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Generalized Height-Diameter Models for *Pinus brutia* stands in Syria

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Abstract

The relationship between height and diameter is an essential component in forest growth and yield models and is also necessary for the estimation of the timber stocks of a forest stand. Using permanent sample plot data, eight tree height and diameter models were evaluated for their predictive abilities for pure even-aged Pinus brutia stands in Syria. The data used to build the generalized height-diameter model came from 1327 sample trees from two inventories; all sample trees in the sample plots had their diameter at breast height and height. 1115 sample trees were used for modeling, while 212 sample trees were used for validation.

Based on statistical analysis, graphical diagnostics, and biological interpretability, the model that performed best was the model proposed by Mirkovich (1958). The model can be recommended for estimating tree heights for P. brutia in Syria.

Keywords: *Brutia pine–forest inventory-Model performance*

I. INTRODUCTION

Tree height and diameter at breast height are essential individual tree variables used in forest measurements and inventories [1]. The tree diameter can be measured easily and at little cost, but measuring the height tree is more difficult because it is equally time-consuming and difficult, especially in mountainous terrain and in dense forest stands, and that often results in inaccurate measurements [2]. Therefore, the height-diameter relationship is commonly used in forest inventories to estimate the heights of trees for which the only diameter was measured. The height-diameter relationship is a common precursor when using inventory and sample plot data to calculate the volume and other stand attributes, e.g., site index, growth, yield, and biomass.

The height-diameter relationship can be expressed in mathematical functions. Most papers use generalized diameter-height relations, and at least 30 different functions have been used to describe the relationships ([3], [4], [5], [6]).

Every forest stand has its own height curve. The relationship between tree diameter and tree height differs among stands, related to site index, stand density, tree species, tree age, and stand structure, competition, and time ([7], [8]). Because of these factors, height-diameter relationships are often not easy to describe ([9], [10]), so the best alternative is to develop a generalized height-diameter relationship, which includes stand variables as predictors such as dominant height, quadratic mean diameter, dominant diameter, number of trees per hectare, stand basal area, etc. [10].

Pinus brutia Ten., commonly known as Turkish red pine, Brutia pine, or Calabrian pine, is a coniferous tree species dominating the forests of the eastern coast of the Mediterranean sea, which constitute one of the most important coniferous ecosystems in the Mediterranean region. In Syria, *Pinus brutia* forests are the most important and abundant species. They are valued for multiple objectives in most cases. They are used for hunting, as a source of firewood and construction materials, and for the collection of various non-wood forests products such as resin, honey, mushrooms, as well as the environmental importance, e.g., soil protection, water regulation, and providing various services [11]; but for many years, they have been subject of deforestation and over-exploitation [12]. Climate change, intensive use of wood for timber and firewood, overgrazing, as well as repeated forest fires [13]. Only Effective management of *P. brutia* forests, which put the sustainable use of the forest resources as a priority, can put an end to this situation. For these reasons, there is a need to build the growth and yield model that can not be achieved without exploring the height-diameter relationship. In Syria, until now, no generalized height-diameter functions were developed.

The objective of this paper is to develop generalized height-diameter models to estimate total height based on the diameter at breast height and stand variables in even-aged *Pinus brutia* stands. The hypothesis was that the generalized height-diameter models accurately describe the variability of the total height by incorporating stand variables.

II. MATERIAL AND METHODS

A. Study area

This study focuses on pure even-aged *Pinus brutia* plantations in the coastal region of Syria (Figure 1), where 38.7% of the Syrian forests are located, and the dominating tree species is *P. brutia*.

The elevation in the region ranges between 0 and 1600 m, and the climate can be characterized as the Mediterranean. Over the past ten years, the annual precipitation varied between 600 and 1200 mm; the mean annual temperature between 14 and 16°C [14].

B. Data

This study uses inventory data from 61 plots that were established in P. brutia stands, which management can be described as ranging from irregular to not at all. The plots (Table 1), which were mainly of circular shape (except for five rectangular ones), were measured in 2008 and 2016. Plots varied in size from 70 to 1963 m^2 depending upon stand density, so that about 50-75 trees were measured per plot. Stand density ranged between 137 and 3144, and the average was 1036 tree-ha^{-1}. Standage varied between 16 years and 129 years; and the average was 56 years in the first

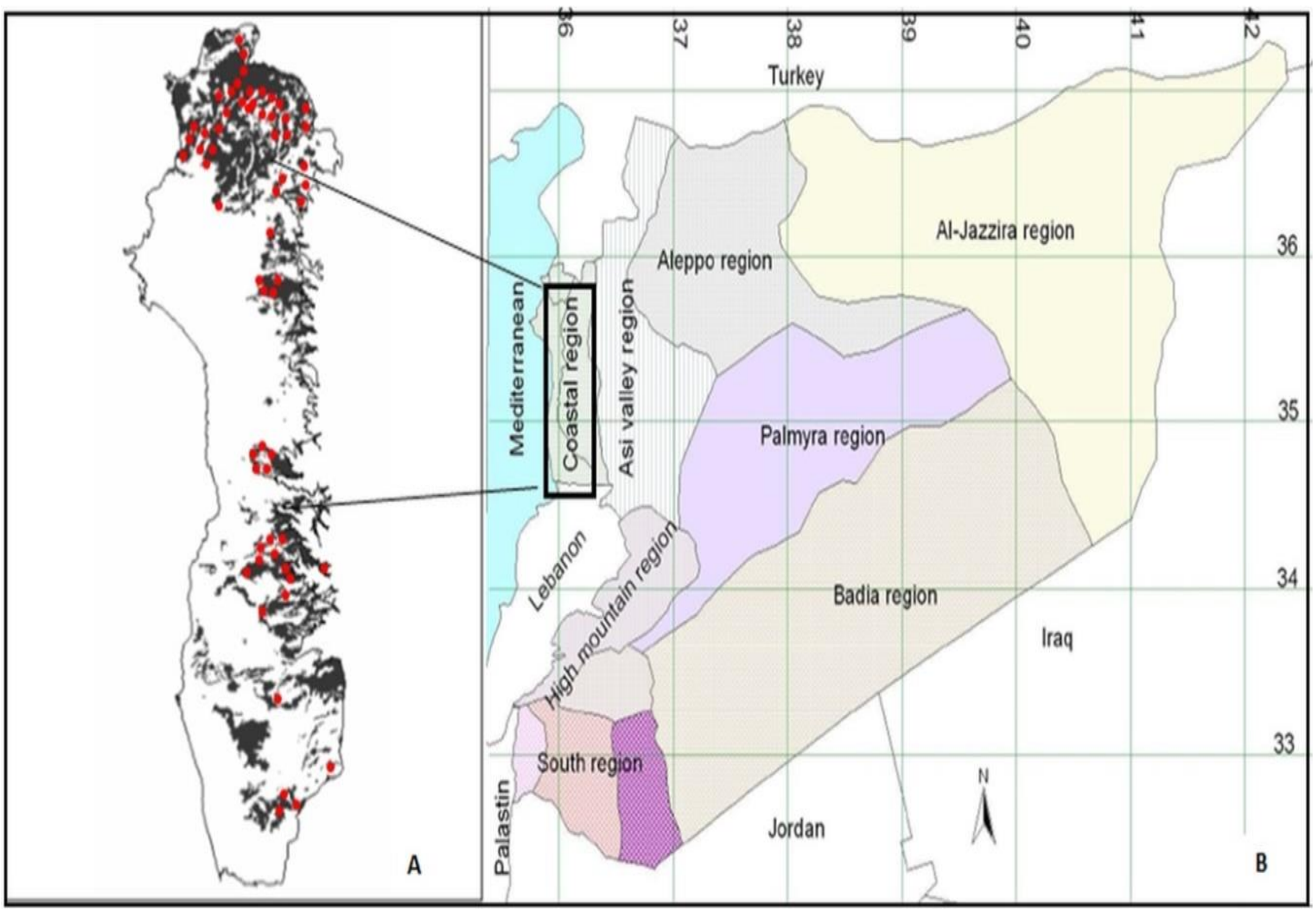

Fig. 1 A) Distribution of plots among coniferous forests in the coastal region. B) Major regions and sub-regions of Syria.

Table 1. Characterisation of tree and stand variables of the modeling and validation data for two inventories

	Permanent plots					Validation plots				
Variable	Year	Mean	Sd	Min	Max	Year	Mean	Sd	Min	Max
$d_{1.3}$	2008	26.4	12.3	5	64.5	2008	25	13.4	5.5	60
	2016	29.1	12	6.2	67.2	2016	27.6	13.6	7.6	67
h	2008	14.6	5.4	3.5	31.4	2008	14.1	5.2	4.8	25.1
	2016	16.5	5.2	5.9	31.9	2016	16.2	5.2	6.5	28.2
Age (years)	2008	56	21	16	121	2008	56	29	33	102
	2016	64	21	24	129	2016	64	29	41	110
D_q(cm)	2008	23.6	8.03	9.5	40.9	2008	20.8	10.1	11.1	42.4
	2016	26.4	7.99	11.8	43.2	2016	23.5	11.1	13.4	43.8
H(m)	2008	14.6	4.48	5.9	23.7	2008	14.14	4.6	7.3	19.7
	2016	16.4	4.43	9.2	24.7	2016	16.5	4.9	8.6	23.8
H_{100} (m)	2008	16.7	4.5	9.4	25.8	2008	15.1	4.9	8.3	21.3
	2016	18.3	4.7	10	26.8	2016	17.2	5	9.2	24
D_{100} (cm)	2008	33.1	9.3	13.6	51.9	2008	30.4	10.9	19.2	47.6
	2016	35.8	9	17.6	52.4	2016	29.7	9.1	20.9	50.4
BA ($m^2.ha^{-1}$)	2008	38.4	14.2	6.07	67.3	2008	37.2	12.2	20.5	60.3
	2016	46.2	14.4	15.4	77.4	2016	45.8	13.06	23.2	64.9
Density($N.ha^{-1}$)	2008	1026	672	224	3144	2008	1362	931	137	2934
	2016	999	653	219	3065	2016	1258	825	137	2585

Where:

h= Total tree height (m) $d_{1.3}$ = Diameter at breast height (cm) Age= Stand age (years)

H_{100}= Dominant height(m) D_{100}= Dominant diameter (cm) D_g=Quadratic mean diameter

H= Measn stand height(m) BA = Stand basal area($m^2.ha^{-1}$) Density: Number of trees per hectare

Inventory. In each plot, all trees were numbered, stand age was determined and diameter at breast height ($d_{1.3}$) measured by using tree caliper. For a selection of trees (i.e., 10-11 per plot), tree height was measured by using Haglöf Electronic Clinometer as well.

Stand variables calculated from the data collected in the inventories included basal area, stand density, quadratic mean diameter, maximum diameter, dominant diameter, mean height, and dominant height. The mean, maximum and minimum values and standard deviations of the main dendrometric and stand variables were given in Table 1.

In addition to the stand density and age, the site productivity also plays an influential role in the height-diameter Relationship. The effect of the site productivity was measured by the site index, expressed by the dominant height at the reference age 50 years, estimated based on the GADA the approach of the Sloboda model (Equation 1)fitted by [15].

$$\mathrm{H}_{100}(t_2) = 2075.73 \cdot \left(\frac{\mathrm{H}_{100}(t_1)}{2075.73}\right)^{e^{-\frac{1.446}{1-0.804}\times(t_2^{(1-0.804)}-t_1^{(1-0.804)})}}$$

(Equation 1)

Where: $H_{100}(t_1)$ and $H_{100}(t_2)$ are top heights (in m) at age t_1 and t_2 (in years), respectively

The data used to build the generalized height- diameter model came from 1327 sample trees from two inventories; all sample trees in the sample plots had their diameter at breast height and height. 1115 sample trees (51 sample plots) were used for modeling, while 212 sample trees(10 sample plots) were used for validation.

C. Candidate models

A large number of generalized height-diameter models have been used in the forestry literature, many of which have been developed for a particular species or specific area. For this study, a total of eight generalized height-diameter models were selected for *Pinus brutia* ([16], [17], [18], [19], [20], [21], [22]) (Table 2).

To obtain precise and unbiased estimates of the heights of individual trees under different growing conditions, these tested models used dominant height, dominant diameter at breast height, and quadratic mean diameter as stand variables. The candidate models were fitted by using nonlinear regression analysis.

D. Model selection criteria

Model performance was assessed while focusing on: (1) the behavior of model residuals and (2) the evaluation of statistical indices that describe the goodness-of-fit [23].

Table Error! No text of specified style in document.**: Candidate models to model the general height-**

Model	Author and reference	Model
M1	Harrison et al. (1986) [15]	$h = H_{100} \times (1 + b_0 \times e^{b_1 \times H_{100}})(1 - e^{\frac{b_2 \times d_{1.3}}{H_{100}}})$
M2	Hui and Gadow (1993) [16]	$h = 1.3 + b_0 + b_1 \times {H_{100}}^{b_1} \times {d_{1.3}}^{b_2 \times {H_{100}}^{b_3}}$
M3	Mirkovich (1958) [17]	$h = 1.3 + (b_0 + b_1 \times H_{100} - b_2 \times d_{1.3}) \times e^{\frac{-b_3}{d_{1.3}}}$
M4	Stoffels and Van Soest modified (1953)[18]	$h = 1.3 + (H_{100} \times (\frac{d_{1.3}}{D_{100}})^{b_0})$
M5	Gaffrey (1983) modified by Diéguez-Aranda et al.(2005)[19]	$h = 1.3 + (H_{100} - 1.3)e^{b_0 \times \left(1 - \frac{D_{100}}{d_{1.3}}\right) + b_0 \times (\frac{1}{D_{100}} - \frac{1}{d_{1.3}})}$
M6	Nilson (1999) modified by Diéguez-Arandaet al.(2005)[19]	$h = 1.3 + \frac{H_{100} - 1.3}{1 - b_0 \times (1 - (\frac{D_{100}}{d_{1.3}})^{b_1})}$
M7	Soares and Tomé (2002) [20]	$h = H_{100} \times (1 + (b_0 + b_1 \times H_{100} + b_2 \times D_g) \times e^{b_3 \times H_0}) \times (1 - e^{\frac{b_4 \times d_{1.3}}{H_{100}}})$
M8	Schröder and Álvarez-González (2001) [21]	$h = 1.3 + (b_0 + b_1 \times H_{100} - b_2 \times D_g) \times e^{\frac{-b_3}{\sqrt{d_{1.3}}}}$

Where:

h= total height (m) $d_{1.3}$ = diameter at breast height (cm); e= Euler's constant

H_{100}= dominant height (m) D_{100}= dominant diameter (cm) D_g=Quadratic mean diameter

b_0, b_1, b_2, b_3, b_4 = parameters

Table 3. Methods of evaluation of developed candidate models

Performance criteria	Formula	Ideal value
Model bias	$\frac{1}{n} \cdot \sum_{i=1}^{n} (\hat{Y}_i - Y_i)$	Zero
Relative bias	$\frac{\bar{e} \cdot 100}{\bar{Y}}$	Zero
Model precision	$S_e = \sqrt{\frac{\sum_{i=1}^{n}(\hat{Y}_i - \bar{e} - Y_i)^2}{n-1}}$	Zero
Relative model precision	$S_e\% = \frac{S_e \times 100}{\bar{Y}}$	Zero
Model accuracy	$m_x = \sqrt{{S_e}^2 + \bar{e}^2}$	Zero
Relative model accuracy	$m_x\% = \frac{m_x \times 100}{\bar{Y}}$	Zero
Coefficient of determination	$R^2 = 1 - \frac{\sum_{i=1}^{n}(\hat{Y}_i - Y_i)^2}{(Y_i - \bar{Y})^2}$	One

Y_i = Observed value $\bar{e}$ = Model Bias $i = 1, \dots, n$
k = Number of variables in the equation

$\bar{Y}$ = Average value of observations $\hat{Y}$ = Fitted value

For the latter, model bias, relative bias, model precision, relative model precision, model accuracy, and relative model accuracy were used [8], while the coefficient of determination (R^2)was used as an index for model efficiency (Table 3). Data analysis was conducted with R 3.4.0 [24]. A nonlinear regression was conducted using them for the package.

III.RESULTS AND DISCUSSION

Based on the parameter estimates of each fitted model (Table 4), as well as on their goodness of fit parameters and significance level at value = 0.05, the total tree height was precisely predicted using the diameter at breast height and some stand variables, such as the quadratic mean diameter, dominant diameter and the dominant height (Table 2) as predictors.

The coefficient of determination (R^2) values for all the fitted functions were ranged from 0.50 to 0.81 (Table 4). The model that performed best was the model proposed by [18] (Table 5).

In addition to the previous steps, the tested models involved visual examinations of residuals against the predicted values. (Figure 2) shows the residuals plotted against predictions of height for the tested models.

Graphical diagnostics of residuals for the height predictions indicated that the differences between predicted and actual values are approximately normally distributed in all models. Methods of the evaluation were also applied in the second group of data (212 sample trees).

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So, based on the different performance evaluations, the model (M3) proposed by [18] provides more satisfactory results as compared to the other tested models.

The tested models showed overall good behavior and meet the biological knowledge; where the height increases as diameter increase, the height-diameter curves change their direction, and plausible (Figure 3); therefore, the models developed in this study take into account the mathematical properties when selecting a functional form for the height-diameter relationship according to [25].

The variables used adapted the models to different stand conditions, directly related to site productivity and different degrees of competition within the stand [26]. Of these variables used in this study were the dominant height,

dominant diameter, and quadratic mean diameter. The good performance showed by the tested models is due in part to the inclusion of the dominant height as an independent variable, where the dominant height is considered as a critical variable for reasonable height predictions of individual trees because it is closely related to the site productivity and the stand age in pure even-aged stands [27].

In the same context, because of the close relationship between the diameter and the number of trees per hectare, the inclusion of the dominant diameter and the quadratic mean diameter as an explanatory variable takes into account the competition degree within the stand, M7 and M8 could be indicated as examples

Table 4: Estimates of R^2 and the parameters of generalized height-diameter

Model	R^2	Estimated Parameters				
		b_0	b_1	b_2	b_3	b_4
M1	0.506	441.06	0.037	3.98×10^{-5}	-	-
M2	0.808	0.323	0.397	0.387	0.480	-
M3	0. 81	2.927	1.033	0.003	9.489	-
M4	0.76	0.559	-	-	-	-
M5	0.78	0.312	-	-	-	-
M6	0.79	0.336	1.105	-	-	-
M7	0.81	0.02	0.015	-0.007	-0.003	-1.137
M8	0.82	7.905	1.93	0.276	4.529	1

Table 5: Selection statistics of the general height-diameter models for brutia pine

Model	Bias	Relative Bias	Precision	Relative Precision	Accuracy	Relative accuracy
Modeling data						
M1	0.74	4.73	3.98	25.4	6.1	39.5
M2	0.07	0.50	2.58	16.5	2.6	16.8
M3	0.01	0.11	2.53	16.2	2.5	16.2
M4	0.7	4.47	2.82	18.0	5.2	33.8
M5	0.20	1.31	2.52	16.1	2.8	18.1
M6	0.19	1.27	2.49	15.9	2.8	17.9
M7	-0.17	-1.12	2.45	15.6	2.6	17.2
M8	0.12	0.82	2.43	15.5	2.5	16.4
Validation data						
M1	0.5	3.3	2.9	19.5	4.4	29.2
M2	-0.5	-3.7	2.76	18.16	4.6	30.3
M3	-0.4	-3.1	2.7	18	4.2	27.8
M4	0.7	4.9	3.1	20.4	5.8	38.2
M5	0.5	3.4	2.68	17.54	4.4	28.6
M6	0.6	3.8	2.67	17.44	4.7	30.5
M7	-0.8	-5.3	2.75	17.94	6.0	39.1
M8	-0.7	-4.3	2.74	17.84	5.1	33.5

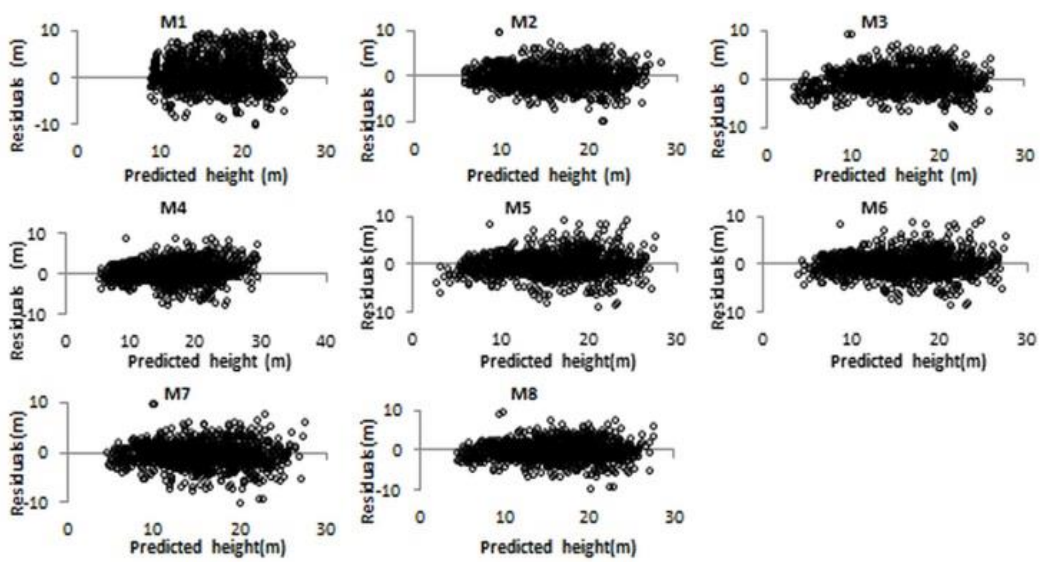
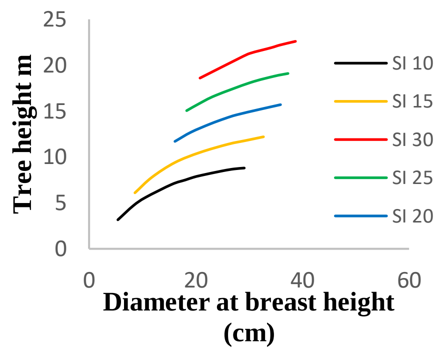


Fig. 2 Analysis of residuals for the tested models

The model (M3) was used to estimate the diameter-height relationship for different site indices and different ages. The simulations of the site index effect on the height-diameter relationship were made using the age of 35 and values of dominant height estimated by Equation 1 (Figure 3 left).

In more productive sites, the height-diameter curves of *Pinus brutia* were steeper and presented larger asymptotes than in poor sites. The height estimates of *Pinus brutia* for different ages have been made using site index (20 m) and values of dominant height computed from Equation 1 (Figure 3 right).

Although fixed intervals of 10 years were used to describe the effect of age on the height-diameter relationship of *Pinus brutia*, there is a decrease in the distance between height-diameter curves with increasing age (Figure 3 right), i.e., the



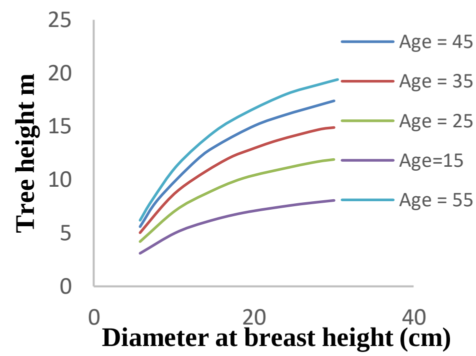


Fig. 3 Effect of site index(Left) and age (Right) on the height-diameter relationship according to the developed generalized height-diameter model for *Pinus brutia.*

The distance between the height-diameter curve of age 15 and 25 is larger than the distance between the height-diameter curve of age 45 and age 55. Probably that is attributed to the reduction in height and diameter growth in old ages, making the changes in the height-diameter curves become very small.

The generalized height-diameter relationship model could apply it in inventories where height data is missing for many trees on a sample plot and could be used as the main component of the growth and yield model of *Pinus brutia* stands. These developed generalized height diameter models will help decision-makers in forestry to reduce costs and save time during the inventory process and at the same time to make better decisions in forest management and planning.

IV. CONCLUSIONS

- The developed generalized height-diameter models are good behavior, meet the biological knowledge, and reliable for the prediction of the individual tree heights of even-aged *Pinus brutia* stands.
- The predicting variables used in the models are diameter at breast height, dominant height, dominant diameter, and quadratic mean diameter, which require a not high sampling effort.
- The developed models, in particular M3, improve the accuracy of height prediction that ensures compatibility among the various estimates in a growth and yield model.
- The developed models facilitate the quantification of existing timber forest resources.

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