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Communication

Modeling Tree Characteristics of Individual Black Pine (*Pinus nigra* Arn.) Trees for Use in Remote Sensing-Based Inventory

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Abstract: The main aim was to develop models for predicting diameter at breast height (DBH), merchantable tree volume (V), and aboveground biomass (AGB) of individual black pine (*Pinus nigra* Arn.) trees grown in Sub-Mediterranean Croatian pure even-aged forests, which will be suitable for remote sensing based forest inventories. In total, eight variables obtained from field measurement, existing database, and digital terrain model were candidates for independent variables in regression analysis. DBH, V, and AGB were modeled as linear function of each of the independent variables, and all possible linear combinations thereof. Goodness of fit of every model was then evaluated using R^2 statistic. Comparison between selected models showed that the variability of all dependent variables are explained best by models which include both crown diameter and tree height as independent variables with coefficients of determination of 0.83, 0.89, 0.82 for DBH, V, and AGB, respectively. Consequently, these models may be recommended as the most suited for DBH, V and AGB estimation of black pine trees grown in pure Sub-Mediterranean forest stands using high-resolution aerial images or high-density airborne laser scanning data. This assumption should be further validated by conducting remote sensing inventory and comparing the obtained results with field measurement results.

Keywords: estimation models; regression analysis; diameter at breast height; volume; aboveground biomass; pure even-aged stands; Sub-Mediterranean region

1. Introduction

Tree height and diameter at breast height (DBH) are two of the more fundamental measurements in forest inventories and provide the basis for many other computations (e.g., basal area, volume, biomass, carbon stock, stand growth, *etc.*) [1,2]. While tree height may be directly estimated from various remote sensing data (e.g., aerial or satellite images, airborne laser scanning, *etc.*), direct estimation of e.g., DBH, tree volume and tree biomass in most cases is not possible. Hence, the determination of these variables using remote sensing methods is usually done by estimation models (allometric equations) in which one or more variables (e.g., tree height, crown diameter or crown area) that may be easily estimated from remote sensing data are the most commonly used independent variables (predictors) [3].

Research on tree allometry, *i.e.*, on relationships between dependent and independent variables used in estimation models has been therefore the object of numerous studies. Crown diameter, crown area and tree height are the most commonly used variables in modeling of DBH [4–6], stem volume [6–10] or tree aboveground biomass [7,11] for remote sensing-based inventory. However, in some cases, inclusion of additional variables (e.g., stand density, stand age, soil type, elevation, *etc*.) may considerably improve the estimates [12–14]. For example, Prieditis *et al.* [14] built a model with tree height as the only independent variable which provides reasonably accurate estimates of DBH ($R^2 = 0.792$), but when the crown diameter and information about tree age and soil type obtained from existing forest database were added to the model, the accuracy of DBH increases ($R^2 = 0.872$). Furthermore, according to Maltamo *et al.* [12], besides above-mentioned variables, the allometric relationship between main tree parameters (DBH, crown dimensions and tree height) could also be affected by other variables, such as stand silvicultural history, genetic factors of tree seed, tree position in a stand, site fertility, stand development class, *etc.* Therefore, which and how many independent variables should be used in allometric equations are very important issues in modeling of tree characteristics.

Estimation models may be built using field measurement [4–6,13,14] or combination of field and remote sensing measurement [8,9]. In that case positions of trees in the field have to be measured with high precision and determined on remote sensing data which often is not easy [10].

European black pine (*Pinus nigra* Arn.) is an important tree species of the Mediterranean and Sub-Mediterranean regions, occurring in the discontinuous area which includes Southern Europe (from Spain to Turkey), Minor Asia, and North-Western Africa [15,16]. Due to its discontinuous and wide distribution, black pine is a very variable species in regards of its morphological, anatomical and physiological characteristics and therefore occurs in a large number of subspecies, varieties and forms [17]. In the Mediterranean and Sub-Mediterranean parts of Croatia, European black pine occurs mostly in pure even-aged stands or in forest cultures, but could also form small groups in Sub-Mediterranean deciduous forests and scrubs [17].

Due to lower commercial values of timber stocks, high costs of classical forest inventory make the management and inventory of Mediterranean forests difficult. Using data from remote sensing could help in reducing the forest inventory costs. Although tree and stand characteristics of European black pine has been widely researched e.g., [18–20], to the best of our knowledge there are no adequate allometric equations that may be used for estimation of DBH, tree volume and aboveground biomass of black pine trees using remote sensing data. Therefore, the main aim of this research was to develop models for predicting DBH, merchantable tree volume (V), and aboveground biomass (AGB) of individual black pine trees grown in Sub-Mediterranean Croatian forests which will be suitable for remote sensing-based forest inventories. The purpose of new models is not only to add knowledge about tree allometry of black pine and to help in local forest inventories, but also to facilitate data collection for national reports on biomass and carbon stocks.

2. Materials and Methods

2.1. Research Area

The research was conducted in the state-owned forests of the management unit Borovača, which is located in the Sub-Mediterranean part of Croatia, 30 km north of Split (Figure 1). Covering the total area of 3804.32 ha, the management unit extends from 43°41′18″ to 43°44′57″ north latitude and from 16°23′38″ to 16°34′11″ east longitude (Transverse Mercator projection, GRS 1980 ellipsoid, Croatian Terrestrial Reference System datum). The research area included 23 subcompartments of pure even-aged stands of European black pine covering all age classes with the exception of the first age class (<20 years). The basic stand structural elements of 23 subcompartments grouped in age classes obtained from valid Forest management plan are shown in Table 1. Those stands have never been intensively harvested as may be seen from the high values of stand densities.

Figure 1. The location of the research area. Gray shaded subcompartments were selected for data collection.

Table 1. The average values and ranges (in brackets) of basic stand structural parameters of 23 stands (subcompartments) grouped in age classes obtained from valid Forest management plan.

Age Class	Age (years)	Number of Stands	Site Class	Stand Density (Trees·ha^{-1})	Basal Area (m^2·ha^{-1})	Volume (m^3·ha^{-1})	Annual Increment (m^3·ha^{-1})
II	21–40	6	II	944 (794–1186)	17.8 (15.5–22.6)	80.7 (70.9–105.1)	4.7 (3.7–6.2)
III	41–60	3	II	1246 (981–1401)	34.9 (28.9–38.2)	278.7 (298.8–304.1)	6.7 (5.5–7.3)
IV	61–80	6	II	876 (496–1221)	26.7 (17.0–34.2)	224.2 (144.6–285.1)	4.2 (2.5–5.1)
V	81–100	6	II	493 (348–859)	25.0 (21.5–35.4)	237.9 (182.8–308.3)	3.5 (2.8–5.0)
VI	101–120	2	II	700 (681–719)	36.3 (34.7–37.9)	330.7 (283.7–377.7)	5.2 (5.1–5.3)

The valid Forest management plan was approved for the period from 2004 to 2013, while the Plan for the period 2014–2023 is still not approved by the relevant Ministry; The data from the Table present the situation at the beginning 2004; According to the valid Plan and data from relevant Forest office Split, in the period from 2004 to present there were no harvest activities on the research area.

The altitude of the selected part of the research area ranges from 460 to 695 m and slopes from 5° to 35° although slopes can locally reach up to 85°. According to Köppen classification, the climate is typical temperate mesothermal with warm and dry summers. The Adriatic Sea is the main factor influencing the climate of the area. Based on the data from 1981 to 2000, the average annual rainfall is 1123 mm with the most precipitation in November (163 mm), and with the lowest precipitation in July (39 mm) and August (56 mm). The annual average temperature is 12.8 °C, with the lowest monthly average of 3.5 °C recorded in January (the coldest month) and the highest monthly average of 23.1°C recorded in July (the warmest month). The meteorological data were obtained from the meteorological station Sinj located about 12 km east of the management unit Borovača. The pine stands in the research area occur on the following soil types: rendzina on dolomite, rendzina on carbonate, and silicate-carbonate regosol [21].

2.2. Data Collection

Field measurement of tree variables (DBH, tree height, crown diameter) was conducted on the sample of 501 randomly selected black pine trees distributed throughout the research area (23 subcompartments). An attempt was made to achieve an equal distribution of sampled trees within all age classes and regular spatial distribution throughout the research area as well as proportional participation of the diameter degrees over the sample DBH distribution. From each age class approximately 100 trees were sampled. The following variables were measured for all trees in the sample: (i) DBH, by using a calliper with a centimeter graduation; (ii) tree height (H); and (iii) two mutually perpendicular projections of crown diameter (CD) on the ground, both (H and CD) using a Vertex III hypsometer with a precision of 0.1 m. The edges of the visible light part of the crown (the part of the crown that is not overlapped by the crown of another tree and for which may be assumed that is visible on the aerial or satellite images) were projected on the ground in two mutually perpendicular directions. The lengths of both projections were measured from edge to edge through the crown center. The CD was calculated as the average of two measured projections.

The position (x, y coordinates) of each tree was recorded with a GPS receiver. The positional (horizontal) accuracy quoted by the manufacturer of the MobileMapper 6 GPS receiver (Magellan Navigation Inc., Santa Clara, CA, USA) is 2–5 m for ideal conditions (e.g., open sky, a substantial number of available satellites and their geometry, *etc*.).

Additional stand parameters, namely distance to the closest tree (DCT) and number of the trees in the circle of 5 m radius, were detected for each tree in the sample. Detected number of trees in the circle of 5 m radius was then used to calculate stand density (N) in terms of number of trees per ha ($trees \cdot ha^{-1}$) for each tree. Stand age (SA) was obtained from the Forest management plan.

Furthermore, additional site variables (altitude, slope, aspect) were derived for each tree based on GPS recorded tree's coordinates overlaid upon generated digital terrain model (DTM). The DTM, that is a regular grid (raster) with 1 m cell size was generated from triangulated irregular network (TIN) created from digital terrain data (breaklines and mass points) using software QGIS 2.4.0. The digital terrain data used for TIN creation were obtained from the Croatian State Geodetic Administration (Product Specification 301D150).

The merchantable tree volume (V), comprising of stemwood and branchwood up to 7 cm overbark diameter measured on thinner end, was calculated for each tree from field-measured DBH and H using the Schumacher-Hall function [22] and parameters from Croatian black pine volume tables [23] (Equation (1)). The black pine tables were built using a destructive sampling of 843 trees from forest cultures and pure even-aged stands of black pine, mainly located in the Mediterranean and Sub-Mediterranean parts of Croatia. The DBH of sampled trees ranged from 5 cm to 79 cm and heights from 5 m to 39 m.

$$V = b_0 \times DBH^{b1} \times H^{b2} \times f \quad (1)$$

where V is the merchantable tree volume up to a diameter of 7 cm overbark in m^3, b_0 (0.00004935), b_1 (1.913996) and b_2 (1.021436) are parameters of black pine volume tables, f (1.003441) is Meyer's correction factor, DBH is field measured diameter at breast height in cm, and H is field measured tree height in m.

To calculate the aboveground biomass (AGB) of each tree field-measured DBH and equation (Equation 2) applied from the results of research conducted by Zečić and Vusić [24] were used. Based on 16 randomly selected and destructively sampled black pine trees in the management unit Borovača, with DBH ranging from 11 cm to 30 cm, Zečić and Vusić [24] determined the relationships between the measured values of individual tree components (merchantable tree volume including bark, branchwood, and smallwood) and the DBH. Branchwood includes branch sections with overbark diameter ranging from 7 cm to 3 cm measured on thinner end, whereas smallwood includes branches and twigs thinner than 3 cm. In order to express biomass in kg for the purpose of this study, both merchantable tree volume including bark and branchwood were multiplied with fresh wood density ($WD = 1020\ kg \cdot m^{-3}$) of black pine taken from domestic Croatian literature [25]. Finally, oven-dry aboveground biomass of each tree was obtained by multiplying the biomass sum of all tree components with 0.5. Namely, according to

Zečić *et al.* [26] oven-dry biomass of black pine approximately weighs 50% less than its biomass in fresh (green) condition.

$$AGB = [(0.0002 \times DBH^{2.3351}) \times WD + (0.0227 \times DBH^{-0.671}) \times WD + (0.0882 \times DBH^{2.1924})] \times 0.5 \quad (2)$$

where AGB is the oven-dry aboveground biomass in kg, DBH is field measured diameter at breast height in cm, and WD is wood density of black pine in kg·m^{-3}.

Description and descriptive statistics of variables considered for modeling of DBH, V and AGB are summarized in Table 2.

Table 2. Description and descriptive statistics (Mean, SD—standard deviation), Min—minimum), Max—maximum) of variables considered for modeling of diameter at breast height (DBH), merchantable tree volume (V) and aboveground biomass (AGB) of individual black pine trees.

Group	Variable	Description	Type	Units	Mean	SD	Min	Max
	DBH	Diameter at breast height	Dependent	cm	22.2	7.7	10.2	55.0
	V	Merchantable tree volume	Dependent	m^3	0.32	0.28	0.02	1.97
Tree variables	AGB	Aboveground biomass	Dependent	kg	215.46	179.19	32.72	1467.85
	H	Tree height	Independent	m	13.5	3.8	4.6	25.9
	CD	Crown diameter	Independent	m	2.88	1.41	0.42	8.35
	DCT	Distance to the closest tree	Independent	m	2.05	1.05	0.30	8.82
Stand variables	N	Stand density	Independent	trees·ha^{-1}	1038	580	127	891
	SA	Stand age	Independent	years	70	25	33	102
	Z	Terrain altitude	Independent	m	564.3	45.8	467.4	694.7
Site variables	S	Terrain slope	Independent		21.5	17.3	0	84.8
	A	Terrain aspect (0–360°)	Independent		190.2	93.9	0	357.9

2.3. Statistical Analysis

Modeling of DBH, merchantable tree volume (V) and aboveground biomass (AGB) of individual black pine trees was based on linear regression analysis (univariate or multiple) using the program SAS 9.3 [27] with a 5% significance level considered statistically significant.

Prior to the modeling, normality of dependent variables (DBH, V, AGB) was checked using Shapiro-Wilk test [28,29]. To meet the normality condition necessary for further statistical analysis, dependent variables were transformed into appropriate forms.

Potential models of DBH, V and AGB estimation were initially selected using R^2 selection method. All combinations of independent variables and their contribution to model goodness expressed through coefficient of determination (R^2) were evaluated, and the following criteria for selection of potential models were adopted and used: (i) models with one independent variable were selected if R^2 of the model is higher than 0.60; (ii) models with two or more independent variables were selected if inclusion of second or each subsequent variable increases the R^2 of the model for more than 0.05.

The selected potential models were then built using univariate or multiple linear regressions depending on a number of independent variables used in modeling. Models were evaluated and compared based on statistical significance of models and theirs parameters, coefficient of determination

(R^2), root mean square error ($RMSE_{sqrt}$ or $RMSE_{ln}$) calculated from the transformed predicted and observed values of dependent variables, back-transformed root mean square error ($RMSE_{bt}$), and graphical analysis of the predicted *vs.* observed values. The $RMSE_{bt}$ was calculated from the predicted and observed dependent variables back-transformed to their original values. For the final recommendation between observed models, practical applicability of the models was also considered.

3. Results

3.1. Diameter at Breast Height (DBH) Models

A preliminary evaluation indicated a non-normality of DBH variable. Therefore, prior to modeling, DBH data were transformed into square root (sqrt) form. The resulting distribution of sqrt (DBH) was normal ($p > 0.05$). Among eight independent variables evaluated by R^2 selection method (Supplementary Data Table S1), only three variables (CD, H, SA) have proved to be potentially good predictors of DBH, while five variables (N, DCT, Z, S, A) were excluded from further analysis due to low R^2. In total, three DBH models with different combinations of selected independent variables were chosen as the most appropriate for the fit data by regression analysis. The models' description and evaluation statistic are summarized in Table 3.

Table 3. Description and evaluation statistics for five selected black pine diameter at breast height (DBH) models.

No.	Regression model	Parameters			R^2	$RMSE_{sqrt}$ (cm)	$RMSE_{bt}$ (cm)
		Symbol	Value	Standard Error			
D1	sqrt(DBH) = $\beta_0 + \beta_1 \cdot$CD	β_0	3.351*	0.050	0.625*	0.491	4.634
		β_1	0.448*	0.016			
D2	sqrt(DBH) = $\beta_0 + \beta_1 \cdot$CD + $\beta_2 \cdot$SA	β_0	2.809*	0.062	0.712*	0.430	4.145
		β_1	0.393*	0.014			
		β_2	0.010*	<0.001			
D3	sqrt(DBH) = $\beta_0 + \beta_1 \cdot$CD + $\beta_2 \cdot$H	β_0	2.225*	0.056	0.832*	0.328	3.226
		β_1	0.377*	0.011			
		β_2	0.099*	0.004			

* $p < 0.0001$; DBH—diameter at breast height, CD—crown diameter, SA—stand age, H—tree height, β_0, β_1, β_2 —regression coefficients, R^2—coefficient of determination, $RMSE_{sqrt}$—root mean square error calculated from the transformed predicted and observed DBH data, $RMSE_{bt}$—back-transformed root mean square error calculated from the predicted and observed DBH data back-transformed to their original values.

All models were highly significant ($Pr >$ F < 0.001), as well as their parameters ($Pr > |t| < 0.001$). In all models the estimated slope parameters (β_1, β_2) of all independent variables were positive indicating that the DBH increases progressively with the increase of CD, H and SA.

According to evaluation statistics (Table 3), CD has proved to be the strongest predictor of DBH in all three models. Among all three models, model D1 that uses only CD as a predictor can be expected to produce less accurate estimates of DBH in terms of R^2, $RMSE_{sqrt}$, and $RMSE_{bt}$ values. When SA was included into the model (model D2) the performance of the model was improved increasing considerably the prediction accuracy (R^2) and reducing slightly the errors of estimates ($RMSE_{sqrt}$, $RMSE_{bt}$). However, the model with CD and H as predictors (model D3) had the best performance producing the highest prediction accuracy (R^2) and the least errors ($RMSE_{sqrt}$, $RMSE_{bt}$) in comparison with all other models. This is also confirmed by a graphical analysis (Figure 2 and Supplementary Data Figure S1), where it can be seen that the strongest relationship between predicted and observed DBH is obtained by model D3. Models D1 and D2 showed slightly weaker relationship tending to underestimate DBH. The underestimation is particularly higher for trees with observed DBH greater than 30 cm. In addition, it may be seen that the models D1 and D2 produced greater variability of predicted DBH which increases with observed DBH than the model D3. Therefore, for reasonably accurate estimates of DBH it is recommended to use model D3 with CD and H as independent variables.

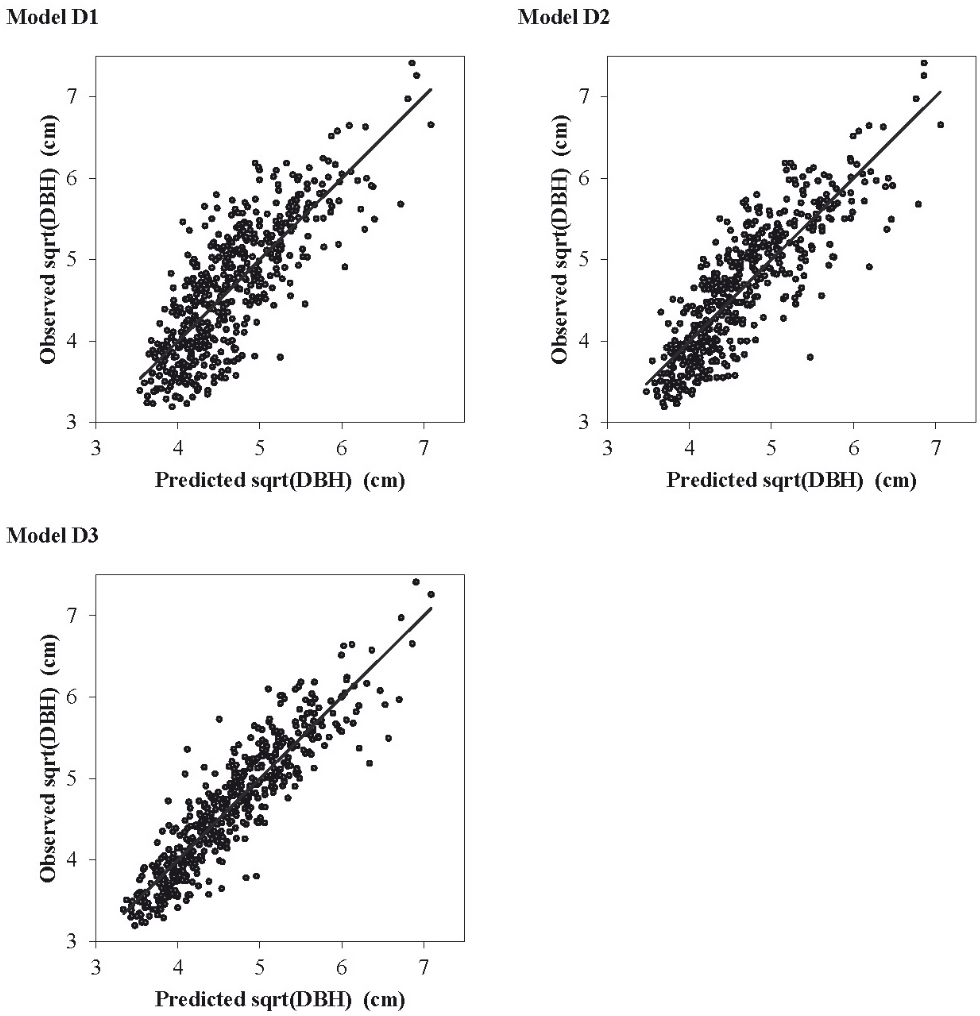

Figure 2. Predicted *vs.* observed diameter at breast height (DBH) for three selected black pine DBH models. The solid line represents fitted linear model. Models' description and evaluation statistic are presented in Table 3.

3.2. Merchantable Tree Volume (V) Models

To meet the normality condition ($p > 0.05$) of dependent variable necessary for regression analysis, logarithm transformations were used for volume data. By conducted R^2 selection method (Supplementary Data Table S2), the set of four independent variables (H, CD, N, DCT) has proven to be a potentially good volume predictor forming four models selected for further regression analysis (Table 4).

Table 4. Description and evaluation statistics for four selected black pine merchantable tree volume (V) models.

No.	Regression Model	Parameters			R^2	$RMSE_{ln}$ (m^3)	$RMSE_{bt}$ (m^3)
		Symbol	Value	Standard Error			
V1	$\ln(V) = \beta_0 + \beta_1 \cdot H$	β_0	−4.106 *	0.083	0.684 *	0.506	0.233
		β_1	0.195 *	0.006			
V2	$\ln(V) = \beta_0 + \beta_1 \cdot H + \beta_2 \cdot DCT$	β_0	−4.503 *	0.085	0.738 *	0.461	0.223
		β_1	0.194 *	0.005			
		β_2	0.199 *	0.020			
V3	$\ln(V) = \beta_0 + \beta_1 \cdot H + \beta_2 \cdot N$	β_0	−3.745 *	0.081	0.747 *	0.453	0.226
		β_1	0.198 *	0.005			
		β_2	−0.001 *	<0.001			
V4	$\ln(V) = \beta_0 + \beta_1 \cdot CD + \beta_2 \cdot H$	β_0	−4.574 *	0.051	0.889 *	0.299	0.144
		β_1	0.165 *	0.004			
		β_2	0.299 *	0.010			

* $p < 0.0001$; V—merchantable tree volume, H—tree height, CD—crown diameter, N—stand density, DCT—distance to the closest tree, β_0, β_1, β_2—regression coefficients, R^2—coefficient of determination, $RMSE_{ln}$—root mean square error calculated from the transformed predicted and observed volume data, $RMSE_{bt}$—back-transformed root mean square error calculated from the predicted and observed volume data back-transformed to their original values.

According to the evaluation statistic (Table 4), all models ($Pr > F < 0.001$), as well as their parameters ($Pr > |t| < 0.001$) were highly significant. Estimated slope parameters (β_1, β_2) of all independent variables, except for N, were positive in all models, indicating that the volume increases progressively with the increase of H, CD and DCT.

In contrast to DBH models, results of regression analysis indicated H as a better predictor of volume than the CD. The addition of stand variables to H, namely the addition of DCT in model V2 and N in model V3, increased slightly the prediction accuracy (R^2) and also slightly reduced the errors ($RMSE_{ln}$, $RMSE_{bt}$) of both models in comparison to model V1 that uses only H as a predictor. However, the best performance according to the evaluation statistic had the model V4 with H and CD as individual variables, which was also confirmed by graphical analysis (Figure 3, Supplementary Data Figure S2). Furthermore, graphical analysis indicated that all models, with exception of model V4, have a tendency to slightly underestimate volume. Consequently, model V4 may be recommended as the most suited for merchantable tree volume prediction, but it can also be expected that models V2 and V3 may provide reasonably accurate estimates of tree volume.

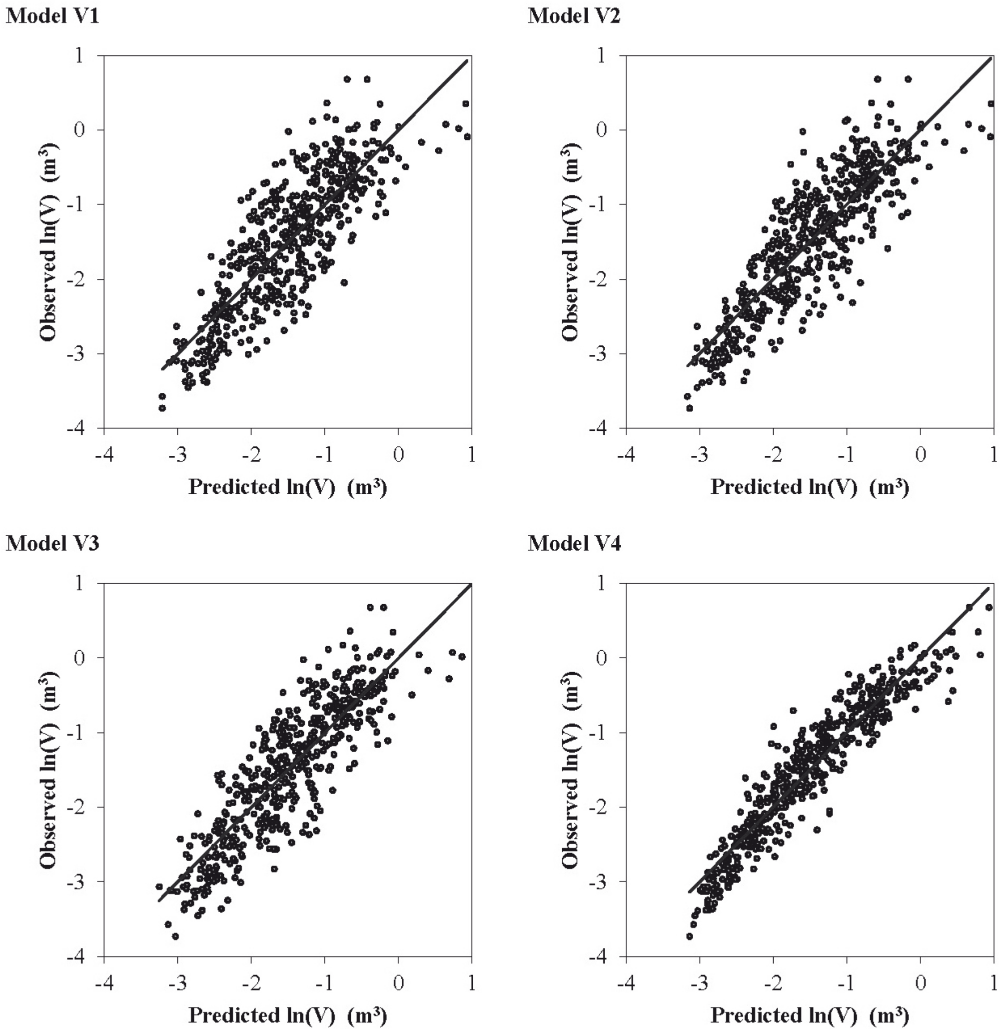

Figure 3. Predicted *vs.* observed merchantable tree volume (V) for four selected black pine merchantable tree volume models. The solid line represents fitted linear model. Models' description and evaluation statistic are presented in Table 4.

3.3. Aboveground Biomass (AGB) Models

In order to meet the normality of dependent variable necessary for regression analysis ($p > 0.05$), biomass data were transformed into a logarithm form. Identical to DBH models, by conducted R^2 selection method (Supplementary Data Table S3) the same three variables (CD, H, SA) were identified as potentially good AGB predictors, while other five variables (N, DCT, Z, S, A) were excluded from further analysis due to low R^2. Moreover, three models that have the same combination of independent variables, like in the case of DBH models, were selected for regression analysis (Table 5).

Table 5. Description and evaluation statistics of the three selected black pine aboveground biomass (AGB) models.

No.	Regression Model	Parameters			R^2	$RMSE_{ln}$ (kg)	$RMSE_{bt}$ (kg)
		Symbol	Value	Standard Error			
B1	$\ln(AGB) = \beta_0 + \beta_1 \cdot CD$	β_0	3.845 *	0.050	0.598 *	0.495	117.313
		β_1	0.427 *	0.016			
B2	$\ln(AGB) = \beta_0 + \beta_1 \cdot CD + \beta_2 \cdot SA$	β_0	3.302 *	0.063	0.691 *	0.434	113.676
		β_1	0.372 *	0.015			
		β_2	0.010 *	< 0.001			
B3	$\ln(AGB) = \beta_0 + \beta_1 \cdot CD + \beta_2 \cdot H$	β_0	2.707 *	0.057	0.821 *	0.331	96.538
		β_1	0.356 *	0.011			
		β_2	0.010 *	0.004			

$^*p < 0.0001$; AGB—aboveground biomass, CD—crown diameter, SA—stand age, H—tree height, β_0, β_1, β_2—regression coefficients, R^2—coefficient of determination, $RMSE_{ln}$—root mean square error calculated from the transformed predicted and observed biomass data, $RMSE_{bt}$—back-transformed root mean square error calculated from the predicted and observed biomass data back-transformed to their original values.

Regression analysis revealed that all models ($Pr > F < 0.001$), as well as their parameters ($Pr > |t| < 0.001$) were highly significant. Estimated slope parameters (β_1, β_2) of all independent variables in all models were positive indicating that the AGB increases progressively with the increase of CD, SA and H. Among all tree independent variables used in regression analysis, CD has been identified as the strongest predictor of aboveground biomass.

However, there was a considerable variation among models' performance. The least favorable, *i.e.*, the lowest R^2 values and the highest errors (RMSE, $RMSE_N$), was produced by the model B1 with CD as the only independent variable. The addition of SA to CD improved model performance considerably by increasing prediction accuracy (R^2) and slightly reducing the errors of estimates ($RMSE_{ln}$, $RMSE_{bt}$). However, the greatest improvement of the model performance was achieved by inclusion of H in addition to CD (model B3). Among all three models, model B3 produced the highest prediction accuracy (R^2) and the least errors ($RMSE_{ln}$, $RMSE_{bt}$) (Table 5). In addition, graphical analysis (Figure 4, Supplementary Data Figure S3) confirmed model B3 as the model with the strongest relationship between predicted and observed aboveground biomass. Consequently, Model B3 may be recommended as the most suited for prediction of aboveground biomass of individual black pine trees in Sub-Mediterranean Croatian forests.

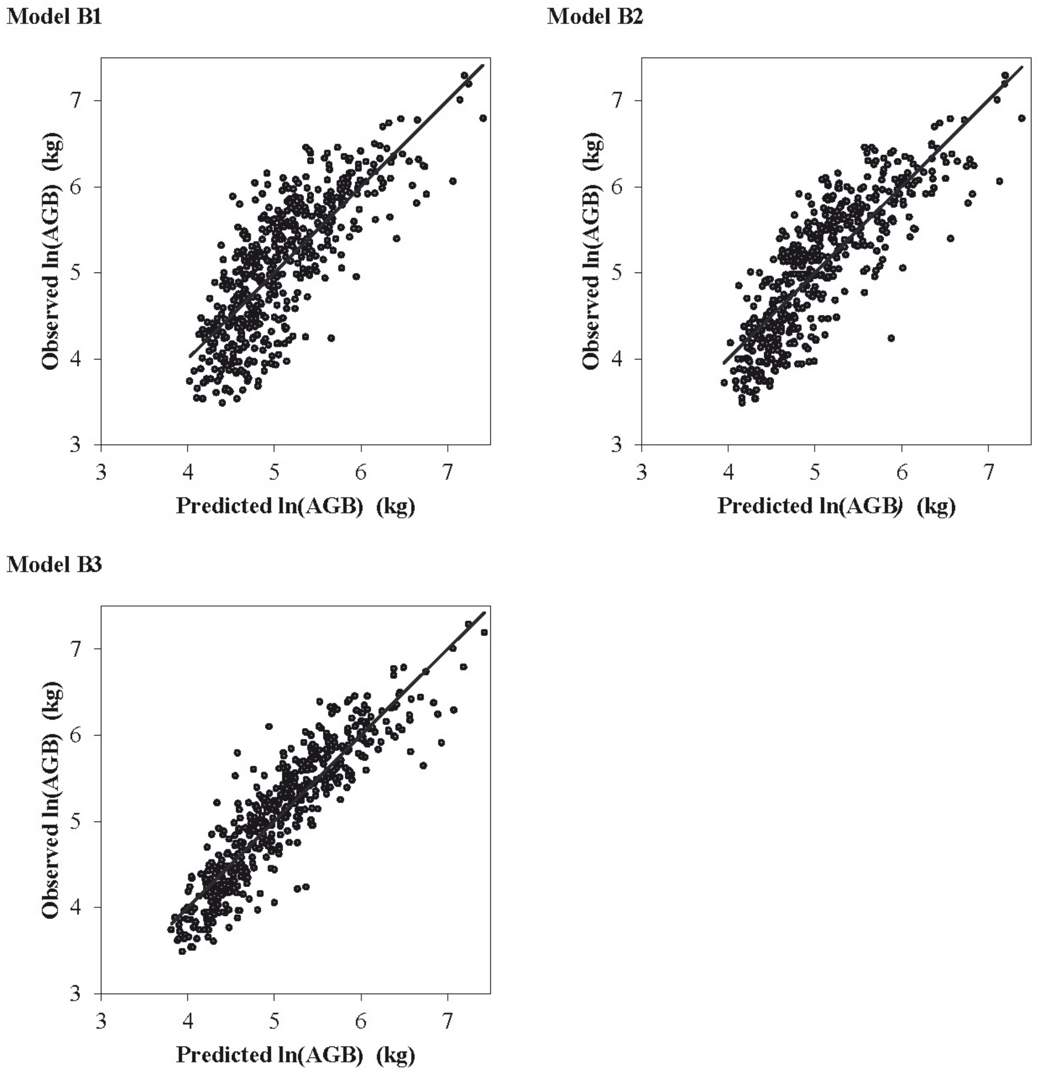

Figure 4. Predicted *vs.* observed aboveground biomass (AGB) for three selected black pine aboveground biomass models. The solid line represents fitted linear model. Models' description and evaluation statistic are presented in Table 5.

4. Discussion

The objective of this research was to develop models for predicting three characteristics of individual black pine trees grown in Sub-Mediterranean Croatian forests suitable for remote sensing-based inventory. Models for predicting diameter at breast height (DBH), merchantable tree volume (V) and aboveground biomass (AGB) were developed based on data collected from field measurement, existing database, and DTM using regression analysis, the most commonly used statistical method in forest modeling [30]. Research by Prieditis *et al.* [14] showed that inclusion of extra variables in addition to H and CD may considerably improve the DBH estimation accuracy. Therefore, within this research, besides H and CD, additional stand and site variables were also considered as potential predictors of DBH, V and AGB of individual black pine trees. The first condition while selecting the potential predictors was that variables should be easy obtainable from remote sensing data. In total, eight variables (H, CD, N, DCT, SA, Z, S, A) were candidates for independent variables (Table 2).

A preliminary evaluation indicated a non-normality of all dependent variables (DBH, V, AGB). Therefore, prior to modeling, DBH data were transformed into a square root form, while V and AGB data were transformed into a logarithm form. Similar transformations of dependent variables may be observed in other research as well [4,6,9,10,14]. However, unlike these researches, the independent variables in this research were not transformed because the relationships between transformed dependent and non-transformed independent variables were linear.

Of all eight independent variables evaluated by R^2 selection method, the three variables (CD, H, SA) have proved to be potentially good predictors of DBH and AGB, whereas four variables (H, CD, N, DCT) were selected as potential predictors of V. According to established criteria, site variables (Z, S, A) were excluded from further analysis in all three cases due to low R^2 value ($R^2 < 0.05$) and their small contribution to model goodness. The main reason for that may lie in the fact that trees were sampled in only one management unit (locality) where a variation in, e.g., elevation (465–695 m) of location of the sampled trees, is not so high to have great influence on tree characteristics. It may be assumed that site variables could have greater influence in large-scale models (e.g., on national or regional level) for which trees are usually sampled from various locations with various site characteristics. In that case, additional stand (e.g., stand index, site class) or site variables (e.g., soil type) should also be observed and their contribution to model goodness evaluated. Based on the conducted R^2 selection method, the set of three models with identical combination of independent variables was selected as the most appropriate to fit DBH (Table 3) and AGB (Table 5) data by regression analysis, whereas for fitting V data the set of four models was selected (Table 4). Although all models (Pr > F < 0.001), as well as their parameters (Pr > |t| < 0.001) were highly significant (Tables 3–5), there was a considerable variation among models' performance (R^2, $RMSE_{sqrt}$, $RMSE_{ln}$, $RMSE_{bt}$) in all three cases.

Results of regression analysis indicated the CD as the most important predictor of both DBH and AGB, and H as the most important V predictor of individual black pine trees. However, according to evaluation statistics (Tables 3–5) and graphical analysis (Figures 2–4) it seems that neither CD nor H as only predictors are capable to produce highly accurate estimates of DBH, V or AGB. Namely, coefficients of determination (R^2) provided by these models amounted to 0.63, 0.68, and 0.60 for DBH, V, and AGB, respectively. The inclusion of stand variables, namely the inclusion of SA in addition to CD in DBH and AGB models (D2, B2, B3), as well as inclusion of N or DCT in addition to H in V model (V2) improved considerably the models' performance. The addition of stand variables increased R^2 values in these models to 0.71 (DBH model D2), 0.74 (V model V2), 0.75 (V model V3), and 0.69 (AGB model B2). Therefore, it may be assumed that these models (D2, V2, B2, B3) could provide reasonably accurate estimates of tree DBH, V and AGB. However, among all tested models, the best performance in all three cases (predicting DBH, V and AGB) had the models with both CD and H as individual variables (models D3, V4, B3) producing the highest prediction accuracy (R^2) and the least errors ($RMSE_{sqrt}$ or $RMSE_{ln}$, and $RMSE_{bt}$). By using these models the coefficients of determination (R^2) for DBH, V and AGB amounted to 0.83, 0.89 and 0.82, respectively. According to the results of R^2 selection method, the inclusion of any third variable to the models, in addition to CD and H, only slightly improved the models increasing R^2 value of the models for less than 0.02. Therefore, models with tree variables were not included in the regression analysis.

The results of this research are in accordance with numerous other studies on modeling tree variables for remote sensing-based inventory [4–6,10,31], which also showed that models with H and CD as independent variables are the most suitable for predicting DBH, V or AGB biomass of individual trees. Moreover, similar to this research, some of the mentioned studies [4,6] revealed that inclusion of stand or site variables in addition to CD and H brought only small improvements to the model performance, whether for predicting DBH or V. Therefore, inclusion of the third variable in models for predicting DBH, V or AGB in most cases is not necessary, especially for local-scale models. In this research, the addition of stand variables (SA, N, DCT) had greater influence on models' performance only when they were added as a secondary variable.

Among various remote sensing methods, the developed models could be primarily used for inventories based on measurements from high-resolution digital aerial stereo-images or from airborne laser scanning data (ALS) [4,6]. Currently, both methods (digital stereo-photogrammetry and ALS) are suitable and enable estimation of H and CD at tree level [6,32]. Research on applicability of high-spatial resolution stereo-images [33–36] or high-density ALS data [14,37,38] for H estimation showed that H could be estimated with both methods with high accuracy and with no statistically significant difference compared to field measurements. Unlike H, it is more time-consuming and more difficult to accurately estimate crown size (area or diameter) of individual trees from remote sensing data, especially in densely canopied stands where overlapping of the crowns of the adjacent trees is common and complicates crowns measurement of individual trees [4,7,33,38,39]. Besides stand structure, estimated results of crown dimensions could be influenced by the pulse density of airborne laser scanning or spatial resolution of aerial images, but also by the computer algorithm used for crown delineation in cases when automatic method of delineation was used. Namely, visibility and detection of small branches and irregular crown parts are dependent upon resolution of aerial images or density of ALS data [3,38]. However, despite potential obstacles in estimating crown dimensions by remote sensing methods, in our case CD should not be omitted from the models, since it was revealed that it is a very strong predictor of all tree dependent variables.

Results of this research are promising and suggest that the use of developed models with H and CD as predictors (models D3, V4, B3), estimated from high-resolution aerial stereo-images or high-density ALS data, could provide reasonably accurate predictions of DBH, V and AGB of individual black pine trees, at least for the forest management unit for which they were developed. This assumption relies on the following reasons: (i) results of regression analysis showed good performance of the proposed models in terms of high prediction accuracy (R^2) and reasonably small errors ($RMSE_{sqrt}$ or $RMSE_{ln}$, and $RMSE_{bt}$), and (ii) homogeneous structure of the researched pure even-aged black pine stands may facilitated detection and estimation of H and CD of individual trees. However, this assumption should be further validated by conducting remote sensing-based inventory and by comparing the obtained results with field measurement results. In the case that differences between field- and remote sensing-based estimates of predictor (independent) variables will be detected, it may be necessary to develop calibration functions to adjust any biases in the remote sensing-based estimates [13]. To examine wider applicability of the proposed models, validation should also be conducted on another Mediterranean and Sub-Mediterranean areas of black pine stands. It should be noted that models developed in this research may not be appropriate in mixed or open forest stands, because the research was conducted in pure, densely canopied stands.

5. Conclusions

This research provides a set of models (allometric equations) for diameter at breast height (DBH), merchantable tree volume (V) and aboveground biomass (AGB) estimation of individual black pine trees grown in Sub-Mediterranean parts of Croatia. These models intended to be used in remote sensing-based inventory, but also could be used in classical field inventory for V and AGB estimation. Regression analysis indicated the CD as the most important predictor of both DBH and AGB, and H as the most important V predictor of individual black pine trees. However, neither CD nor H as only predictors are capable to produce highly accurate estimates of DBH, V or AGB. The inclusion of stand variables (SA, N, DCT) in addition to CD or H improved considerably the models' performance. Nevertheless, among all tested models, the best performance in all three cases (predicting DBH, V and AGB) had the models with both CD and H as individual variables (models D3, V4, B3). The inclusion of any third variable to the models in addition to CD and H is not necessary since they just slightly improved the models' performance. Consequently, models with CD and H as independent variables may be recommended as the most suited for DBH, V and AGB prediction of individual black pine trees grown in pure Sub-Mediterranean forest stands using high-resolution aerial images or high-density ALS data. Future research should be focused on validation of this assumption by conducting remote sensing inventory and comparing the obtained results with the results of field measurement, on both local and regional scales.

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Author Contributions

The research was designed by Ivan Balenović, Hrvoje Marjanović and Dijana Vuletić. The data were collected by Ivan Balenović and Elvis Paladinić. Statistical analysis were mainly done by Anamarija Jazbec. All authors were contributed in data analysis. The manuscript was written by Ivan Balenović supported by Hrvoje Marjanović, Elvis Paladinić and Dijana Vuletić.

Conflicts of Interest

The authors declare no conflict of interest.

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