Disentangling carbon stocks and structural characteristics of secondary forests in Tuyen Quang, Vietnam

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Abstract. Forest structure is a key to effective forest management. This study analyzed diameter and height data collected from two plots in Tuyen Quang, Vietnam to elucidate the structural characteristics and carbon stocks of the forests. The forest volume varied between 77.59 and 103.93 m³, while the carbon stock ranged from 32.53 to 43.83 (Ton/ha). Additionally, the number of carbon credits spanned from 119.38 to 160.86. The best function for simulating the diameter frequency distribution was Wakeby and Gen. Gamma (4P). Meanwhile, the best function for the height frequency distribution was Dagum and Log-Logistic (3P). The regression between diameter and height was best described by the Power and Naslund equation. A strong association between diameter, height and forest tree quality was revealed in both plots. Good trees were typically clustered within groups with larger diameters and heights, whereas bad trees were predominantly found in the smallest groups. These findings will support the assessment of a forest's ecological functions, contributing to effective carbon sequestration initiatives and climate change mitigation efforts in the future.

Keywords: association, carbon credit, frequency distribution modeling, forest volume, regression analysis.

1. Introduction

The structure of forests is crucial for maintaining the balance of forest ecosystems and supporting life on Earth (Anfodillo et al., 2013). Forests are often referred to as the 'lungs' of the planet because they absorb carbon dioxide and release oxygen, which is vital for all living organisms (Sedjo & Sohngen, 2012; Shugart et al., 2010). A well-structured forest provides habitats for numerous species, promotes biodiversity, and ensures the survival of countless plants, animals, and microorganisms (Spies, 1998 Hämäläinen et al., 2024). Forests also play a key role in regulating the climate, mitigating the effects of global warming, and reducing carbon emissions (Coomes et al., 2014). Their root systems help prevent soil erosion, maintain soil fertility, and protect water resources by regulating the water cycle (Blanco & Lal, 2008). Additionally, forests offer renewable resources such as timber, food, and medicinal plants, contributing to local economies and sustainable development (Führer, 2000). Natural forests serve as barriers against natural disasters like floods and landslides, safeguarding human settlements, particularly in mountainous regions (Führer, 2000; Moos et al., 2023).

In Vietnam, there have been studies on the structure of natural forests in many different areas and for many different types of forests such as natural secondary forests in the Central Highlands, Vietnam (Hung, 2016); natural forests in Bac Kan (Tuan & Hung, 2018), Quang Ninh (Tran Van et al., 2022). Studies have also analyzed many different aspects of forest structure. There are studies on the layered structure of natural forests in Thanh Hoa. The results showed that natural forests often have five layers (Huyen & Dung, 2022). Studies analyzed the non-spatial structural characteristics of forest trees such as the relationship between diameter and height. The characteristics of the frequency distribution of diameter and height were also analyzed and modeled for forests in Ba Vi, Ba Be, Phu Tho, Gia Lai and so on (Hung, 2022; Hung et al., 2022; Phong, 2019; Trieu & Hung, 2018). The spatial structural patterns of forest trees and tree stages were also examined for forests Nghe An, Tuyen Quang and Binh Thuan (Nguyen et al., 2021; Pham et al., 2022; Van Khoa et al., 2024). The spatial distribution of forest trees is mainly random.

Currently, there are still some limitations in the study of forest structure in Vietnam such as using simple functions with few parameters to model frequency distribution, or analyzing the relationship between tree-size quantities (Phong, 2019; Phong & Hung, 2019; Tuan & Hung, 2018). The relationship between forest tree quality and tree-size quantities is also rarely analyzed. In Tuyen Quang, there are currently no specific studies analyzing and quantifying forest structure based on growth quantities such as diameter and height. At the same time, there are no results on carbon stocks of the forests here. Therefore, this study was conducted on secondary forests in Tuyen Quang, Vietnam to: 1) calculate forest volume, biomass, carbon stock and the number of carbon credits obtained in the forests; 2) analyze and model the frequency distribution of diameter and height; 3) clarify the correlation between diameter and height in the research area and finally 4) analyze the association between forest tree quality and tree diameter and height to provide a scientific basis for proposing sustainable forest management solutions and assessing the CO_2 absorption capacity of natural forests in Tuyen Quang.

2. Materials and methods

2.1. Study site

Two plots were set up in secondary tropical forests located in Khau Tinh commune, Na Hang district, Tuyen Quang province, Vietnam (Fig. 1). Khau Tinh commune has about 100 hectares of secondary natural forests, accounting for 85% of the total area of the commune. The total number of forest tree species in the whole commune is about 150 species. The growth of tree species is assessed as average to good (Luc et al., 2019). Plot investigation results show that plot 1 has 62 species, of which 7 are dominant species and the species with the largest number of individuals is *Machilus bonii*. Plot 2 has 69 species, of which 3 are dominant species, and the species with the largest number of individuals is *Saraca dives*. The Simpson index of both plots is 0.95. The tree species are not endangered. The storey structure in the 2 plots is not much different. The plots both include 3 layers: dominant layer, middle layer and understory layer. The study area features a complex terrain with numerous caves. It has an average slope of 30-35 degrees and an elevation of 439 meters above sea level. The region experiences tropical monsoon weather, characterized by two distinct seasons. The rainy season lasts from April to September, marked by hot and humid conditions, while the dry season spans from October to March. The average yearly temperature is 23.5°C (Luc et al., 2019). Annual rainfall ranges between 1,390 and 1,600 millimeters, with approximately 80% occurring in July and August. The average annual humidity is 75%. The area is influenced by two primary wind patterns: the Northeast wind during the dry season and the Southeast wind during the rainy season. Yellow-red feralitic soil predominates across the landscape (Luc et al., 2019).

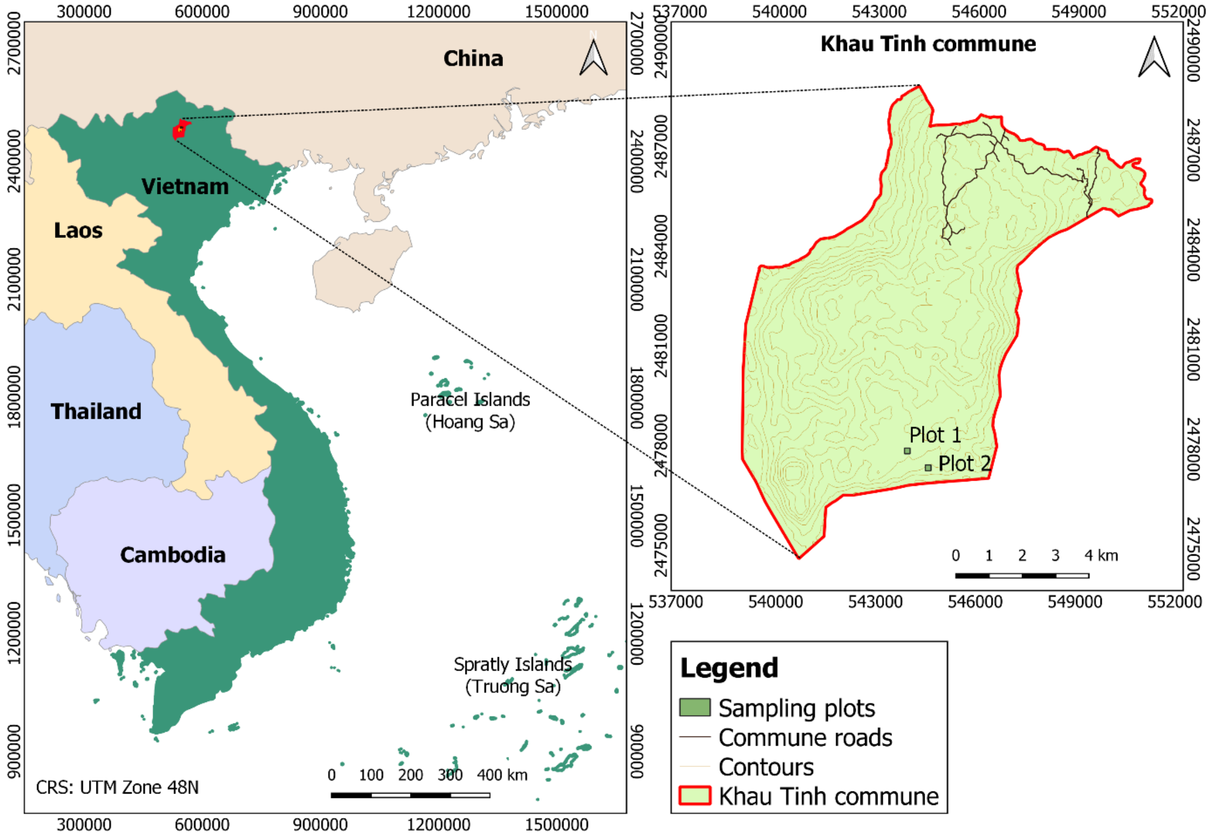


Figure 1. Study site. Maps of Vietnam (left) and Khau Tinh commune (right)

2.2. Data collection method

Two main plots were established in the study area. The size of each plot was 1 hectare (100 m x 100 m). Each plot was divided into 25 sub-plots (20 m x 20 m). In each sub-plot, all trees with a diameter at breast height (DBH) of 6 cm or greater were measured for DBH and total height (H) (Van Khoa et al., 2024). The diameter was measured using calipers with millimeter-level precision. The total height was measured using the Blume-Leiss with decimeter-level precision (Hung et al., 2022; Tuat & Khoi, 2009). The study assessed and categorized tree growth quality into three groups: Good, Medium, and Bad. Trees classified as Good exhibited straight boles, robust growth, well-formed crowns, no signs of disease, and intact tops. Bad trees, on the other hand, were characterized by crooked shapes, signs of disease, truncated tops, weakly developed crowns, and poor growth. Medium trees displayed characteristics that fell between those of the Good and Bad categories (Hung et al., 2022, 2023).

2.3. Data processing method

2.3.1. Calculating mean, forest volume, carbon stock and comparing the two plots

The average diameter and height were calculated for each plot using the arithmetic mean formula, as follows (Tuat & Khoi, 2009):

$$\bar{X} = \frac{\sum_1^i (X_i)}{n} \quad (1)$$

where: $\bar{X}$ was the mean value, Xi was the observed values and n was the number of observed values.

The total volume of forest trees in each plot was calculated as follows (Hung, 2016):

$$V = \sum_1^i \left(\left(\left(\frac{DBH}{2} \right)^2 \times 3.14 \right) \times H \times f \right) \quad (2)$$

where: V was the total volume of trees in the plot, DBH was the diameter at breast height of the tree (m), H was the height of the tree (m) and f was the tree form. The value of f was taken as 0.45 for natural forests in Vietnam (Hung, 2016).

The total dry biomass of forest trees in each plot was calculated using the following formula. The following formula was used for forests in the Northern region of Vietnam (Hung, 2015).

$$AGB = \sum_1^i (0.1080 \times DBH^{2.1234} \times H^{0.3598}) \quad (3)$$

where: AGB was the total dry biomass of the forest trees in the plot (kg). DBH was the diameter at breast height and H was the height of each tree.

The total carbon stock contained in each plot was calculated using the following formula (Hung et al., 2023):

$$Carbon\ stock = AGB \times 0.5 \quad (4)$$

where: Carbon stock was calculated in Kg. AGB was the total dry biomass of forest trees in each plot (kg).

The carbon dioxide stock corresponding to the carbon stock calculated above was computed according to the formula (Quality, 2024):

$$CO_2 = Carbon\ stock \times 3.67 \quad (5)$$

where: CO_2 was the carbon dioxide stock that forest trees absorbed, calculated in Kg. Carbon stock was the carbon stock of forest trees in each plot (kg).

Then, the number of carbon credits was calculated using the following formula (Quality, 2024):

$$Carbon\ credit = CO_2/1000 \quad (6)$$

where: Carbon credit was the number of carbon credits and CO_2 was the equivalent amount of carbon dioxide that the forests absorbed in each plot.

Next, Canonical Correspondence Analysis (CCA) was used to compare the differences between the two plots based on a matrix created by variables such as diameter, height, tree volume, carbon stock, and number of carbon credits. CCA is a multivariate analysis commonly used in ecological data analysis. It is also a very suitable analysis when comparing samples based on multiple variables at the same time (McCune et al., 2002).

CCA was also used to analyze associations between the forest quality and tree diameter and height. This analysis was performed after dividing the diameter and height variables into groups (McCune et al., 2002).

2.3.2. Frequency distribution modeling

Sixty-four theoretical functions were tested in this study: Beta, Burr, Burr (4P), Cauchy, Chi-Squared, Chi-Squared (2P), Dagum, Dagum (4P), Erlang, Erlang (3P), Error, Error Function, Exponential, Exponential (2P), Fatigue Life, Fatigue Life (3P), Frechet, Frechet (3P), Gamma, Gamma (3P), Gen. Extreme Value, Gen. Gamma, Gen. Gamma (4P), Gen. Logistic, Gen. Pareto, Gumbel Max, Gumbel Min, Hypersecant, Inv. Gaussian, Inv. Gaussian (3P), Johnson SB, Kumaraswamy, Laplace, Levy, Levy (2P), Log-Gamma, Log-Logistic, Log-Logistic (3P), Log-Pearson 3, Logistic, Lognormal, Lognormal (3P), Nakagami, Normal, Pareto, Pareto 2, Pearson 5, Pearson 5 (3P), Pearson 6, Pearson 6 (4P), Pert, Phased Bi-Exponential, Phased Bi-Weibull, Power Function, Rayleigh, Rayleigh (2P), Reciprocal, Rice, Student's t, Triangular, Uniform, Wakeby, Weibull, Weibull (3P) (Technologies, 2020).

The Anderson-Darling test was then used to analyze the goodness of fit of the diameter and height frequency distributions to the 64 theoretical distributions used. The Anderson-Darling test was also used to find the best function for the observed distribution (Shin et al., 2012; Technologies, 2020).

2.3.3. Regression analysis between diameter and height

The study used 10 correlation equations as shown in the table below to analyze the regression between diameter and height of forest trees in each plot. In Table 1 below, X was the diameter at breast height and Y was the total height of the forest trees (Bui et al., 2023).

Table 1. Ten used regression models in the study.

Growth model	Equation	Reference
Power	$Y = aX^b$	(Fang & Bailey, 1998)
Naslund	$Y = 1.3 + (X^2 / [\exp(a) + bX]^2)$	(Chenge, 2021)
Chapman-Richards	$Y = 1.3 + a(1 - \exp[-bX])^c$	(Scaranello et al., 2012)
Exponential	$Y = 1.3 + \exp(a + b / [X + c])$	(Anacioco et al., 2018)
Weibull	$Y = 1.3 + a(1 - \exp[-bX^c])$	(Sharma et al., 2016)
Logistic	$Y = 1.3 + a / (1 + b \exp[-cX])$	(Thanh et al., 2019)
Gompertz	$Y = 1.3 + a(\exp[-b \exp[-cX]])$	(Chenge, 2021)

Prodan	$Y = 1.3 + X^2 / (a+bX+cX^2)$	(Fang & Bailey, 1998)
Ratskowky	$Y = 1.3 + a(\exp[-b/(c+X)])$	(Chenge, 2021)
Korf	$Y = 1.3 + a(\exp[-bX^c])$	(Anacioco et al., 2018)

The study used three statistics in Table 2 to select the best correlation model in each plot. The best model was the one that has the smallest Akaike's information criterion (AIC), the largest coefficient of determination (R^2) and the smallest root of mean square error (RMSE) (Bui et al., 2023; Zar, 1999).

Table 2. The used statistics to find the best model in each plot.

Evaluation statistic	Formula
Akaike's information criterion (AIC)	$AIC = n\ln(RMSE) + 2k$
Coefficient of determination (R^2)	$R^2 = 1 - \left[\frac{\sum_{i=1}^{n}(Y_i - \hat{Y}_i)^2}{\sum_{i=1}^{n}(Y_i - \bar{Y})^2}\right]$
Root of mean square error (RMSE)	$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(Y_i - \hat{Y}_i)^2}{n}}$

3. Results

3.1. Carbon stocks and forest stand features

Two plots were established in natural secondary forests in the study area. The number of trees in the two plots was 1050 and 1023 trees, respectively. However, the number of tree species in Plot 1 was slightly lower than that in Plot 2. In Plot 1, 62 tree species were found, while 69 species were found in Plot 2. The number of families was similar in both plots (36 families). The average diameter of Plot 1 (11.11 cm) was slightly smaller than that of Plot 2 (12.55 cm). Similarly, the mean height of Plot 1 was also smaller than that of Plot 2 (8.47 and 8.82 m, respectively).

The calculation results in Table 1 indicated that forest volume, biomass, carbon stock and number of carbon credits in Plot 1 were smaller than in Plot 2. Plot 1 had 62 species, while Plot 2 had 69 species. The wood volumes in Plot 1 and Plot 2 were 77.59 and 103.93 m^3/ha, respectively. The number of ecological important species in Plot 1 was 7 and and Plot 2 was 3. Simpson index in both plots was 0.95. The total carbon stock in Plot 1 was 32.53 (Ton/ha), while that in Plot 2 was 43.83 (Ton/ha). The number of carbon credits in the two plots were 119.38 and 160.86 credits, respectively.

Table 1. Stand indicators of two plots.

Plot	DBH (cm)	H (m)	V (m^3)	AGB (Ton/ha)	Carbon stocks (Ton/ha)	CO_2 (Ton/ha)	Carbon credit
Plot 1	11.11 ± 6.24	8.47 ± 3.39	77.59	65.06	32.53	119.38	119.38
Plot 2	12.55 ± 7.69	8.82 ± 3.49	103.93	87.66	43.83	160.86	160.86

The CCA comparison results showed that tree-size variables as well as forest volume, carbon stock and number of carbon credits were indeed statistically different between the two plots (CCA goodness of fit, p-value=0.004 < 0.05). This was also visualized in Figure 2. The two 95% estimated ellipses had no overlap.

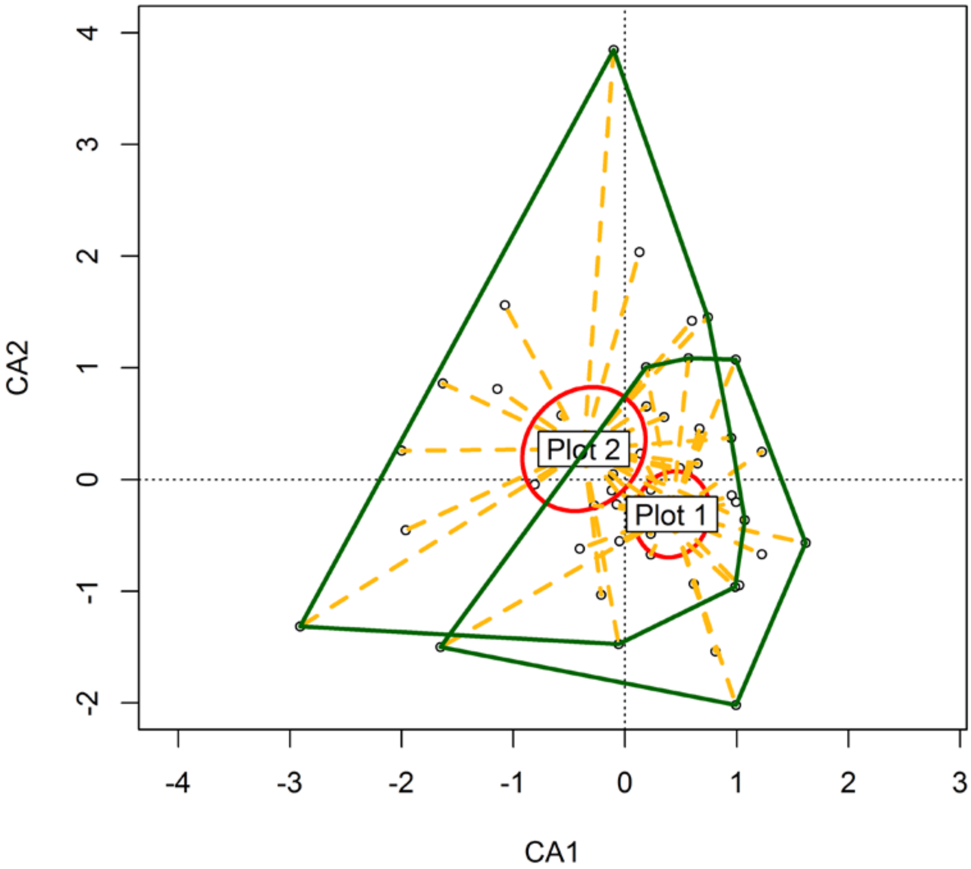


Figure 2. Comparison results of tree-size variables, volume, biomass and carbon stock by CCA between two plots. Dots are the sub-plots and the red line is the 95% estimation

3.2. Tree-size variable frequency distribution

3.2.1. Diameter frequency distribution

The diameter frequency distribution in the two plots was not statistically different (K-S test = 0.183, p-value > 0.05). In both plots, the diameter frequency distribution tended to decrease as the diameter size increased. The most significant rate of decline occurred in the first three classes, then slowed down in the subsequent classes. The first class had the largest number of trees (632 and 618 trees, respectively). Following that, the number of trees in the second class in the two plots was 227 and 209, respectively. In the third class, the number of trees was 100 and 84. The majority of trees were concentrated in the first three classes, accounting for 91.33% in Plot 1 and 89.05% in Plot 2.

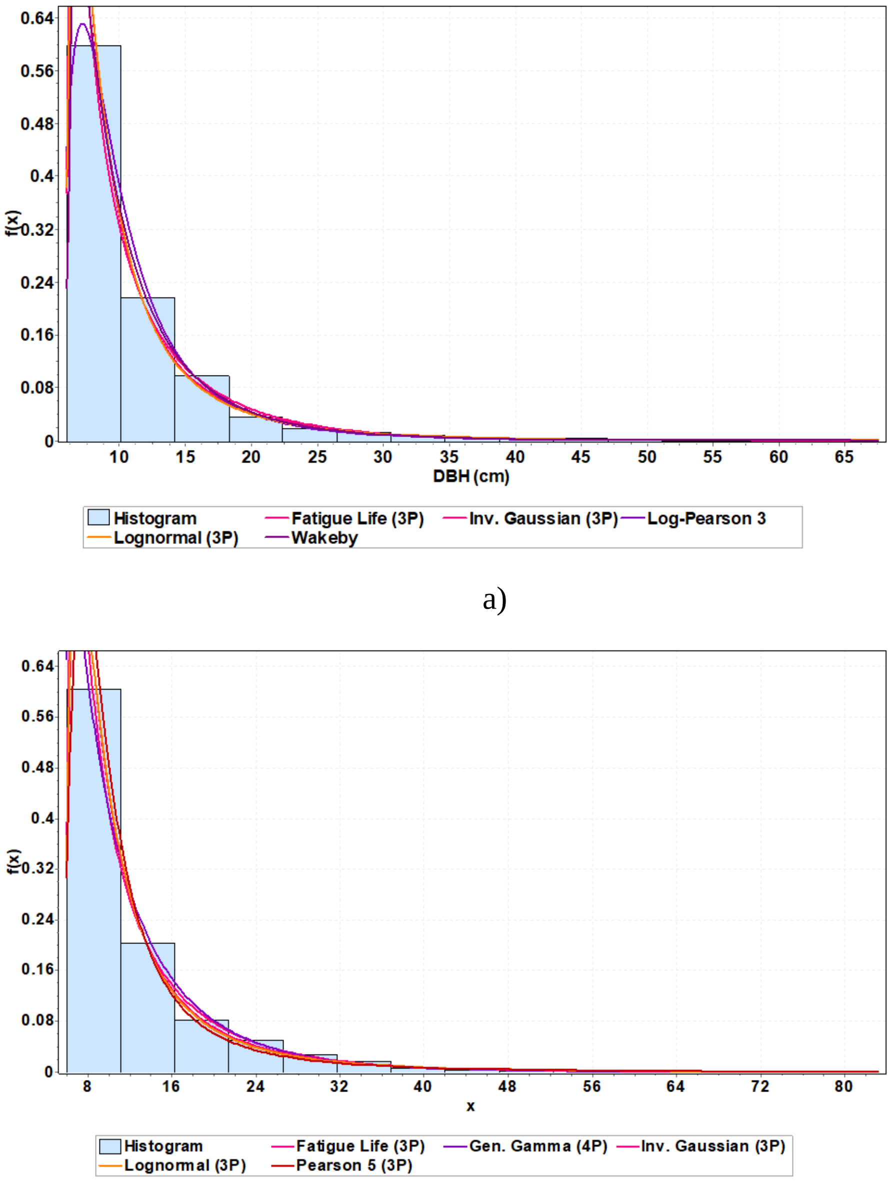
The modeling results using 64 theoretical functions showed that several theoretical functions could effectively simulate the diameter frequency distribution. For Plot 1, the five best functions were Fatigue Life (3P), Inv. Gaussian (3P), Log-Pearson 3, Lognormal (3P), and Wakeby (Fig. 3a). Among them, the Wakeby function was the best for describing the diameter frequency distribution. The empirical distribution was indeed determined by the Wakeby distribution (Anderson-Darling test = 1.6430 < Critical value = 2.5018). The parameters of the Wakeby distribution were $\alpha = 49.914$, $\beta = 56.516$, $\gamma = 3.9681$, $\delta = 0.20405$, and $\xi = 5.2592$. The parameter results of other good distributions were presented in Table 2.

The modeling results for Plot 2 had some differences. The five best functions, selected based on the Anderson-Darling test, were Fatigue Life (3P), Gen. Gamma (4P), Inv. Gaussian (3P), Lognormal (3P), and Pearson 5 (3P) (Fig. 3b). The best function for simulating the diameter frequency distribution in Plot 2 was Gen. Gamma (4P). This function was also able to determine the empirical distribution (Anderson-Darling test = 1.4229 < Critical value = 2.5018). The parameters of the Gen. Gamma (4P) distribution were $k = 0.70418$, $\alpha = 1.5753$, $\beta = 2.9268$, and $\gamma = 5.9969$. The parameters of the other four distributions that could be used to simulate the diameter frequency distribution in Plot 2 were also indicated in Table 2.

Table 2. Parameter results for the five best distributions for the diameter variable.

Plot	Theoretical distribution	Parameters	Anderson Darling	
			Statistic	Rank
Plot 1	Wakeby	α=49.914 β=56.516 γ=3.9681 δ=0.20405 ξ=5.2592	1.6430	1*
	Inv. Gaussian (3P)	λ=4.3302 μ=5.6888 γ=5.4236	2.0596	2*
	Fatigue Life (3P)	α=1.1295 β=3.3411 γ=5.6258	2.1714	3*
	Lognormal (3P)	σ=1.0668 μ=1.1602 γ=5.7336	2.2611	4*
	Log-Pearson 3	α=2.7796 β=0.24775 γ=1.6184	2.4904	5*

Plot 2	Gen. Gamma (4P)	k=0.70418 α=1.5753 β=2.9268 γ=5.9969	1.4229	1*
	Fatigue Life (3P)	α=1.1206 β=4.288 γ=5.55	1.6288	2*
	Inv. Gaussian (3P)	λ=5.5387 μ=7.2403 γ=5.3054	1.661	3*
	Lognormal (3P)	σ=1.0657 μ=1.4056 γ=5.697	1.7976	4*
	Pearson 5 (3P)	α=1.9617 β=8.5161 γ=4.5811	2.6041	5*



a)

b)

Figure 3. Five best fitted curves for the diameter variable a) for Plot 1; b) for Plot 2

3.2.2. Total height frequency distribution

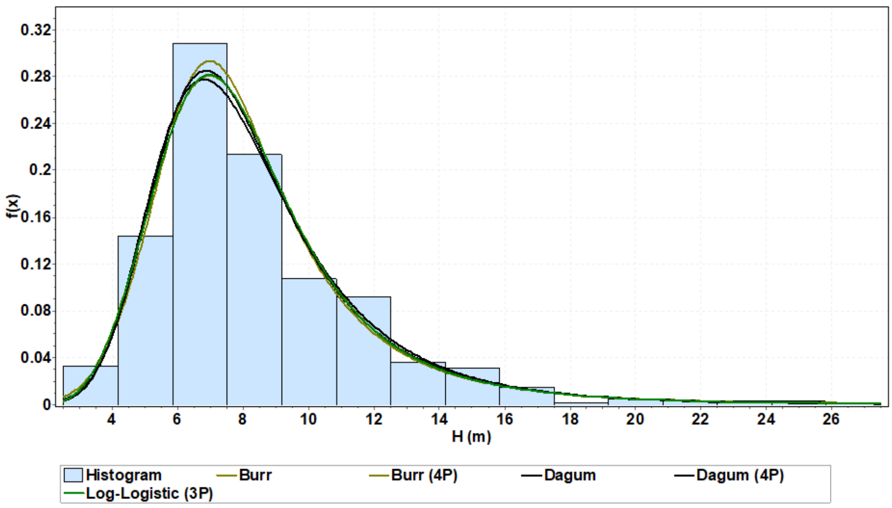
For the frequency distribution of the height variable, there were some dissimilarities compared to the diameter frequency distribution. The height frequency distribution had a bell-shaped form, with the frequency decreasing toward both the right and left tails. In both plots, the height frequency distribution was not significantly different (K-S test = 0.354, p-value > 0.05). In Plot 1, the largest number of trees was concentrated in the third class with 324 trees, followed by the fourth class with 224 trees, and the second class ranked third with 151 trees. The number of trees in these three classes accounted for 66.57%. Meanwhile, in Plot 2, there were four classes with a large number of trees. The third and fourth classes had 229 and 228 trees, respectively. The fifth class had 167 trees, and the second class had 122 trees. The number of trees in these four classes contributed to 72.92% of the trees in the sample plot.

Therefore, the modeling results had some interesting differences from the results for the diameter variable. In general, the best theoretical functions for modeling the height variable were significantly different from those for the diameter variable. In Plot 1, the five best functions for modeling the height frequency distribution were Burr, Burr (4P), Dagum, Dagum (4P), and Log-Logistic (3P) (Fig. 4a). Among these, the Dagum function was the best fit for simulating the distribution. It also determined the empirical distribution (Anderson-Darling test = 0.8932 < Critical value = 2.5018). The parameters of the Dagum distribution in Plot 1 were k=1.6958, α=4.2673, β=6.5918. Meanwhile, the modeling results for Plot 2 were as follows. The best function selection indicated that the five best functions were Burr, Dagum, Dagum (4P), Gen. Extreme Value, and Log-Logistic (3P) (Fig. 4b). The Log-Logistic (3P) function was the best among the five selected. It was also able to determine the empirical distribution (Anderson-Darling test = 1.0926 < Critical value = 2.5018). The calculated parameters of this distribution were α=4.0072, β=7.022, γ=1.1138. The parameters of other distributions in both plots were illustrated in Table 3.

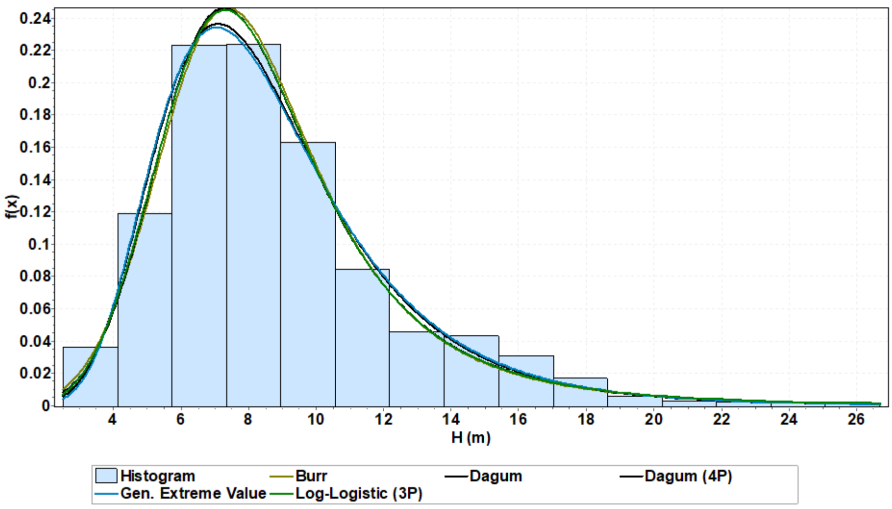
Table 3. Parameter results for the five best distributions for the height variable.

	Theoretical distribution	**Parameters**	**Anderson Darling**	
			Statistic	**Rank**
Plot 1	Dagum	k=1.6958 α=4.2673 β=6.5918	0.8932	1*
	Dagum (4P)	k=5.0646 α=6.6135 β=10.55 γ=-6.349	0.9292	2*
	Log-Logistic (3P)	α=3.7987 β=6.0297 γ=1.7278	1.0000	3*

	Burr (4P)	k=1.019 α=3.749 β=6.0377 γ=1.7636	1.0085	4*
	Burr	k=0.6738 α=5.8205 β=6.9861	1.0396	5*
Plot 2	Log-Logistic (3P)	α=4.0072 β=7.022 γ=1.1138	1.0926	1*
	Dagum	k=1.2574 α=4.3553 β=7.5757	1.0961	2*
	Burr	k=0.89102 α=4.8895 β=7.8807	1.1845	3*
	Dagum (4P)	k=13.358 α=13.305 β=26.577 γ=-25.008	1.2611	4*
	Gen. Extreme Value	k=0.06011 σ=2.5394 μ=7.1989	1.2866	5*



a)



b)

Figure 4. Five best fitted curves for the height variable a) for Plot 1; b) for Plot 2

3.3. Relations between diameter and height

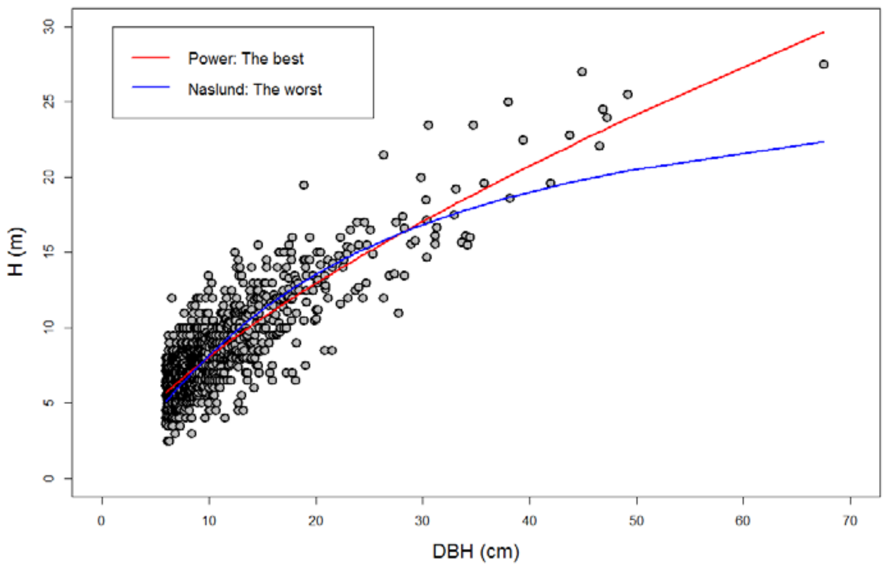
The correlation analysis results between diameter and height using ten theoretical models revealed some interesting findings. The relationship between diameter and height was positively correlated. The correlation between diameter and height was relatively strong. The parameters and relationships were statistically significant (P-value < 0.05), except for the Weibull function in Plot 1. The correlation coefficient in Plot 1 ranged from 0.705 to 0.7288. In Plot 2, this coefficient ranged from 0.7074 to 0.7260. The analysis results showed some differences between the best and worst functions. In Plot 1, the best function was the Power function (Smallest AIC = 4180.62) with the estimated parameters of 1.6823 and 0.6813, while the worst function was the Naslund function (Biggest AIC = 4267.07) with the estimated parameters of 0.6552 and 0.1894. However, in Plot 2, the best and worst functions were Ratskowky (Smallest AIC = 4145.33) and Naslund (Biggest AIC = 4215.8), respectively. The estimated parameters for the Ratskowky function were 37.8350, 41.9160, and 13.8860, while the parameters for the Naslund function were 0.6203 and 0.2022. Therefore, the examination results indicated that the Naslund function was not suitable for modeling the correlation between diameter and height in the area. The estimated parameters for all models in both investigated plots were presented in Table 4. The best and worst functions were visualized in Figure 5.

Table 4. Parameter estimates for the non-linear models.

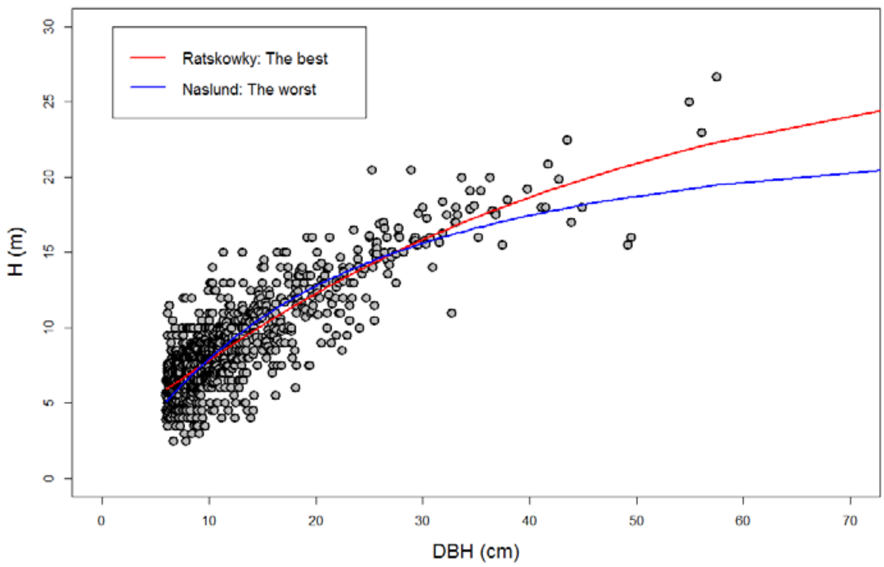
Type	Model	Parameter	Estimation	SE	t-value	Pr(>|t|)	AIC	R-square	RMSE
Plot 1	Power	a	1.6823	0.0491	34.25	<2e-16	4180.62	0.7288	1.7665
		b	0.6813	0.0108	62.84	<2e-16			
	Naslund	a	0.6552	0.0184	35.68	<2e-16	4267.07	0.7075	1.8407
		b	0.1894	0.0025	75.06	<2e-16			
	Chapman-Richards	a	61.8056	26.8169	2.31	0.0214	4182.72	0.7287	1.7665
		b	0.0072	0.0048	1.49	0.1365			
		c	0.8306	0.0414	20.08	<2e-16			
	Exponential	a	3.8742	0.0849	45.62	<2e-16	4187.30	0.7276	1.7704
		b	-49.4396	5.5788	-8.86	<2e-16			
		c	15.0368	1.7594	8.55	<2e-16			
	Weibull	a	72.8884	40.2203	1.81	0.0702	4182.72	0.7288	1.7665
		b	0.0140	0.0067	2.08	0.0383			
		c	0.8422	0.0453	18.60	<2e-16			
	Logistic	a	22.6787	0.7691	29.49	<2e-16	4226.46	0.7174	1.8037
		b	6.4095	0.2177	29.44	<2e-16			
		c	0.0960	0.0039	24.72	<2e-16			
	Gompertz	a	26.0662	1.2549	20.77	<2e-16	4200.35	0.7242	1.7814
		b	2.3527	0.0377	62.48	<2e-16			
		c	0.0540	0.0032	16.63	<2e-16			

	Prodan	a	-1.4420	0.5226	-2.76	0.00589	4183.83	0.7285	1.7675
		b	1.4826	0.0749	19.80	< 2e-16			
		c	0.0149	0.0021	7.12	1.97e-12			
	Ratskowky	a	48.1400	4.0880	11.78	<2e-16	4187.30	0.7276	1.7704
		b	49.4380	5.5790	8.86	<2e-16			
		c	15.0360	1.7590	8.55	<2e-16			
	Korf	a	1192	1846	0.65	0.51873	4185.43	0.7281	1.7688
		b	7.5150	1.3430	5.59	2.83e-08			
		c	0.1624	0.0528	3.08	2.14e-03			
Plot 2	Power	a	1.9232	0.0569	33.78	<2e-16	4153.34	0.7232	1.8370
		b	0.6153	0.0105	58.42	<2e-16			
	Naslund	a	0.6203	0.0199	31.18	<2e-16	4215.8	0.7074	1.8939
		b	0.2022	0.0024	83.79	<2e-16			
	Chapman-Richards	a	32.3008	4.8721	6.63	5.44e-11	4147.67	0.7252	1.8301
		b	0.0158	0.0047	3.40	7.06e-04			
		c	0.8268	0.0421	19.64	< 2e-16			
	Exponential	a	3.6332	0.0750	48.42	< 2e-16	4145.34	0.7259	1.8280
		b	-41.9167	4.8607	-8.62	< 2e-16			
		c	13.8864	1.7688	7.85	1.04e-14			
	Weibull	a	34.6994	6.5745	5.28	1.60e-07	4148.19	0.7251	1.8305
		b	0.0296	0.0038	7.76	2.03e-14			

		c	0.8528	0.0417	20.43	< 2e-16			
	Logistic	a	20.0584	0.6344	31.62	<2e-16	4158.32	0.7224	1.8396
		b	5.3370	0.1815	29.41	<2e-16			
		c	0.0926	0.0040	22.94	<2e-16			
	Gompertz	a	22.3124	0.9499	23.49	<2e-16	4147.07	0.7254	1.8295
		b	2.1490	0.0375	57.36	<2e-16			
		c	0.0553	0.0034	16.21	<2e-16			
	Prodan	a	-1.6362	0.5668	-2.89	3.98E-03	4146.88	0.7255	1.8294
		b	1.4624	0.0791	18.49	< 2e-16			
		c	0.0222	0.0022	10.27	< 2e-16			
	Ratskowky	a	37.8350	2.8390	13.33	< 2e-16	4145.33	0.7260	1.8280
		b	41.9160	4.8610	8.62	< 2e-16			
		c	13.8860	1.7690	7.85	1.04e-14			
	Korf	a	591.0344	766.8383	0.77	4.41e-01	4151.71	0.7242	1.8337
		b	6.6745	1.0912	6.12	1.36e-09			
		c	0.1720	0.0547	3.14	1.71e-03			



a)



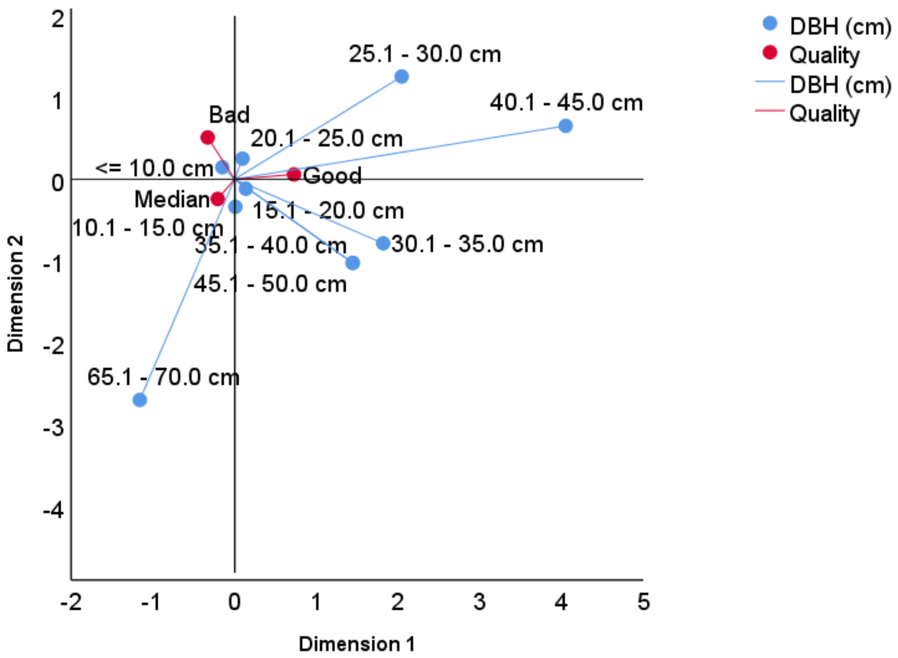
b)

Figure 5. Regression charts for the best (red line) and the worst (blue line) models for a) Plot 1, and b) Plot 2

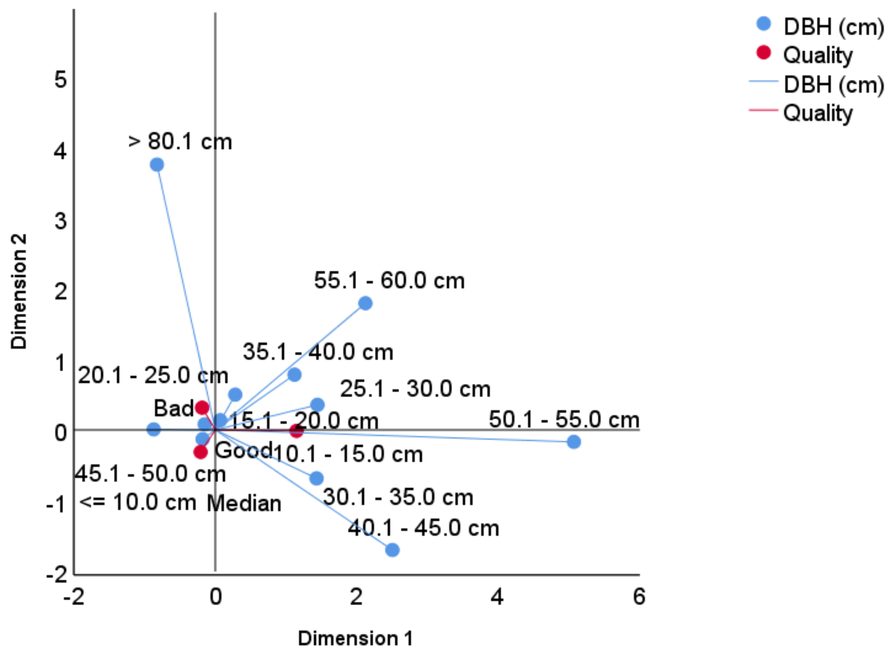
3.4. Associations between tree-size variables and the tree quality

3.4.1. The relation between the diameter and the tree quality

The calculation results indicated that there was a strong association between diameter and forest tree quality in both plots (Chi-squared test, p-value < 0.05). Trees with good quality were often found in relatively large diameter classes in the stand, while trees with poor quality were closely associated with smaller diameter classes. Specifically, in Plot 1, good-quality trees were more strongly related to the diameter groups of 30.1-35.0, 40.1-45.0, and 25.1-30.0 cm. On the other hand, poor-quality trees were typically found in diameter classes smaller than 10.0 cm and 20.1-25.0 cm (Fig. 6a). Meanwhile, in Plot 2, good-quality trees were most strongly associated with diameters of 25.1-30.0 and 50.1-55.0 cm, and had a relatively strong relationship with the groups of 31.1-35.0, 40.1-45.0, and 35.1-40.0 cm. Poor-quality trees, on the other hand, were those with diameters ranging from 20.1-25.0 cm (Fig. 6b).



a)

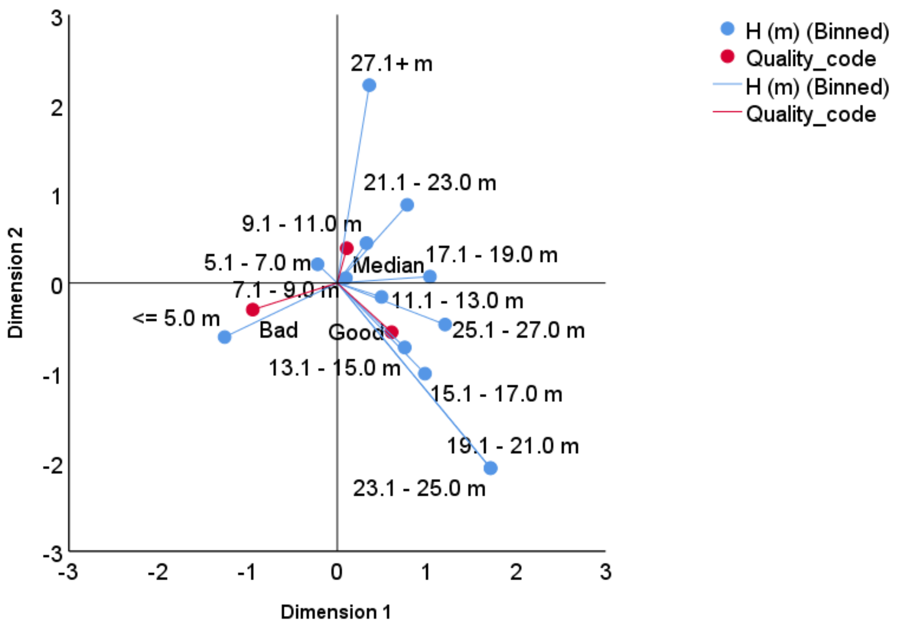


b)

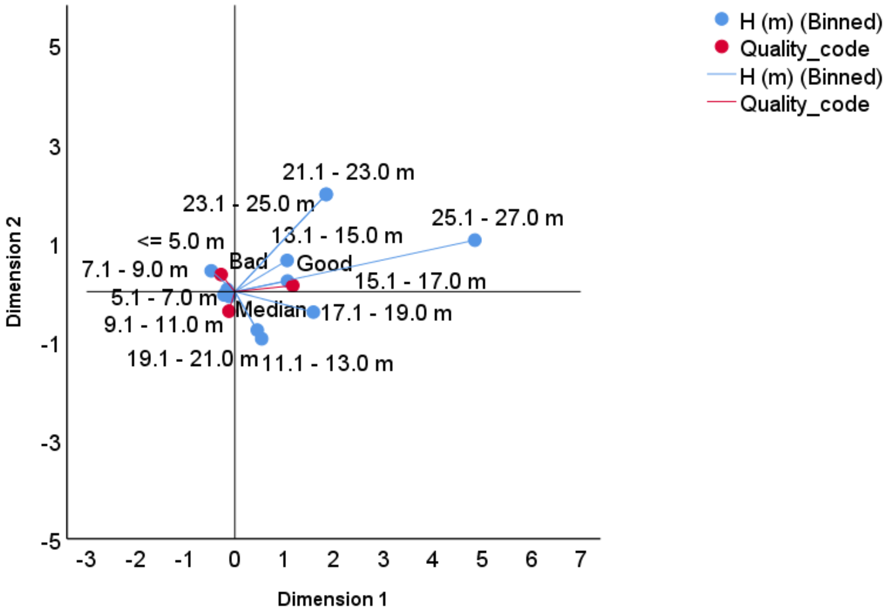
Figure 6. Association analysis between the diameter and the tree quality for a) Plot 1, and b) Plot 2

3.4.2. The relation between the total height and the tree quality

The association between height and the tree quality was quite similar to that between the diameter and the tree quality. In both plots, this relationship was statistically significant (Chi-squared test, p-value < 0.05). Trees with good quality were generally those with relatively greater height, whereas trees with poor quality tended to have shorter heights. This association was even more apparent than the one between diameter and tree quality. Specifically, in Plot 1, good-quality trees were strongly associated with the height groups of 15.1-17.0, 19.1-21.0, and 23.1-25.0 m, while poor-quality trees were strongly related to the group with a height of less than 5.0 m (Fig. 7a). Similarly, in Plot 2, good-quality trees were typically found in the height groups of 13.1-15.0, 15.1-17.0, and 25.1-27.0 m. On the other hand, poor-quality trees had the strongest association with heights below 5 m (Fig. 7b).



a)



b)

Figure 7. Association analysis between the height and the tree quality for a) Plot 1, and b) Plot 2.

4. Discussion

4.1. Characteristics of secondary forests and carbon accumulation capacity

The forest in the study area has many characteristics of poor secondary natural forests in Northern provinces of Vietnam. The findings of the study fully support previous research (Cao Thi Thu et al., 2019; Hai, 2011; Trieu & Hung, 2018). The tree density in the study area is higher compared to the secondary forests in Phu Tho (Trieu & Hung, 2018), Bac Kan (Cao Thi Thu et al., 2019), and Thanh Hoa (Hai, 2011). This may be the reason why the tree diameter and height are smaller than forest trees in the above locations. Because, with higher density, forest trees compete for nutrients and light, making the growth process of diameter and height is somewhat hindered (Hoan & Ngu, 2003). However, the density of forest trees is relatively similar to natural forests in Quang Ninh (Tran Van et al., 2022), Son La (Bao & Thi, 2013) and Nghe An (Pham et al., 2022). In addition, the average diameter and height are also similar to the results of the study conducted in Quang Ninh (Tran Van et al., 2022). In terms of volume, the forest in Plot 1 is classified as poor forest according to Vietnam's standards, because the poor forest in Vietnam is a forest with a volume of 10-100 m^3/ha. And the forest in Plot 2 is a medium forest, because according to regulations, the medium forest is a forest with a volume of 101 - 200 m^3/ha (Stas et al., 2020). This volume is also completely comparable to secondary forests that have been studied in Phu Tho, Bac Kan, Thanh Hoa, Son La (Bao & Thi, 2013; Cao

Thi Thu et al., 2019; Hai, 2011; Trieu & Hung, 2018). Because poor forests and medium forests account for a very large proportion in Vietnam (56% of natural forests) (Stas et al., 2020).

Regarding to dry biomass, carbon stocks and carbon credits of forests in the study area, results are also consistent with poor and medium forests in different provinces of Vietnam. Secondary natural forests in Son La had dry biomass from 23.16 to 128.99 ton/ha. And carbon stocks were from 19.99 to 102.93 ton/ha (Bao & Thi, 2013). The biomass of secondary natural forests in Ninh Thuan was from 26.8 to 87.5 ton/ha (Hoang, 2016). Calculation results of biomass and carbon stocks for poor secondary forests in Hue also support this research, because, biomass fluctuated between 46.56 - 148.76 ton/ha and carbon stocks were from 23.28-74.38 ton/ha (Tinh & Dung, 2012). However, the dry biomass and carbon stocks in the study area are lower than those in Tay Ninh (Quoc & Quy, 2023). The average biomass of the forest in Tay Ninh was from 202.6 to 227.8 ton/ha and the carbon stocks ranged from 101.3 to 113.9 ton/ha (Quoc & Quy, 2023). Biomass and carbon stocks of natural forests in Nghe An based on satellite image analysis also were greater than those in the study region (Do Thi et al., 2023). This can be explained by the fact that the forests in the study area are mostly poor forests. The number of trees with small diameters and heights accounts for a large proportion (>80% of the forest trees). If we assume that the value of each carbon credit is 5 USD (Le, 2024), then the forests in the study area are worth from 596.9 to 804.3 USD/ha. This figure is also very meaningful for forest owners in the study area. This can motivate them to be more active in protecting and developing natural forests in the study area.

4.2. Modeling ability of multivariate theoretical distributions

Frequency distribution modeling has many meanings in forestry science and forest management such as: calculating, forecasting carbon stocks and biomass of forests, being the basis for proposing silvicultural measures, predicting the number of forest trees in different groups (Hung, 2022; Lima et al., 2017). Frequency distribution modeling for diameter and height variables has been conducted in many types of forests and in many different provinces in Vietnam (Cao Thi Thu et al., 2019; Nguyen Van et al., 2018; Trieu & Hung, 2018). However, in Vietnam, many studies often use only four theoretical functions for modeling, namely Nornal, Weibull 2P, Mayer and Distance. Very few studies apply other functions with many distribution variables (Cao Thi Thu et al., 2019; Hai, 2011; Trieu & Hung, 2018). In 2022, Hung used 64 different theoretical functions to model the distribution of Ba Be tree size quantities. This is probably one of the first studies conducted in Vietnam with the application of many different theoretical functions (Hung, 2022). The results showed many differences compared to the results of traditional studies, because none of the four traditional functions was selected as the best function to simulate the frequency distribution of the quantities. This gradually showed the superiority of the new theoretical functions with more parameters in the equation.

In this study, the general characteristics of diameter and height frequency distributions match those observed in earlier researches. The diameter frequency distribution had a decreasing shape from the first class to the last class. Meanwhile, the height frequency distribution had a shape similar to a bell shape, but the peak of the distribution was shifted to the right. These characteristics are also found in natural forests in Bac Kan, Phu Tho, Ba Vi, Gia Lai and so on (Cao Thi Thu et al., 2019; Hung, 2016, 2022; Trieu & Hung, 2018). The modeling results also show that the traditional functions used in Vietnam have lower modeling capabilities than the new multivariate functions. In both plots, the best function to describe the diameter frequency distribution was Fatigue Life (3P) (with 3 parameters) and the best function for the height distribution was Burr (with 3 parameters). These outcomes also have some differences compared to the study in Ba Be, although both studies applied the same 64 theoretical functions. For diameter, the results of the study in Ba Be indicated that the best distribution for rich forests was Weibull (3P) with 3 parameters, for medium forests was Pearson 6 (4P) with 4 parameters, for poor forests was Wakeby with 5 parameters. For height, Pearson 6 (4P) with 4 parameters was the best function for rich forests, Dagum (4P) with 4 parameters was the best for medium forests and Gen. Extreme Value with 3 parameters was the best for poor forests (Hung, 2022). These findings further confirm that functions with many parameters are able to model frequency distributions better than functions with few parameters, because, functions with many parameters are often more flexible (Tuat & Khoi, 2009). At the same time, it is very necessary to conduct specific studies in small research areas to find the best functions for that specific region. Because the results of different regions are very dissimilar, despite using the same methods of data collection and analysis.

4.3. Relationship between diameter and height

The regression between diameter and height has been analyzed for many types of forests in Vietnam and around the world (Chenge, 2021; Liu et al., 2017; Monteiro et al., 2016; Phong, 2019; Trieu & Hung, 2018). Studies have also tested many different nonlinear models: from simple (few parameters) to complex (many parameters); from nonlinear models to mixed nonlinear models (Ogana et al., 2020; Özçelik et al., 2018; Phong, 2019; Trieu & Hung, 2018). However, the results in different regions are very dissimilar. This may be the consequence of differences in forest types, tree species, living conditions, and growth characteristics of forest trees (Bui Manh et al., 2022). In Vietnam, there have been many studies analyzing the relationship between diameter and height. However, most of these studies use traditional non-linear models such as: Linear, Logarithmic, Power, Inverse, Quadratic, Cubic, S, Compound, Growth and Exponential. And the best functions are also very different between provinces such as: Binh Dinh, Lao Cai, Bac Kan, Vinh Phuc, Gia Lai and Hanoi (Bui Manh et al., 2022; Cao Thi Thu et al., 2019; Phong, 2019; Trieu & Hung, 2018). In 2023, Hung and colleagues conducted analyses for natural forests in Gia Lai. The research used 10 multivariate models: Power, Naslund, Chapman-Richards, Exponential, Weibull, Logistic, Gompertz, Prodan, Ratskowky and Korf. The outcomes revealed that the best model for secondary forests was Power, and for old-growth forests was Prodan (Bui Manh et al., 2023). In this study, we also used the same 10 multivariate models, but the findings showed both similarities and differences. The Power model was the best for Plot 1, but Ratskowky was the best for Plot 2. These findings again illustrate that the best models should only be applied to the measured area, should not apply them to other regions. Therefore, it is necessary to conduct specific studies for each area, for each forest type, even for each tree species and family if having enough data. At the same time, studies in Vietnam should apply both traditional and modern models to see which one is better.

4.4. Forest management based on associations between tree-size variables and the plant quality

The association between tree-size variables and forest tree quality is a good basis for forest resource management in the study area. However, this relationship has received little attention and analysis in forestry research in Vietnam as well as in the world. The analysis results showed a general trend that good trees often have great diameters and heights. On the contrary, trees with poor quality often have a relatively close relationship with trees with small diameters. This trend was also found in secondary forests in Bak Kan (Tuan & Hung, 2018) and pure Acacia plantations in Ba Vi (Hung et al., 2023; Phong & Hung, 2019). With this result, an important point when applying silvicultural techniques and forest tending measures is to pay close attention to small-sized trees. These trees are often concentrated in the lower layers. These trees are often under a lot of pressure and competition from larger trees. And sometimes they are the losers in the competition for survival. And this can be the main reason for their poor growth quality. Therefore, it is necessary to provide more light for these trees by opening up the canopy, or cutting off the branches that shade them. Or, it is possible to remove vines and bushes around these trees to reducing the competition, providing more space for them to grow. Foresters can also loosen the soil around the base of the small tree to provide more oxygen to the soil, helping to improve the soil structure and create favorable conditions for plant growth.

5. Conclusions

In conclusion, the study analyzed and demonstrated the characteristics of carbon stock and structural features of secondary forests in Tuyen Quang, Vietnam detailly and quantitatively. The calculations on tree density, size, forest volume, and carbon stock revealed that the forests in the area are classified as poor to medium forests. The diameter frequency distribution followed a decreasing pattern, while the height frequency distribution resembled an inverted bell shape. Multi-parameter models have shown better potential for simulating the frequency distributions of both diameter and height. For the diameter-height relationship, the Power and Ratskowsky functions proved to be the most effective for modeling this relationship across the studied plots. Trees with larger diameters and heights were generally better quality, while smaller trees tended to be lower quality. Forest restoration, maintenance, quality control, and tree growth management solutions are essential for improving the quality and carbon stock of secondary forests in the study area. Increasing the number and size of observation plots in future surveys is recommended to better capture the characteristics of the forests in this region.

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Compliance with ethical standards

The author declares that he has no conflicts of interest. This article does not contain any studies involving animals or human participants performed by the author.

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