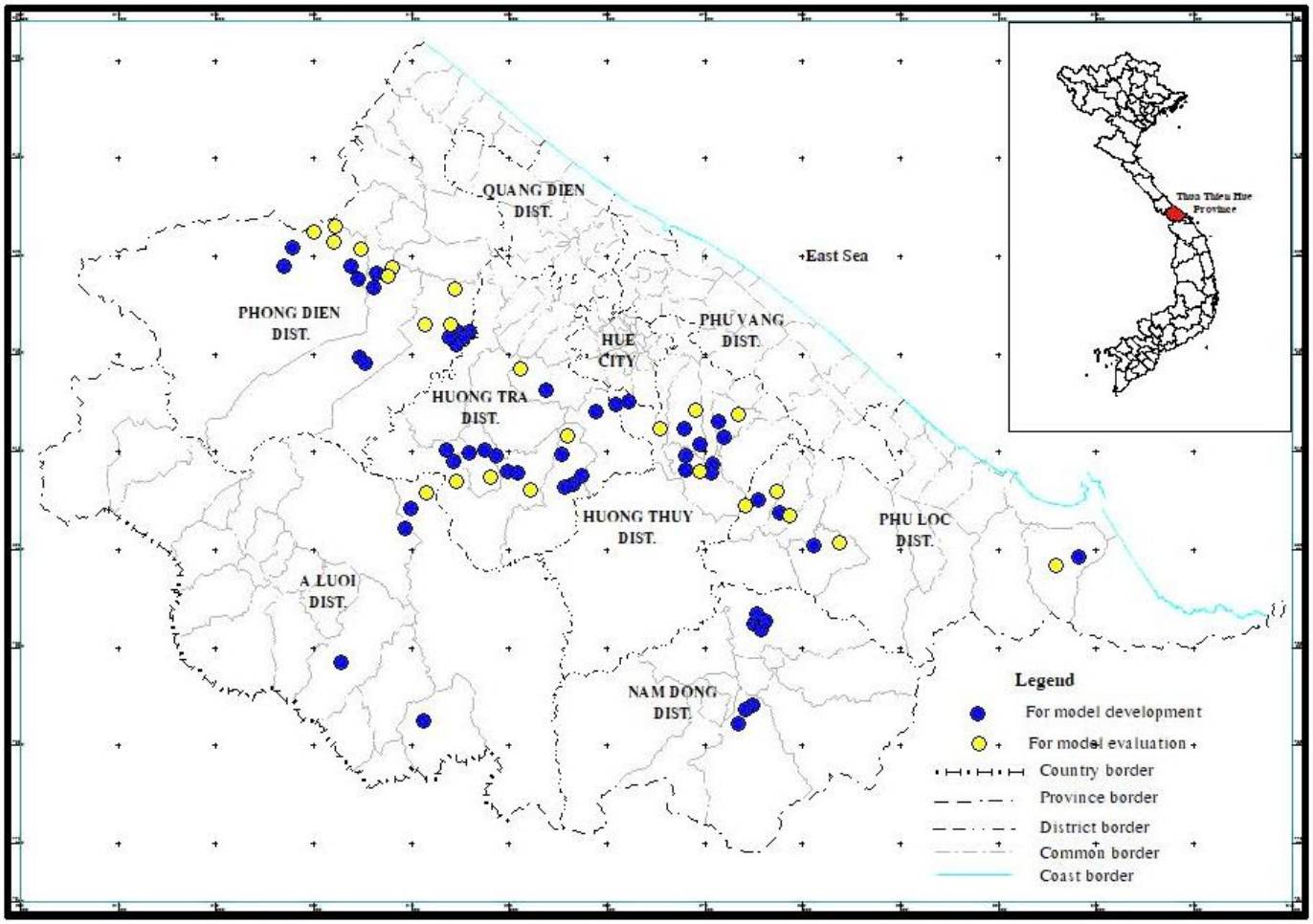

Figure 1. Location of sample plots surveyed for model development and evaluation in Thua Thien Hue province

Data analysis

Establishing the correlation between dominant diameter (Dgo) and diameter at breast height (DBH)

Based on 4 common correlation function forms: linear, power, exponential, and parabolic functions to describe the correlation between Dgo and DBH. The best correlation equation is selected based on the correlation coefficient (R) and coefficient of determination (R^2) of each equation (Vu Tien Hinh, 1997).

Determination of growth function and site index curves

The site index of Acacia hybrid plantations can be classified by constructing the function Dg0 = f(A) for average Acacia hybrid plantations for all soil classes. Selecting the appropriate equation describing the dominant diameter growth was done by testing two popular equations, the Schumacher and Korf functions.

The Schumacher equation: $Dgo = m \cdot e^{-\frac{b}{A^c}} = m*EXP(-b/A\text{^}c)$ (1)

The Korf equation: $Dgo = m. e^{-c_1 \cdot A^{-c_2}} = m*EXP(-c1*A\text{^}-c2)$ (2)

Where:

Dgo: Dominant diameter

A: Age of forest stand

m, b, c, c1, c2: parameters of the functions

However, there is a major difference between the two functional forms as follows: with the Schumacher function, it is necessary to determine the parameters m and b according to different values of c (with c varying between 0 and 2). Meanwhile, with the Korf function, it is necessary to determine the parameters c1 and c2 according to different values of m (m is the maximum value of the dependent variable) (Vu Tien Hinh, 2012)

For the model evaluation, the coefficient of determination (R^2) and root mean square error (RMSE) were used. These statistical evaluations were computed as follows:

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(Dgoi - \widehat{Dgoi})^2}{\sum_{i=1}^{n}(Dgoi - \overleftarrow{Dgo})^2} \quad (3)$$

$$RMSE = \frac{\sqrt{\sum_{i=1}^{n}(Dgoi - \widehat{Dgoi})^2}}{n} \quad (4)$$

where

Dgoi: observed dominant diameter for the ith tree or forest stands

$\widehat{Dgoi}$: predicted dominant diameter for the ith tree or forest stands, and

$\overleftarrow{Dgo}$: observed mean dominant diameter.

Applying the Affill method to develop the site index curves for certified Acacia hybrid plantations in Thua Thien Hue province includes the following steps:

- Determine the theoretical diameter value at the basic age (Ao) by substituting Ao into the growth equation developed:

Dg_0(Ao) = Dmax. $e^{-\frac{b}{A^c}}$ =Dmax*EXP(-b/A^c) (5)

- Determine the intermediate equation by dividing the growth equation by the theoretical diameter value at age Ao.

$$Dg_0(A^*) = \frac{\text{Dmax}.e^{-\frac{b}{A^c}}}{\text{Dgo(Ao)}} = \text{Dmax.EXP(-b/A^c)/Dgo(Ao)} \quad (6)$$

- Determine the upper, middle, and lower boundary equations of the intermediate site index equations.

Dgoi(A) = Dgo(A).SI (7)

- Substitute the value of A into the above growth equations to get the soil classes table. (Vu Tien Hinh, 2012)

Using 20 other sample plots, not involved in model development, to verify the site index curves as well as the soil classification table. Firstly, determining the dominant diameter values of the 20 selected sample plots. Secondly, plot the dominant diameter growth curves combined with the 20 dominant diameters of the 20 selected sample plots. Finally, evaluating the results. The soil classes table and site index curves are considered suitable when all the tested dominant diameters are contained within the soil classes table and have the same direction as the site index curves.

Results

With 50 sample plots investigated from 2nd to 10th year old of certified Acacia forest in Thua Thien Hue, it shows that DBH has relatively good growth, fluctuating from 3.32 Cm at age 2 to 18.89 Cm at age 10, averaging 1.66 to 2.15 Cm/year. However, diameter growth also fluctuates strongly due to the difference between the smallest and largest diameter values in the same year of age being quite high. The dominant diameter of the forest plots is relatively high, fluctuating from 3.79 Cm in 2nd-year-old forests to 19.01 Cm in 10th-year-old forests. With relatively small Standard Deviation values, it can be used to build forecasting models with acceptable accuracy.

To determine the dominant diameter based on the average DBH, four common correlations were used to develop the correlation between Dgo and DBH. The results are shown as follows.

The growth of the dominant diameter of certified Acacia forest in Thua Thien Hue province

Table 1. Average and dominant diameter at breast height of Acacia hybrid plantations

Forest age (year)	n (plot)	DBH				Dominant diameter (Dgo)	
		Mean (Cm)	SD (Cm)	Max (Cm)	Min (Cm)	Mean (Cm)	SD (Cm)
2	4	3.32	1.08	5,95	1,20	3.79	0.48
3	6	6.45	1.59	10,52	2,58	8.61	0.70
4	6	7.55	1.64	13,26	4,06	11.02	0.50
5	7	9.90	2.06	15,10	6,16	12.83	0.95
6	8	11.11	1.88	15,85	7,61	14.80	1.35
7	10	13.45	2.76	17,83	9,87	16.24	1.13
8	2	16.21	2.93	20,24	11,46	17.03	1.25
9	4	16.86	4.05	22,85	14,17	17.91	2.14
10	3	18.83	3.13	23,55	14,23	19.01	0.71

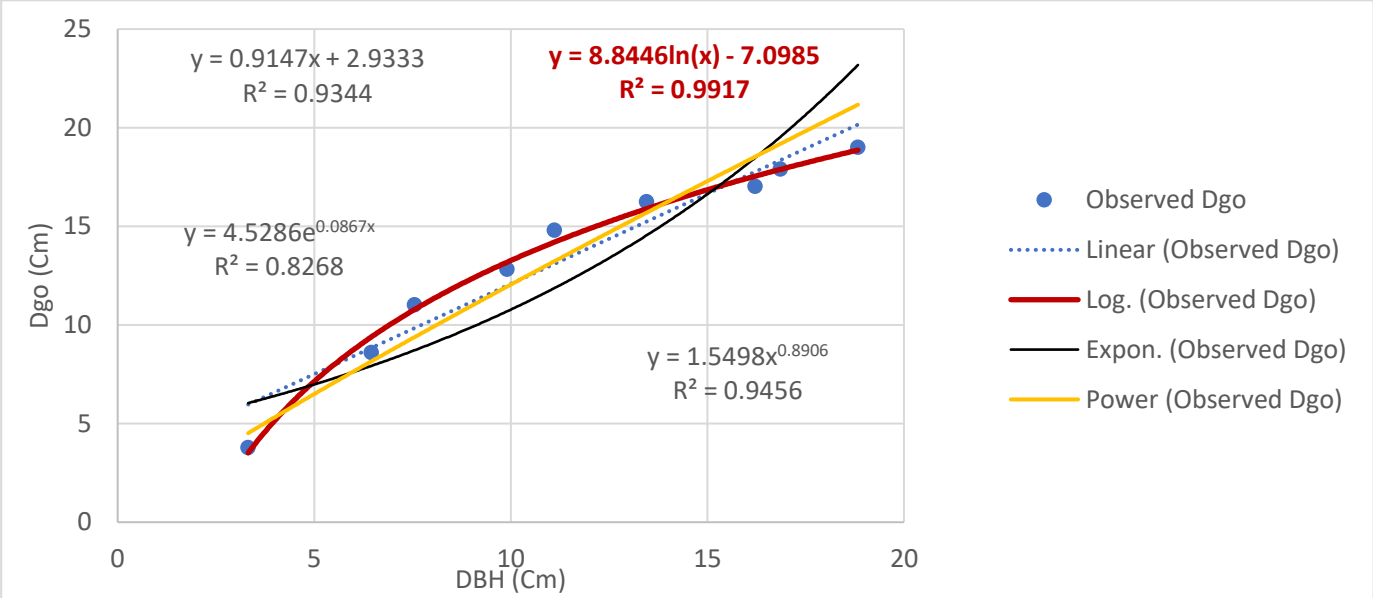

Figure 2. Four common forms for correlation between dominant diameter (Dgo) and DBH

Table 2. Correlation between dominant diameter (Dgo) and DBH of forest stands

STT	Regression form	developed equation	R	R^2	RMSE
1	Linear	Dgo = 0.9147*DBH + 2.9333	0.966	0.934	0.399
2	**Logarithmic**	**Dgo = 8.8446*ln(DBH) – 7.0985**	**0.996**	**0.992**	**0.142**
3	Power	Dgo = 1.5498*DBH^0.8096	0.975	0.951	0.437
4	Exponential	Dgo = 4.5286*exp(0.0867*DBH)	0.891	0.794	9.516

Among the four common functional forms describing the correlation between Dgo and DBH, the Logarithmic functional form gives the best results with the largest values of correlation coefficient (R), coefficient of determination (R^2), and the smallest value of RMSE. Therefore, to determine the dominant diameter according to the average DBH value for certified acacia forests, the following formula should be used: Dgo = 8.8446*ln(DBH) – 7.0985.

Table 3. The growth of the dominant diameter of the Certified Acacia forest

Forest age(year)	Mean(Cm)	CAI(Cm/year)	MAI(Cm/year)	Max (Cm)	Min(Cm)	Range(Cm)
2	3.79	3.79	1.89	5.95	4.25	1.70
3	8.61	4.83	2.87	10.52	7.79	2.73
4	11.02	2.41	2.76	13.26	11.24	2.02
5	12.83	1.81	2.57	15.10	9.47	5.63
6	14.80	1.98	2.47	15.85	12.72	3.13
7	16.24	1.44	2.32	17.83	14.00	3.82
8	17.03	0.79	2.13	20.24	15.20	5.04
9	17.91	0.88	1.99	22.85	16.19	6.66
10	19.01	1.11	1.90	23.55	21.8	1.75

Note: CAI: Current Annual Increment

MAI: Mean Annual Increment

CAI is the increment of a tree or stands of trees during each year, whereas the MAI is equal to the volume (total increment) divided by age or number of years in which the volume (total increment) was attained (Vu Tien Hinh, 1997)

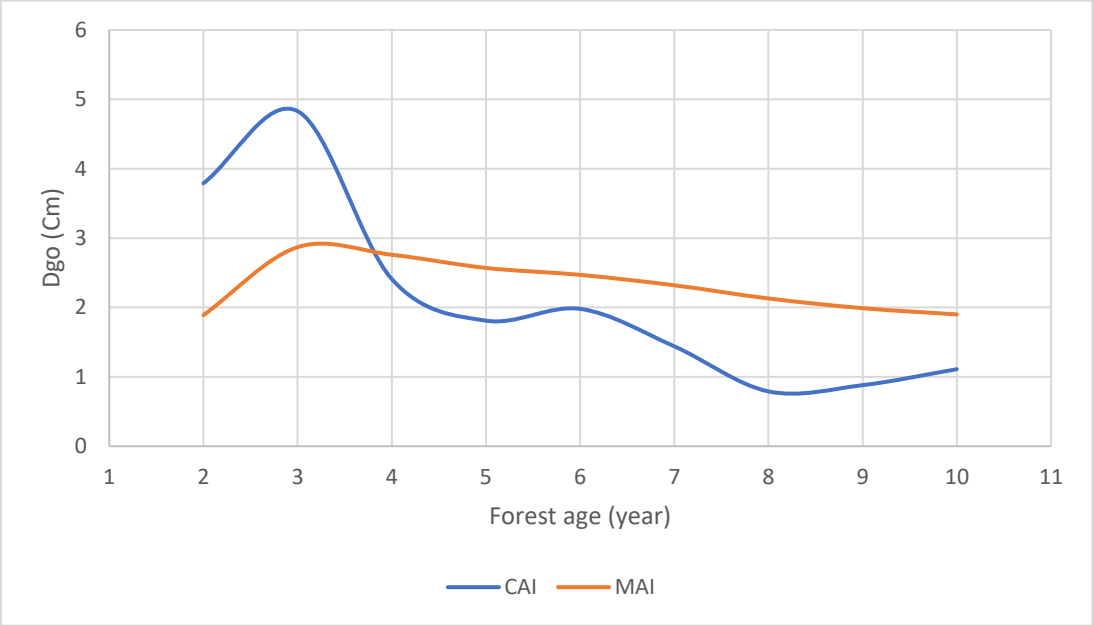

Figure 3. CAI and MAI of certified Acacia hybrid forests from age 2 to age 10

Through the CAI and MAI charts, it can be seen that the Acacia forest in Thua Thien Hue has reached maturity at around age 4 when the curves of CAI and MAI intersect. Therefore, the Acacia forest over age 4 has begun to grow stably.

Development of growth function for dominant diameter

To select the most suitable model describing the correlation between the dominant diameter (Dgo) and the forest age (A), the Schumacher function and the Korf function were tested with experimental data. Based on experimental data and appropriate methods, the parameters for the Schumacher and Korf functions were determined as follows:

Table 4. Determination of the appropriate parameters for the Schumacher function

	c = 0.8	**c = 1**	**c = 1.2**	**c = 1.4**
b	3.710	3.884	4.193	4.611
m	34.4	28.27	24.366	21.9
R^2	0.984	0.991	0.997	0.996
RMSE	0.189	0.127	0.072	0.133

The table above shows that the values of the coefficient of determination (R^2) are very high and there is almost no significant difference. However, the RMSE values based on different values of c have significant differences. With the parameter value c = 1.2, the smallest RMSE value is 0.072 while the highest RMSE value is 0.189 when the parameter c = 0.8. Therefore, to determine the dominant diameter value (Dgo) based on the forest age (A), the Schumacher function can be used with the following equation: Dgo = 24.366*exp(- 4.193/A^1.2).

Similar to the Schumacher function, the parameters of the Korf function are defined as follows.

Table 5. Determination of the appropriate parameters for the Korf function

	m =20	m = 25	m = 30	m =35
c1	7.980	4.250	3.586	3.473
c2	1.951	1.227	0.898	0.765
R2	0.941	0.995	0.992	0.988
RMSE	0.680	0.097	0.134	0.211

The table above shows that the highest coefficient of determination (R^2) values are 0.995 with m = 25 while at m = 20 the R^2 value is only 0.941. Similar to the R^2 value, the RMSE values at different m values also have significant differences. With the parameter value m = 25, the RMSE value is 0.097, the smallest of all RMSE values, and the highest is 0.680 when the parameter m = 20. Therefore, to determine the dominant diameter value (Dgo) based on forest age (A), if using the Korf function, the following equation should be used: Dgo = 25*exp(- 4.250*A^(-1.227)).

Thus, through the two growth functions for dominant diameter determined, it shows that the Schumacher function gives better results than the Korf function because the Schumacher function gives a smaller RMSE value of 0.072 compared to 0.097 although the coefficient of determination of the two functions is not significantly different. Therefore, to simulate the growth of dominant diameter based on forest age for certified acacia forests in Thua Thien Hue, the Schumacher function should be used with the specific equation: Dgo = 24.366*exp(- 4.193/A^1.2).

Development of SI curvers based on the dominant diameter

The appropriate base age (Ao, years) is chosen at the time when the growth of the tree has stabilized. In the study area, due to the actual business cycle, the base age (Ao) of the Acacia hybrid usually fluctuates from 4 to 6 years old. As shown in the CAI and MAI charts, the certified Acacia hybrid forest has grown stably after the age of 4. Therefore, age 5 is chosen as the base age to build SI functions and SI curves for certified Acacia hybrid plantations in Thua Thien Hue province.

The range of variation of dominant diameter at age 5 is 6.0 cm (rounded). Therefore, dividing 6 cm into 3 levels, each level will be 2 cm. Dividing certified Acacia hybrid plantations in Thua Thien Hue province into 3 soil levels from I - III with the gap in dominant diameter between soil levels at the basic age of 2 cm. The three SI indices at Ao (5 years) take on values of 14 cm, 12 cm and 10 cm respectively. The boundary indices between site index levels I, II, and III are 13 cm and 11 cm respectively. Similarly, the SI index at the lower boundary of site index level III is 9 cm, and the upper boundary of site index level I is 15 cm.

Theoretical dominant diameter at base age (5 years)

Dgo (A=5) = 24.366*EXP(-4.193/5^1.2) = 13.268 (Cm)

Intermediate growth equation: Dgo(A^*) = 1.836* EXP(-4.193/5^1.2)

Table 6. Equations of lower limit, middle limit and upper limit of each soil class for certified Acacia forest in Thua Thien Hue province

SI	Boundary	Phương trình sinh trưởng

15	Upper limit of soil class I	Dgo(A^*) = 27,55* EXP(-4.193/5^1.2)
14	Midle limit of soil class I	Dgo(A^*) = 25,71* EXP(-4.193/5^1.2)
13	The lower limit of soil class I The upper limit of soil class II	Dgo(A^*) = 23,87* EXP(-4.193/5^1.2)
12	Middle limit of soil class II	Dgo(A^*) = 22,04* EXP(-4.193/5^1.2)
11	The lower limit of soil class II The upper limit of soil class III	Dgo(A^*) = 20,20* EXP(-4.193/5^1.2)
10	Middle limit of soil class III	Dgo(A^*) = 18,36* EXP(-4.193/5^1.2)
9	The lower limit of soil class III	Dgo(A^*) = 16,53* EXP(-4.193/5^1.2)

Substituting A from 2 to 10 into the above growth equations, we get the soil classes table of certified Acacia hybrid forest in Thua Thien Hue province.

Table 7. Soil classes table (based on dominant diameter) of certified Acacia hybrid forest in Thua Thien Hue province.

Forest age (Year)	Dominant diameter Dgo (Cm) / Soil class						
		I		II		III	
	Upper limit	Middle	Boundary	Middle	Boundary	Mid-dle	Lower limit
2	4.4	4.1	3.8	3.6	3.3	3.0	2.7
3	9.0	8.4	7.8	7.2	6.6	6.0	5.4
4	12.4	11.6	10.8	10.0	9.1	8.3	7.5
5	15.0	14.0	13.0	12.0	11.0	10.0	9.0
6	16.9	15.8	14.6	13.5	12.4	11.3	10.1
7	18.4	17.1	15.9	14.7	13.5	12.2	11.0
8	19.5	18.2	16.9	15.6	14.3	13.0	11.7
9	20.4	19.0	17.7	16.3	15.0	13.6	12.2
10	21.1	19.7	18.3	16.9	15.5	14.1	12.7

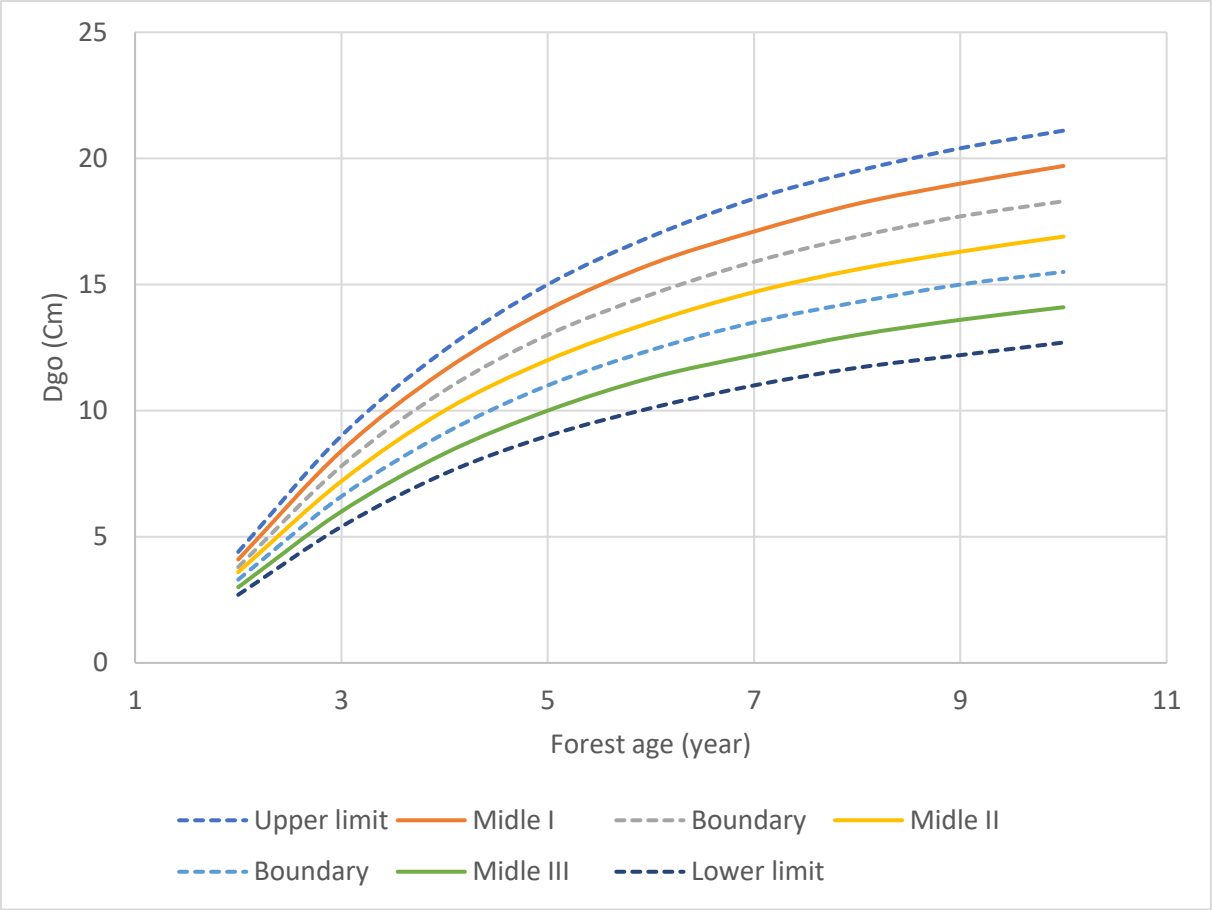

Figure 4. Site index curves based on the dominant diameter of certified hybrid acacia forests in Thua Thien Hue.

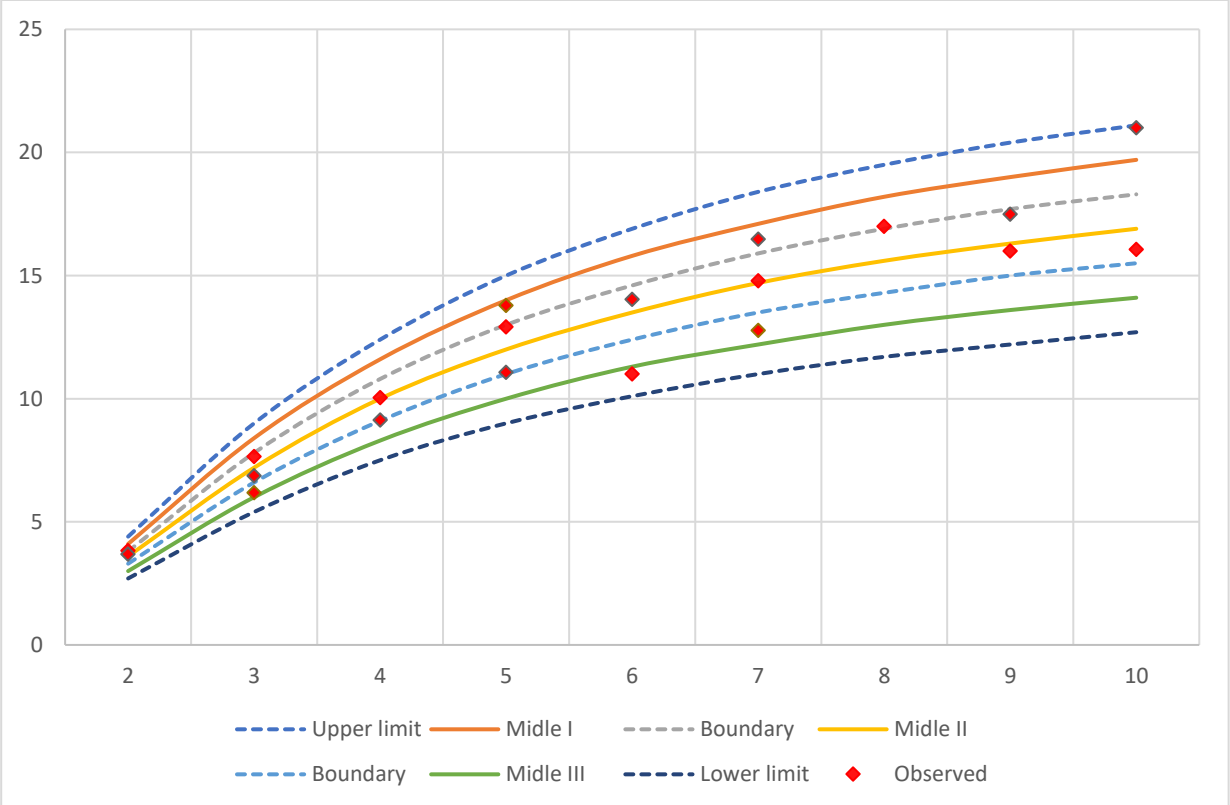

Figure 5. Fitting of soil index curves and soil classes to the actual data

The results of the test from the actual data from 20 sample plots, which were not involved in the development of the models, showed that all 20 dominant diameter values were within the limits of the Site Index. All 20 sample plots belonged to the 3 identified soil classes, of which 12 sample plots belonged to soil class II (average), 3 sample plots belonged to soil class III (poor), and 5 sample plots belonged to soil class I (Good). This shows that the results of the site curves, as well as the established soil class table, are acceptable and should be used in practice.

Conclusions

Using dominant diameter as the basis for soil classification is more advantageous than using dominant height because diameter is easy to measure with high accuracy, the calculation method is similar to using height; diameter is closely related to volume so it reflects well the volume of the forest stands; growth of dominant diameter is affected by site conditions but is less affected by thinning process. For certified Acacia hybrid forests in Thua Thien Hue, the dominant diameter is determined through correlation with diameter at breast height in the form of a logarithmic function with the specific equation Dgo = 8.8446*ln(DBH) – 7.0985.

To describe the dominant diameter growth as a basis for soil classification of certified Acacia hybrid plantations in Thua Thien Hue province, the Schumacher function should be used with the specific equation Dgo = 24.366*exp(- 4.193/A^1.2).

Certified Acacia hybrid plantations in Thua Thien Hue province can be divided into three soil classes based on the dominant diameter at 5 years of age. The site index for good soil class (I), average soil class (II), and poor soil class (III) at 5 years of age is 14 cm, 12 cm, and 10 cm, respectively. The intermediate equation for establishing the soil class table is: Dgo(A*) = 1.836* EXP(-4.193/5^1.2).

The results of the test from the actual data show that the results of the site curves, as well as the established soil class table, are acceptable and should be used in practice.

Acknowledgments

We would like to express our sincere thanks to Hue University for providing funding to carry out the project code DHH2023-02-175. In addition, we would like to thank the Sustainable Bamboo, Acacia, and Rattan Project (SBARP) - WWF Vietnam for providing partial funding for this research. We would like to express our sincere thanks to TTH FOSDA for facilitating the field investigation of FSC-certified Acacia forests.

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