DEVELOPMENT AND EVALUATION OF MODELS FOR THE RELATIONSHIP BETWEEN HEIGHT AND DIAMETER OF THREE FOREST STATES FOR TROPICAL RAINFORESTS IN VIETNAM

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SUMMARY

This paper introduces the result of finding the best equation to describe the relationship between the total tree height and diameter at breast height of three forest states, including: poor, medium and rich forest states. Data were collected on 15 sample plots, each plot area was 10,000 m^2 (100 m x 100 m) in Ha Tinh, Tuyen Quang, Hoa Binh, Quang Binh, Thua Thien Hue and Gia Lai Provinces. 10 different types of equations were tested in this study, including two types of equations, linear equations and nonlinear equations. Based on four criteria to choose the best equation, namely (1) Root of mean square error (RMSE), (2) Adjusted coefficient of determination (R^2_{adj}), (3) Bias and (4) Akaike's information criterion (AIC). The results showed that, equation (3) ($h = a_0 + a_1.d + a_2.d^2$) was the most appropriate to describe the relationship between height and diameter for two forest states, namely poor forest and medium forest, while equation (8) ($h = a_0.e^{-a1/d^{\wedge}a2}$) were recommended for predicting tree height of the rich forest state. Clearly, diameter at breast height was the primary stand variable that influenced the height-dbh relationship. The method and the recommended equations developed in this study were statistically reliable for applications in height estimation for tropical rainforest in Vietnam.

Keywords: Akaike's information criterion, H – D relationship, linear model, nonlinear model, RMSE.

1. INTRODUCTION

The total tree height of a tree is a growth quantity representing the results of growth in height at a specified time of a tree. As well as the diameter at breast height, basal area, volume, ... total tree height is a factor that changes over time. Tree height growth in the stand depends on tree species, site condition, age and density. Besides, the difference in height in the forest stand depends on diameter and also on the growing location and other factors. The total tree height of forest trees is an important basis for computing the mean height of the stand.

In order to determine the yield as well as the stand volume, data on the height of the trees in the stand should be collected. Unlike the diameter at breast height, the total tree height is usually indirectly determined by measuring instruments and is time-consuming. Therefore, to simplify the investigation, it is necessary to find out the relationship between height and some other survey factors that are easier to measure such as diameter at breast height. Hence, study the relationship between the quantities need to be measured of the trees in the stand aims to develop a method to determine the difficult to measure quantities such as the total tree height from the quantity that is easy to measure or simple to compute.

There exists a close relationship between height and diameter at breast height of the forest tree. This relationship is not limited to only one forest stand, but exists in a set of forest stands and when researched does not take into account circumstances and age. From the reality shows that, it is possible to rely on the relationship between height and diameter to determine the height for trees that not measured total tree height.

Many height-dbh models have been developed and used to estimate total tree height from dbh. For example, Khanh (1996) and Tu (1999) chose the equation log (h) = a + b.log(d) to represent the relationship height - dbh for natural forest in Huong Son district, Ha Tinh province. Men (2005) studied the structure of evergreen broadleaf forest in Phu Yen province, used logarithmic, quadratic and Power functions to describe the relationship between height - dbh. Tuan (2017) chose quadratic and logarithmic functions to describe the relationship between height - dbh of forest states III_{A1}, III_{A2} and III_B in the central region of Vietnam. Van (2018) used the quadratic equation to describe the relationship height - dbh for the natural forest state III_A in An Lao district, Binh Dinh province.

However, there still have been very few in-depth studies on height-dbh relations for tropical rainforest in Vietnam. Therefore, the questions are (1) what types of equations describe the relationship between total tree height and diameter at breast height, (2) Based on which criteria to choose the best equation to represent this relationship? To solve these two questions, the objectives of this study are to: (1) develop some models that could be used to predict the relationship between height and diameter, (2) provide some criteria to evaluate and find the best equation to represent this relationship.

2. RESEARCH METHODOLOGY

2.1. Data collection

The objects in this study are four forest states, namely rich forest, medium forest and poor forest (based on Circular No. 33/2018/TT-BNNPTNT dated November 16, 2018 prescribing forest survey, inventory and forest transition monitoring). The study used data in 15 sample plots (each covering 1 ha, 100 m x 100 m) in Tuyen Quang, Ha Tinh, Hoa Binh, Quang Binh, Thua Thien Hue, and Gia Lai Provinces. 5 plots in each forest state were set up, each plot was divided into 25 sub-plots 20 m x 20 m. In each plot, species name was determined and the diameter and height of all trees with a diameter of 6 cm or greater were measured.

2.2. Data analysis

2.2.1. Descriptive statistics

Several general information on forest structure were computed for each sample plot, including: density, mean diameter, mean height, basal area, volume.

2.2.2. Model fitting

Many height-diameter (dbh) models have been developed and used to estimate tree height from dbh (Arcangeli et al., 2014). A large number of generalised height-dbh equations have been reported that have been developed especially for a particular species or for specific areas. The relationship between height and dbh can be expressed by linear functions and nonlinear functions. For example, Huang *et al*. (1992) evaluated 20 nonlinear height-dbh models for major Alberta species. Ecoregion-based height-dbh models have also been developed (Peng *et al*., 2004; Huang *et al*., 2000; Zhang *et al*., 2002; Castedo Dorado *et al*., 2005).

With the relative ease of fitting nonlinear functions, the nature of nonlinear height-dbh functions has now been widely used in height predictions (Schreuder *et al.*, 1979; Farr *et al.*, 1989). In this study, both linear and nonlinear models were used in order to compare their performance, including:

Linear models:

$$h^{-1} = a_0 + a_1.d^{-1} \quad (1)$$

$$\log(h - 1.3) = a_0 + a_1.\log(d) \quad (2)$$

$$h = a_0 + a_1.d + a_2.d^2 \quad (3)$$

$$h = a_0 + a_1.\ln(d) \quad (4)$$

Nonlinear models:

$$h = 1.3 + a_0.d^{a1} \quad (5)$$

$$h = a_0.d^{a1} \quad (6)$$

$$h = a_0.[\ln(d)]^{a1} \quad (7)$$

$$h = a_0.e^{-a1/d^\wedge a2} \quad (8)$$

$$h = 1.3 + a_0.e^{-a1/d} \quad (9)$$

$$h = a_0.a_1^{d} \quad (10)$$

Where:

h: height (m)

d: diameter at breast height (dbh) (cm)

a_0, a_1, a_2: parameters

The base is 10 for logarithm

ln is the natural logarithm

2.2.3. Model selection criteria

Model evaluation and comparison were based on graphical and numerical analysis of the values of the following statistics (Yan-qiong Li *et al.*, 2015):

(1) Root of mean square error (RMSE) (Equation 11), the smaller RMSE, the better.

(2) Adjusted coefficient of determination (R^2_{adj}) (Equation 12 and Equation 13), the greater R^2_{adj}, the higher the interrelation between the variables.

(3) Bias (Equation 14) and relative bias (Equation 15), the smaller Bias, the better.

(4) Akaike's information criterion (AIC) (Equation 16 and Equation 17), the model with the lower AIC values was preferred.

$$\boldsymbol{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(y_i-\hat{y}_i)^2}{n-p-1}} \qquad (11)$$

$$\boldsymbol{R^2} = 1 - \frac{\sum_{i=1}^{n}(y_i-\hat{y}_i)^2}{\sum_{i=1}^{n}(y_i-\bar{y}_i)^2} \qquad (12)$$

$$\boldsymbol{R_{adj}^2} = 1-(1-R^2).\frac{n-1}{n-p-1} \qquad (13)$$

$$\boldsymbol{Bias} = \frac{\sum_{i=1}^{n}(\hat{y}_i-\bar{y})}{n} \qquad (14)$$

$$\boldsymbol{Relative\ bias}(\%) = \frac{\sum_{i=1}^{n}(\hat{y}_i-\bar{y})/y_i}{n}.\mathbf{100} \qquad (15)$$

Residual sum of square:

$$\boldsymbol{RSS} = \sum_{i=1}^{n}(y_i-\hat{y}_i)^2 \qquad (16)$$

Akaike's information criterion:

$$\boldsymbol{AIC} = n.\ln(RSS) = 2(p+1) - n.\ln(n) \qquad (17)$$

Where: y_i, $\hat{y}_i$ and $\bar{y}$ are the observed, predicted and mean values of heights, respectively;

n is the total number of data used in fitting the model; and p is the number of independent variables.

Model fitting was carried out using the SPSS statistical program package 20.0.

3. RESULTS AND DISCUSSION

3.1. Descriptive statistics of diameter at breast height

The summary of the descriptive statistics of diameter for tropical rainforests in Vietnam are presented on Table 1.

Table 1. Descriptive statistics of the sample trees in 15 plots

Province	Plot	N (trees/ha)	$\bar{D}$ (cm)	$\bar{H}$ (m)	BA (m^2/ha)	Volume (m^3/ha)	Forest state
Ha Tinh	1	339	18.9	14.7	11.37	96.72	Poor
Ha Tinh	2	316	18.6	11.5	10.95	78.19	Poor
Tuyen Quang	3	539	14.9	10.8	11.80	72.60	Poor
Tuyen Quang	4	467	13.5	10.5	8.00	53.77	Poor
Hoa Binh	5	999	11.3	12.4	12.17	91.04	Poor
Ha Tinh	6	372	18.47	11.07	14.00	103.01	Medium
Hoa Binh	7	990	11.4	12.4	13.41	101.37	Medium
Quang Binh	8	623	16.2	12.2	17.39	142.39	Medium
Quang Binh	9	831	16.9	13.1	24.12	198.75	Medium
Quang Binh	10	897	16.1	12.3	24.22	197.33	Medium
Gia Lai	11	877	16.4	13.5	27.30	244.71	Rich
Gia Lai	12	825	17.7	12.8	27.73	234.56	Rich
Gia Lai	13	1,079	15.7	12.6	28.61	243.32	Rich
Thua Thien Hue	14	916	16.7	13.6	19.84	262.47	Rich
Thua Thien Hue	15	914	17.9	12.4	34.36	298.72	Rich

N: Number of trees per hectare; $\bar{D}$*: Mean diameter;* $\bar{H}$*: Mean height; BA: Basal area*

The density of 15 plots varied from 316 trees/ha to 1,079 trees/ha. The highest and lowest dbh values found were 18.9 cm and 11.3 cm, respectively (Table 1). The maximum value of dbh came from plot 1 in the poor forest. The highest tree densities were counted in plot 13 of the rich forest with 1,079 trees/ha, whereas the lowest was observed in the plot 2 of the poor forest with 316 trees/ha. The mean height of 15 plots was 10.5 m – 14.7 m. The basal area of 15 plots ranged from 8.00 m^2/ha to 34.36 m^2/ha and the volume was 53.77 m^3/ha – 298.72 m^3/ha.

Based on Circular No. 33/2018/TT-BNNPTNT dated November 16, 2018 prescribing forest survey, inventory and forest transition monitoring, 15 plots belong to three forest states, namely poor forest state with volume ranged from 53.77 m^3/ha to 96.72 m^3/ha, medium forest state and rich forest state were 101.37 m^3/ha – 198.75 m^3/ha and 234.32 m^3/ha – 298.72 m^3/ha, respectively.

3.2. Model fitting

Results of goodness of fit and prediction accuracy for the datasets are given in Table 2.

Table 2. Fitting statistics for 10 models of three forest states

Forest state	Plot	Model	RMSE	Adjusted R^2	Bias	AIC
Poor	1	1	3.949	0.730	0.867	1391.44
		2	3.484	0.748	-0.111	1349.41
		3	2.289	0.768	0.000	1201.50
		4	2.355	0.756	0.000	1211.44
		5	2.461	0.735	0.036	1227.01
		6	2.488	0.750	-0.185	1230.79
		7	2.380	0.754	-0.204	1215.22
		8	2.329	0.763	-0.009	1207.65
		9	2.326	0.763	-0.024	1207.21
		10	2.828	0.650	0.046	1275.94
	2	1	4.155	0.481	0.280	1303.55
		2	3.688	0.566	-0.793	1264.47
		3	2.352	0.597	0.000	1116.8
		4	2.414	0.578	0.000	1125.40
		5	2.388	0.589	0.007	1121.91
		6	2.399	0.569	-0.245	1123.39
		7	2.424	0.551	-0.266	1126.80
		8	2.381	0.591	-0.002	1120.95
		9	2.472	0.560	-0.051	1133.20
		10	2.634	0.530	-0.239	1154.03
	3	1	2.809	0.619	0.067	2156.20
		2	2.626	0.643	-0.966	2118.33
		3	1.690	0.669	0.000	1871.68
		4	1.707	0.664	0.000	1877.08
		5	1.732	0.655	0.011	1885.40
		6	1.734	0.646	-0.132	1885.90
		7	1.711	0.647	-0.137	1878.53
		8	1.702	0.667	-0.001	1875.65
		9	1.718	0.660	-0.011	1880.70
		10	1.987	0.590	-0.142	1962.21
	4	1	2.902	0.882	0.831	1689.58
		2	2.264	0.859	-0.607	1578.37
		3	0.979	0.876	0.000	1202.84
		4	0.996	0.872	0.000	1210.55
		5	1.115	0.841	0.019	1261.06
		6	1.124	0.863	-0.035	1264.49
		7	1.026	0.881	-0.036	1223.69
		8	0.987	0.875	0.000	1206.43
		9	0.989	0.875	-0.003	1207.28
		10	1.574	0.753	-0.056	1415.31
	5	1	8.233	0.304	-7.799	11111.83
		2	6.737	0.373	-6.200	10711.29
		3	2.623	0.456	0.000	8826.60
		4	2.665	0.439	0.000	8858.61
		5	2.635	0.453	-0.005	8835.82
		6	2.655	0.381	-0.305	8851.10
		7	2.683	0.374	-0.311	8871.68
		8	2.642	0.450	-0.011	8840.89
		9	2.716	0.419	-0.010	8895.95
		10	2.652	0.382	-0.295	8848.53

Forest state	Plot	Model	RMSE	Adjusted R^2	Bias	AIC
Medium	6	1	6.052	0.777	2.976	1661.38
		2	3.926	0.777	-0.217	1498.63
		3	1.955	0.833	0.000	1236.56
		4	1.954	0.834	-0.002	1236.26
		5	2.205	0.790	0.050	1281.69
		6	2.319	0.785	-0.114	1300.71
		7	2.087	0.808	-0.117	1261.09
		8	1.914	0.842	-0.003	1228.53
		9	1.912	0.842	-0.002	1228.12
		10	3.289	0.647	-0.176	1432.11
	7	1	8.229	0.313	-7.776	11014.13
		2	6.889	0.371	-6.329	10661.73
		3	2.676	0.433	0.000	8787.58
		4	2.680	0.432	0.000	8790.73
		5	2.676	0.434	0.013	8787.77
		6	2.693	0.379	-0.305	8800.37
		7	2.698	0.377	-0.309	8803.55
		8	2.676	0.435	-0.002	8787.41
		9	2.707	0.421	-0.006	8810.30
		10	2.749	0.364	-0.306	8840.54
	8	1	8.610	0.359	5.026	1846.71
		2	5.315	0.525	1.534	1660.54
		3	2.697	0.625	0.000	1398.68
		4	2.763	0.608	0.000	1408.02
		5	2.773	0.607	0.028	1409.41
		6	2.790	0.562	-0.344	1411.70
		7	2.774	0.552	-0.376	1409.50
		8	2.733	0.619	-0.006	1403.72
		9	2.795	0.601	-0.072	1412.49
		10	3.318	0.489	-0.351	1478.63
	9	1	4.638	0.661	-2.163	8136.61
		2	4.539	0.694	-2.220	8100.55
		3	2.667	0.709	0.000	7216.81
		4	2.682	0.706	0.000	7226.07
		5	2.753	0.691	0.036	7269.79
		6	2.764	0.698	-0.025	7276.12
		7	2.695	0.699	-0.271	7234.07
		8	2.670	0.709	-0.004	7218.77
		9	2.720	0.698	-0.042	7249.71
		10	3.545	0.601	-0.274	7689.63
	10	1	5.501	0.615	-4.176	9157.46
		2	5.139	0.676	-3.580	9035.32
		3	2.399	0.722	0.000	7668.44
		4	2.417	0.718	0.000	7681.64
		5	2.481	0.703	0.020	7728.73
		6	2.497	0.683	-0.212	7740.31
		7	2.421	0.682	-0.234	7685.04
		8	2.402	0.722	-0.003	7670.65
		9	2.491	0.701	-0.045	7736.46
		10	3.578	0.562	-0.235	8385.53

Forest state	Plot	Model	RMSE	Adjusted R^2	Bias	AIC
	11	1	5.880	0.601	-4.564	4407.52
		2	5.559	0.656	-4.128	4356.40
		3	2.459	0.704	0.000	3612.34
		4	3.817	0.708	0.000	4013.40
		5	2.520	0.691	0.028	3634.87
		6	2.540	0.664	-0.219	3642.00
		7	2.458	0.670	-0.233	3611.94
		8	2.440	0.710	-0.002	3605.29
		9	2.502	0.695	-0.033	3628.20
		10	3.228	0.546	-0.262	3860.64
	12	1	4.315	0.652	-1.369	3854.82
		2	4.167	0.701	-1.987	3824.91
		3	2.333	0.714	0.000	3327.22
		4	2.345	0.711	0.000	3331.65
		5	2.328	0.716	0.014	3325.44
		6	2.332	0.705	-0.193	3326.79
		7	2.338	0.700	-0.221	3329.22
		8	2.312	0.720	0.000	3319.41
		9	2.442	0.688	-0.046	3366.52
		10	2.902	0.622	-0.196	3514.35
	13	1	4.397	0.605	-1.695	5212.57
		2	4.319	0.647	-1.966	5192.39
		3	2.590	0.685	0.000	4618.82
		4	2.588	0.686	0.001	4617.73
		5	2.667	0.667	0.036	4651.52
		6	2.688	0.653	-0.253	4660.39
		7	2.603	0.656	-0.271	4624.55
		8	2.579	0.688	-0.003	4613.78
		9	2.617	0.679	-0.035	4630.41
		10	3.507	0.549	-0.275	4958.66
	14	1	5.814	0.518	-3.917	5688.90
		2	5.587	0.564	-3.683	5642.97
		3	2.643	0.626	0.000	4780.81
		4	2.707	0.609	0.000	4808.19
		5	2.792	0.585	0.028	4844.12
		6	2.815	0.573	-0.263	4853.23
		7	2.729	0.583	-0.270	4817.81
		8	2.695	0.613	-0.003	4803.23
		9	2.723	0.605	-0.023	4815.11
		10	3.488	0.446	-0.316	5100.25
	15	1	6.792	0.616	1.620	4747.57
		2	5.105	0.674	-0.659	4476.31
		3	2.605	0.712	0.134	3837.10
		4	2.537	0.725	0.000	3811.88
		5	2.617	0.708	0.042	3841.47
		6	2.648	0.687	-0.233	3852.72
		7	2.546	0.698	-0.254	3815.32
		8	2.530	0.727	0.000	3809.38
		9	2.609	0.709	-0.046	3838.76
		10	3.708	0.548	-0.275	4172.62

The adjusted R^2 and RMSE values were slightly different among plots in the same forest state (Table 2).

In the poor forest state, the adjusted R^2 values ranged from 0.304 to 0.882 and the RMSE values ranged from 1.690 to 8.233. Model 3 produced the best fit to the data with the highest adjusted R^2 and the lowest values of RMSE, bias and AIC. Therefore, it could be considered that this equation with the most accuracy for tree height estimation in the poor forest state. This equation used two independent variables (namely, dbh and dbh^2) for predicting the height and produced a good fit to the data, followed by Model 8, Model 5 and Model 9.

For the medium forest state, the adjusted R^2 values varied from 0.313 to 0.842 and the RMSE values were from 1.912 to 8.610. Similar to the poor forest state, Model 3 also produced the best fit to the data with the highest adjusted R^2 and the lowest values of RMSE, bias and AIC, followed by Model 8, Model 4 and Model 9.

For the rich forest state, the adjusted R^2 values varied from 0.446 to 0.727 and the RMSE values were from 2.312 to 7.792. Model 8 produced the best fit to the data with the highest adjusted R^2 and the lowest values of RMSE, bias and AIC, followed by Model 4, Model 2, Model 3.

3.3. Model selection

For selection, 10 models were ranked in terms of their performance based on adjusted R^2, RMSE, absolute bias, relative bias and AIC. With respect to adjusted R^2, the model with the value closest to one was the highest-ranking, whereas for bias (both absolute and relative bias), the model with the value closest to zero was considered to be the best. For RMSE and AIC, the model with the lowest value had the highest ranking. For each model, its ranking for the five evaluation statistics was summated. The model with the smallest sum total (for instance, the highest overall ranking) was considered to be the best growth function for each of the forest state databases.

According to this ranking, for the poor and medium forest state, Model 3 was the best model for the dataset, whereas Model 8 was the best for the rich forest state (Table 3).

Table 3. Model rank based on performance

Model performance	Forest state		
	Poor	Medium	Rich
Adjusted R^2	3 (1); 8 (2); 5, 7 (3)	3 (1); 8 (2); 4 (3)	8 (1); 4 (2); 3 (3)
RMSE	3 (1); 8 (2); 9 (3)	3 (1); 9 (2); 8 (3)	8 (1); 4 (2); 3 (3)
AIC	3 (1); 8 (2); 5, 9 (3)	3 (1); 9 (2); 8 (3)	8 (1); 4 (2); 3 (3)
Absolute bias	3 (1); 4, 8 (2); 2 (3)	3, 4 (1); 8 (2); 2 (3)	3, 8 (1); 4 (2); 2 (3)

Numbers in parenthesis indicate the rank of the model for the attributes in the table. Rank one represents the best performance

For Models 3 and Model 8, the parameter estimates and fitting statistics were calculated using all of the dataset and all parameters were significant with Sig. is lower than 0.05.

Previous studies had shown that the quadratic function is one of the best fit model to describe the relation ship between height-dbh, such as, Men (2005) used quadratic to predict height from height - dbh of evergreen broadleaf forest in Phu Yen province; Tuan (2017) chose quadratic function to represent the relationship between height - dbh of three forest states III_{A1}, III_{A2} and III_B in the central region of Vietnam; Van (2018) also concluded that the quadratic equation describes well the relationship height - dbh for the natural forest state III_A in An Lao district, Binh Dinh province. However, up to now, there is no researches use model 8 to represent the relationship between height-dbh for natural forest in Vietnam.

The observed heights versus the predicted heights for Model 3 and Model 8, for datasets in three forest states, are shown in Figure 1.

The criterion used to evaluate the performance of a model was the determination coefficient of the straight line between the observed and predicted heights (namely, the solid line represents the diagonal). Each model had a relatively high R^2, so the solid line was closely surrounded by the data points.

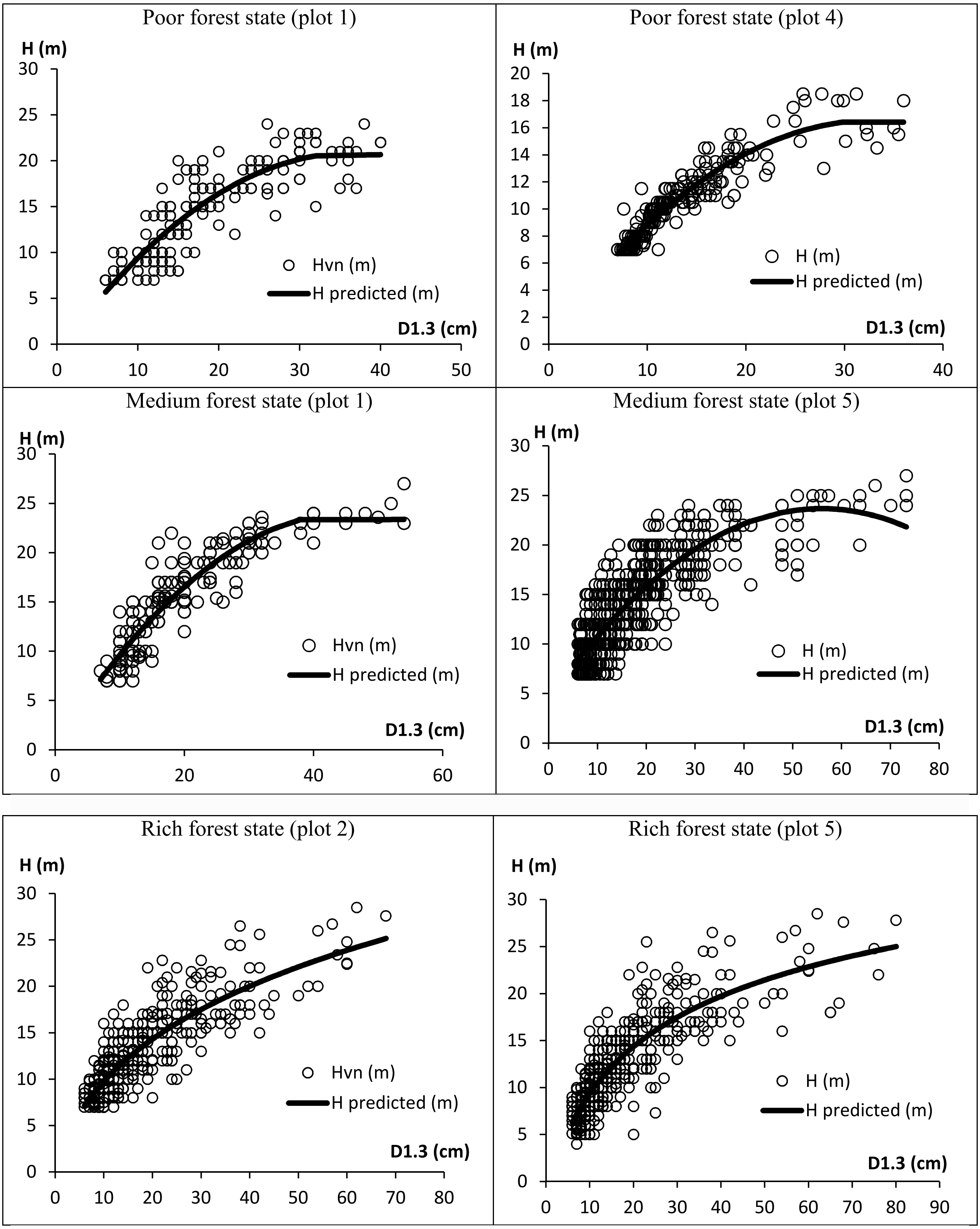

Figure 1. Graph of observed values versus predicted values of the dataset for the two best models (Model 3 and Model 8). The solid line represents the diagonal

The scatter plot of the individual height and dbh values for individual trees of three forest states is presented in Figure 1. At dbh values less than 30 cm, tree height increased rapidly as dbh increased; however, as the dbh increased further, the increase in tree height slowed down and the height-dbh curve became less steep.

4. CONCLUSION

In this study, 15 height-dbh models were tested on 15 plots in the poor, medium and rich forest states. Model selection was based on goodness of fit and precision. Model comparisons were carried out based on the ranking. Model 3 and Model 8 provided a relatively accurate prediction for this three forest states using dbh as independent variable, and were therefore selected as the final models to predict total tree height of the poor, medium and rich forest states.

The development of simple and accurate models that allow forest managers to reliably determine the height of trees in a stand from dbh data is of prime importance in forest management. In this study, the two selected models not only had good statistical reliabilities, but were also easy to apply.

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XÂY DỰNG VÀ ĐÁNH GIÁ CÁC MÔ HÌNH MÔ TẢ MỐI QUAN HỆ GIỮA CHIỀU CAO VÚT NGỌN VÀ ĐƯỜNG KÍNH NGANG NGỰC CỦA 3 TRẠNG THÁI RỪNG TỰ NHIÊN Ở VIỆT NAM

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Bài báo này giới thiệu về kết quả tìm phương trình tốt nhất để mô tả mối quan hệ giữa chiều cao vút ngọn và đường kính ngang ngực của ba trạng thái rừng là rừng nghèo, rừng trung bình và rừng giàu. Số liệu được thu thập trên 15 ô tiêu chuẩn, diện tích mỗi ô là 10.000 m^2 (100 m x 100 m) tại các tỉnh Hà Tĩnh, Tuyên Quang, Hòa Bình, Quảng Bình, Thừa Thiên Huế và Gia Lai. Nghiên cứu thử nghiệm 10 dạng phương trình khác nhau gồm hai dạng phương trình là phương trình tuyến tính và phương trình phi tuyến. Dựa vào bốn tiêu chí để chọn phương trình tốt nhất là (1) sai lệch trung bình giữa giá trị quan sát với giá trị lý thuyết (RMSE), (2) hệ số xác định có điều chỉnh (R^2_{adj}), (3) sai lệch trung bình giữa giá trị lý thuyết với giá trị trung bình và (4) chỉ số AIC. Kết quả cho thấy, dạng phương trình (2.3) là $h = a_0 + a_1.d + a_2.d^2$ mô tả tốt nhất mối quan hệ giữa chiều cao và đường kính cho hai trạng thái rừng là rừng nghèo và rừng trung bình, dạng phương trình (2.8) là $h = a_0.e^{-a1/d^{\wedge}a2}$ biểu diễn tốt nhất cho mối quan hệ này của trạng thái rừng giàu. Kết quả cũng cho thấy, đường kính ngang ngực là biến số lâm phần chính ảnh hưởng đến mối quan hệ giữa chiều cao và đường kính. Phương pháp và các phương trình được chọn trong nghiên cứu này là đáng tin cậy về mặt thống kê để ứng dụng trong ước tính chiều cao cho rừng mưa nhiệt đới ở Việt Nam.

Từ khóa: chỉ số AIC, hàm phi tuyến, hàm tuyến tính, mối quan hệ H – D, RMSE.

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