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USING MATHEMATICAL MODELS BASED ON UNMANNED AERIAL VEHICLE OPTICAL IMAGERY TO ESTIMATE TREE AND STAND CHARACTERISTICS

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Abstract: *This study continues the research in a 100-year-old black pine forest, consisting of stands with different structures. A sample was selected, consisting of six sampling plots (30 subsampling plots) with 508 trees for which the diameter (d), the height (h), and the crown diameter (cw) were measured. Models were generated at sample level (general models), as well as at stand level, based on the cw measured in the field. The general models estimated the sample volume at an relative RMSE (RMSE %) of 20.1% and those adapted to the stand structure at an RMSE of 2.8%. At the level of the sampling plots, the general models underestimated the volume of the higher productivity stands by 24% and overestimated the volume of the lower productivity stands by 27%.*

Key words: *crown diameter, tree diameter, tree volume, black pine, mathematic model.*

1. Introduction

Decisions regarding forest management planning are based on a complex data source about the forest that will undergo planning, which is periodically updated with observations and measurements. The development of unmanned aerial systems (hereinafter UASs) offers new opportunities in this direction. Information related to forest structure can be delivered in a relatively short time frame, and under various conditions of accessibility [17]. UASs consisting of various unmanned aerial vehicles (hereinafter UAVs) equipped with mapping sensors make it possible to obtain digital images that can be used to determine the main dendrometric characteristics of trees and stands [21]. Using data processing software, high spectral resolution images and tridimensional (3D) models can be obtained which can be used in forest monitoring activities [30], [13], [22], as well as in taking forest inventory [23-25] and remotely measuring tree variables [15-18].

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Compared to the values acquired by field measurements, the measurements done using the digital model lead to parameter values within acceptable limits [29]. As such, many studies have focused on individual trees by means of the segmentation of digital models and on the estimation of their dendrometric characteristics [2], [13-14]. UASs equipped with laser sensors are increasingly used in forestry to obtain 3D models [19], as they lead to tree location and tree height values comparable with those attained from ground measurements [26], [8]. The use of laser scanning sensors (UAV-LS) has created the possibility of taking very high-resolution 3D images that allow measurements under the forest canopy [1], [28] and of determining the characteristics of individual trees, such as their coordinates, height (h), diameter (d or DBH), crown width (cw), crown length, biomass change, and rate of pruning [17].

When using terrestrial laser scanning (TLS) in stands characterized by variations in crown size and Kraft class, the detection rate of trees can reach 97.4% when DBH > 12 cm, and 84.62% for regeneration trees with a DBH < 12 cm [5]. The combination of under-canopy and above-canopy UAV laser scanning leads to an accurate inventory of forest resources [6]. One of the latest progresses is UAV-borne laser scanning (ULS), which guarantees tree height measurement with an accuracy required/necessary in forestry application [11]. Low relative RMSE (RMSE %) values (8.6-12.7%) were attained when manual TLS-based DBH and manual ULS-based tree height were used [27]. Due to its high resolution, digital-photography-based canopy height evaluation allows for the extraction of dendrometric features of stands. It is more efficient for estimating the dominant height of even-aged stands [12]. Technological advances such as structure-from-motion (SfM) have expanded the use of UAVs for individual tree detection. However, UAV-SfM data could be used as a complement rather than as an alternative to LiDAR data [9]. As a result, stand structure remains one of the factors that can influence the choice of equipment for recording information, as well as the accuracy of the results [20].

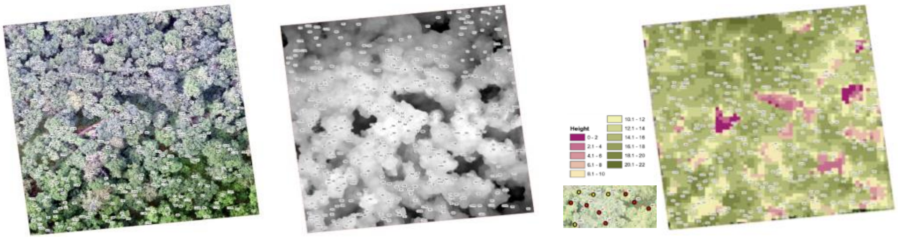
Relations of competition and preference are established among trees, which provide specific features to each structure. Characteristics such as tree diameter, tree height or crown size are variable in relation to the structural conditions of the stands [20]. If structure shapes the size and form of the trees, the mathematical models based on measurements done on digital models (derived from UAVs) best characterize the structures for which they were generated or structures similar to them. Thus, in the case of forests made up of stands with different structures, the application of general models (generated at forest level) for estimates at stand level would lead to an increase in the estimation errors concerning their dendrometric characteristics. The errors could also multiply if the model's characteristic of some structures were used in the case of other stands made up of the same species, but with different structural characteristics. This study presents new investigations at the level of a black pine forest. The aim was to obtain mathematical models based on the tree crown diameter, which can be determined by measurements on the digital model. The starting point for this study is the research conducted in 170-year-old sessile oak stands based on measurements made on a digital model [20]. The current study represents a continuation of that research. To increase the accuracy of the estimates, only the characteristics of the trees measured in the field were used in the models.

Rather, this study shows rather a methodological approach of the combined application of dendrometric methods using UAV technology in order to investigate and evaluate the growing stock of a forest.

2. Materials and Methods

Study area. The study included forests from two locations near the Romanian city of Brasov (45°38′43″ N and 25°34′01″ E; 45°37′55″ N and 25°35′50″ E): sessile oak and beech forests and other mixed species, and black pine forests, aged 110 and 100, respectively. The forests fulfill multiple protection functions, so that the silvicultural works designed by the forest management plans have low intensities, with a pronounced conservative character. The stands are located in various site conditions, they are even-aged with variable densities.

Field measurements and data processing. In the 110-year-old sessile oak stands, the field measurements were carried out in two sampling plots of 1.0 ha each (100x100). On these plots the models that estimate the dendrometric characteristics of the trees (d, h, and v) were applied depending on their cw, and the models were developed for 170-year-old sessile oak stands [20]. To generate these models, two sampling plots of 0.5 ha each (50x100) were placed in the respective stands [20]. In these stands, in a representative sample of trees from the plots, the coordinates (X and Y) were determined by surveying methods using the Leica TC 407 total station (the sample was established to ensure a measurement error of the volume of maximum 10% for a 95% probability coverage). Aerial images were taken of these stands using the DJI Phantom 3 Advanced, from a 56 m height and with a 90% overlap. The crown diameter and the height of the trees in the sample were determined on the digital surface model (DSM) and on the derived models (Figure 1), obtained after generating the 3D point cloud using the Agisoft Photoscan application [20].



a) b) c)

Fig. 1. *Models derived from digital image processing: positioning of points on aerial imagery (a), positioning of trees on the DSM (b), canopy height model (CHM) with detailed view (c),* [20]

The models [20] overestimated the dendrometric characteristics of the 110-year-old stands. For example, the model:

$$d = 0.058cw^3 - 0.3011cw + 2.4391cw + 27.021, \quad (1)$$

estimated the tree diameter with RMSE% of 42%. The research was continued in a 100-year-old pine forest, consisting of stands with different structural conditions. In order to eliminate the influence of the measurement errors of the crown diameters and of the tree height on the digital model, only the field data were used. A sample (S) consisting of six sampling plots (SP) was established to provide a volume measurement error of maximum 12% to a 95% probability coverage. Each SP in the pine stands consisted of five circular subsampling plots (P1 - P5) (each having 500 m^2), four of which were arranged in the direction of the cardinal points, 30 m away from the center of the SP, and one in the center of the SP (Figure 2), a total of 30 plots. In all the inventoried trees, the circumference (at brest height) was measured to determine the diameter as well as the height and crown diameter (cw was measured in two directions). The h and cw characteristics were measured using a Vertex Laser (Geo). A summary of the field data from the inventoried pine stands is presented in Table 1.

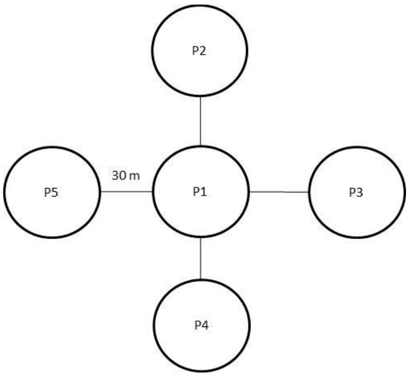


Fig. 2. *Diagram of a sampling plot located in the pine stands*

Dendrometric characteristics of the inventoried pine stands Table 1

SP	Area inventoried [ha]	Species	d_g [cm]	h_g [m]	G [m^2]	SD	V [m^3]
SP1	0.25	Black pine	34.98	19.3	6.82	0.68	62.7
SP2	0.25	Black pine	37.77	18.2	6.58	0.69	57.9
SP3	0.25	Black pine	36.66	19.1	6.44	0.65	59.6
SP4	0.25	Black pine	40.37	25.3	11.52	0.93	132.7
SP5	0.25	Black pine	29.73	19.3	8.05	0.80	74.5
SP6	0.25	Black pine	29.92	18.5	7.59	0.79	67.6
Total	1.50	-	-	-	-	-	455.0

In Table 1: N = number of trees inventoried; d_g = mean squared diameter or quadratic mean diameter (diameter corresponding to mean basal area of stand or group of trees) ($\bar{g} = \frac{G}{N}$, g being synonymous with ba); h_g = height of the tree with d_g (height of the mean basal area tree); cw = crown diameter of the tree with d_g; G = basal area of stand or the basal area for a group of trees) (synonymous with BA); SD = stocking degree; V = stand volume (standing volume) or the volume for a group of trees.

Based on the characteristics of the inventoried trees, models were generated that show the diameter, height, and volume of the trees, depending on the cw. The volume of each tree was determined using the model developed for forest species in Romania [3-4], [10]:

$$\log v = a_0 + a_1 \log d + a_2 \log^2 d + a_3 \log h + a_4 \log^2 h. \quad (2)$$

In model (2), for the sessile oak species, $a_0 = -4.17315$, $a_1 = 2.27662$, $a_2 = -0.09084$, $a_3 = 0.57596$, and $a_4 = 0.093429$. For the black pine, $a_0 = -4.01698$, $a_1 = 1.96342$, $a_2 = 0.01241$, $a_3 = 0.57848$, and $a_4 = 0.094783$. At the level of all the trees inventoried, a correlation coefficient of 0.81 was determined between cw and d ($p < 0.05$). Based on the cw of the trees, models were developed to estimate the dendrometric characteristics of the trees at the level of the sample that is representative for the forest (i.e., 508 trees) and at the level of the stands represented by the six sampling plots (SP1 - SP6). The accuracy of the models was assessed by the mean error (MAE), RMSE%, and coefficient of determination (R^2) values. Even if R^2 showed lower values, the models were accepted because the values of the estimated characteristics in the models are in line with their normal tendency expressed through the growth processes of the stands.

3. Results and Discussions

Model (1), applied to the stands for which it was developed (170-year-old sessile oak), estimated the tree diameters as close to those measured in the field, with an RMSE value of 0.89%. When estimating the tree volume, the MAE% was –0.07% and the RMSE was 9.16% [1]. In the case of other structures, such as those specific to 110-year-old sessile oak stands, located in other site conditions, the respective models overestimated the volume, the MAE being 31%. Based on these results, models were generated for the pine forest both at the sample level (which characterized the investigated forest), and at the level of the sampling plots (which characterized the structural conditions of the stands that make up the respective forest).

Tree diameter and height. At the sample level, the tree diameter was estimated according to the crown diameter (Figure 3 a)) by a linear model:

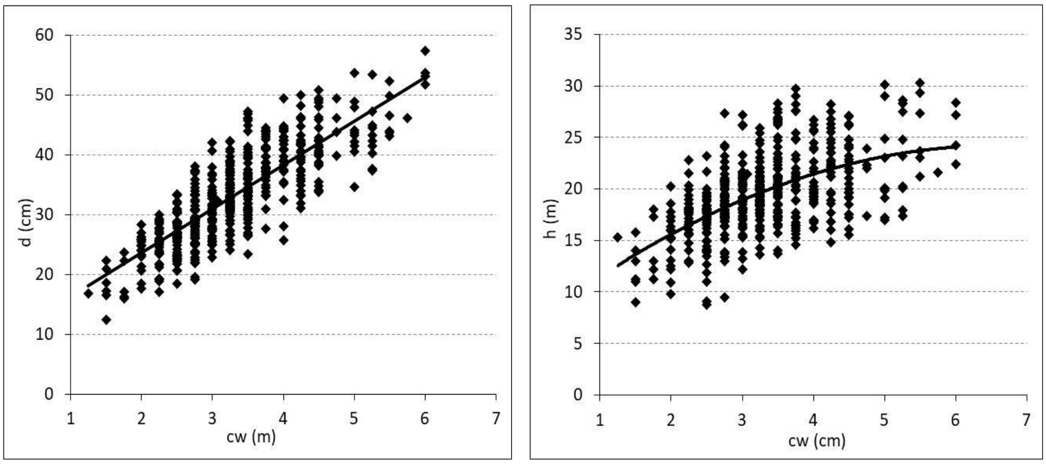
$$d = 7.3306cw + 9.0271, \quad (3)$$

and the tree height, based on the model of the height curve:

$$h = -0.0059d^2 + 0.7338d + 1.906. \quad (4)$$

In model (4), d represents the tree diameter determined on the basis of the crown diameter using model (3). The same results are obtained if the height is determined directly from the tree diameter (Figure 3 b)) with the relation:

$$h = -0.4016cw^2 + 5.3299cw + 6.5477. \quad (5)$$



a) *b)*

Fig. 3. *Relationship between the crown diameter and the tree diameter (a) and between the crown diameter and the tree height (b)*

In order to increase the accuracy of the determinations, given the use of high-performance digital models, the tree height should be measured directly on these models.

At the level of the whole sample, general models (3) and (5) estimated the dendrometric characteristics of the trees (d and h) with an RMSE% value of 13.7% for the tree diameters and 16.4% for the height. The intensity of the correlation between the cw and d characteristics, and between cw and h, respectively, is explained by values of the coefficient of determination (R^2) of 0.67 and 0.33, respectively. Applied at the stand level, the most significant errors resulted in the case of estimating the tree height in SP2 and SP4 for which the site productivity, expressed by h_g, presented the minimum and maximum values (of 18 and 25 m, respectively). For SP2, general model (5) estimated the tree height with an RMSE% of 23.4% and for SP4 with an RMSE% of 19.5%.

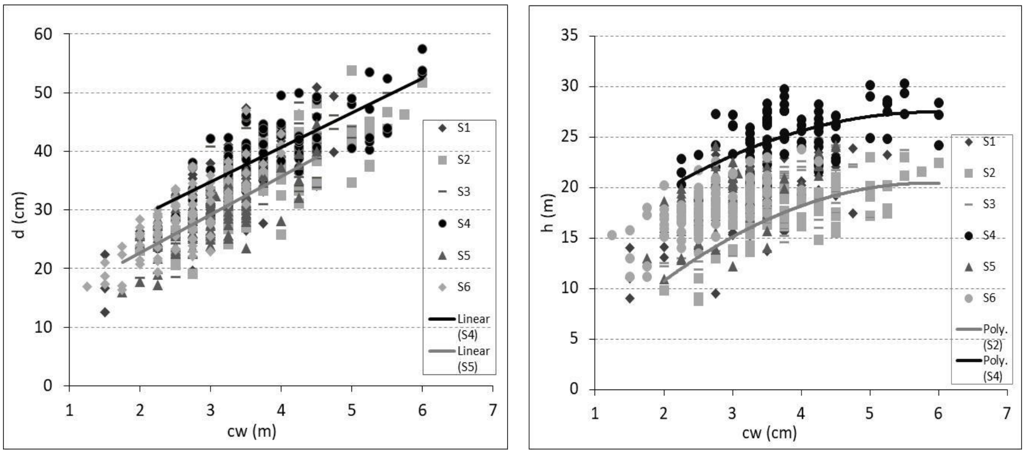
However, the generation of models at the stand level (i.e., SPs) (Figure 4) led to the reduction in the respective errors. For example, to estimate the diameter of the trees in SP4 according to the crown diameter, the following model was generated:

$$d = 5.9021cw + 17.062, \tag{6}$$

and for SP5, the model:

$$d = 6.4651cw + 9.8156. \tag{7}$$

Models (6) and (7) estimated the diameter with RMSE% of 10.1% (for SP4) and 10.7% (for SP5). At the level of the SPs, models were generated that also estimate the tree height depending on the crown diameter (Figure 4). However, they are specific to each SP and characterize the structure of each stand.



a) *b)*

Fig. 4. *The relationship between the tree diameter and the crown diameter (a) and the relationship between the tree height and the crown diameter (b). In the case of the same crown diameters, the trees may have different diameters and heights. The two curved lines that highlight different heights for the same crown diameters (b) characterize the stands in the sites expressed by* h_g *values ranging between 18 m (SP2) and 25 m (SP4)*

The models generated at the level of the SPs also estimated the tree height with low RMSE% values, lower than in the case of the diameters (Figure 5), especially for the sampling plots that characterize structures which deviate far from the sample average. For example, the model:

$$h = -0.647cw^2 + 7.5932cw - 1.8461, \tag{8}$$

estimated the tree height in SP2 with an RMSE of 11.9% (compared to 23.4% as stimated in general model (5)), and the model:

$$h = -0.5001cw^2 + 5.9334cw + 9.8647, \tag{9}$$

estimated the tree height in SP4 with an RMSE of 9.9% (compared to 19.5% as estimated in general model (5)).

The tree volume was determined using model (2), which included the tree diameters and heights determined using general models ((3) - (5)) and those determined using the models elaborated at the level of the SPs (e.g., (6) - (9)) that characterize the structure of the researched stands. Similarly, to the case of the dendrometric characteristics d and h, in the case of the tree volume, the most significant differences at the level of the SPs were recorded when the tree diameter and height determined using the general models were used in the calculation (Table 2).

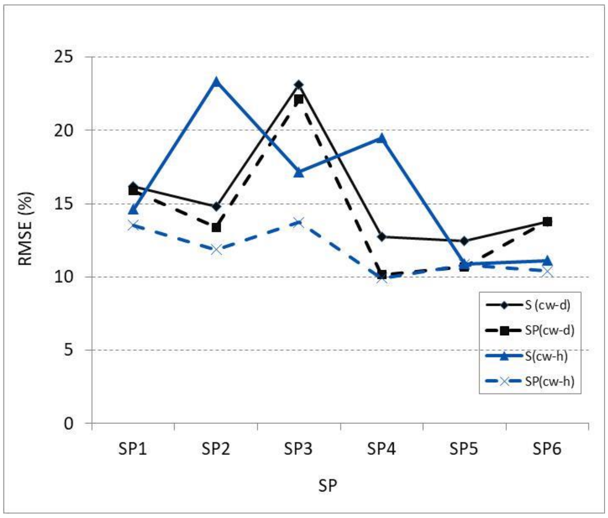


Fig. 5. *The RMSE% in the case of applying the general models (elaborated at the sample level) and those adapted to the stand structure (specific to the sampling plots). In general, the RMSE has lower values when specific models for each stand are used to express d and h according to cw,. This can be explained by the fact that, especially in the case of heights, the stands located in sites of different productivity have different heights with at the same crown diameters (e.g., h_g values of 18 m (SP2) and 25 m (SP4))*

Using these models led to the estimation of the volume of the inventoried sample with an RMSE% of 20.1%. However, the application of the generated models at the level of the SPs reduced the volume differences to –4.4% (e.g., at the level of SP6 in Table 2).

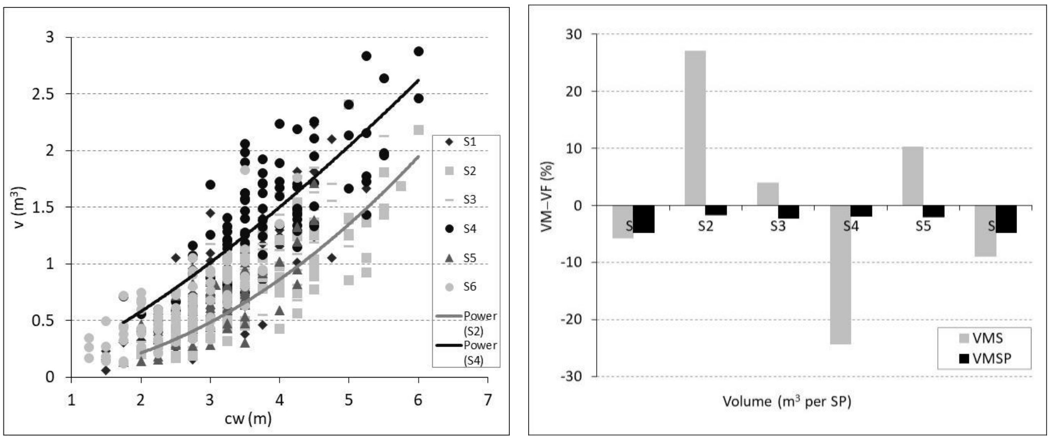
Tree volume (V) at SPs level resulting from the application of the models Table 2

Sampling plot	Volume at SP level (m^3) determined by			Differences from VF			
				VMS-VF		VMSP-VF	
	field measurements (d and h) at the level of each tree (VF)	models generated at the level of the whole sample (VMS)	models generated at the level of each sampling plot (VMSP)	m^3	%	m^3	%
SP1	62.7	59.2	60.1	-3.5	-5.6	-2.6	-4.1
SP2	57.9	73.5	56.9	15.6	27.0	-1.0	-1.7
SP3	59.6	61.9	58.3	2.3	3.9	-1.3	-2.2
SP4	132.7	100.4	130.1	-32.3	-24.3	-2.6	-1.9
SP5	74.5	82.4	73.3	7.9	10.6	-1.2	-1.7
SP6	67.6	62.2	64.6	-5.4	-8.3	-3.0	-4.4
Total	455.0	439.6	443.3	-15.4	-3.4	-11.7	-2.6

In the Table 2, the tree height was determined from the height curve according to the tree diameter, which in turn, was determined according to the crown diameter. If the height determined directly from the crown diameter was used, the maximum volume differences were 27.1% (VMS-VF) (this difference was achieved in the case of the same stand represented by SP2) and -4.8% (VMSP-VF) (this maximum difference was also achieved in the case of SP6).

The differences were reduced in all sampling plots (Figure 6), but mostly in those with dendrometric characteristics different from the average (e.g., SP2 and SP4), a differentiation indicator in this respect being h_g.

In model (4), the tree diameter determined according to the crown diameter was used, both at the level of the whole sample, and at the level of the SPs. The height used was both the height which was indirectly determined from the crown diameters by means of the height curve (i.e., with model 4), as well as the height determined directly according to the crown diameters (with models such as (5), (8) or (9)). Both cases of height determination led to close volumes (in the first case, the maximum volume difference was –4.4 and in the second case –4.8%) (Table 2). As a result, the use of height in models is absolutely necessary to increase the accuracy of volume determination. If the digital model does not allow for height measurement, the relationship between the crown diameter and the tree volume can be used (Figure 6 a). However, the models that would be acquired in this case should be differentiated in relation to the site productivity, and as such, the dominant height or h_g can be used. Differentiation is required because, as shown in this study, in sites of different productivity (e.g., SP2, SP4, and SP6 (Figure 6 b)) tree size and shape differ and lead to specific relationships between the tree dendrometric characteristics.



a) *b)*

Fig. 6. *Variation in the volume of trees with the same crown diameter in stands located in different productivity sites (for which the site-index is highlighted with h_g values between 8 and 25 m) (a) and volume differences recorded by applying the general models (VMS) and those adapted to the stand structure (VMSP) (b)*

At the sample level, using the general models at the level of the sampling plots led to a reduction in the RMSE% from 20.1% to 2.8% (Table 3).

Accuracy of volume determination Table 3

Model application	MAE (m^3)	MAE (%)	RMSE (m^3)	RMSE% (%)
2. General models generated at the sample level (VMS)	–2.6	–3.4	15.2	20.1
3. Models generated at the sampling plot level (VMSP)	–1.9	–2.6	2.1	2.8

In order to determine the volumes entered in the calculations (VMS and VMSP), the heights determined from the height curve were used, depending on the tree diameter, which in turn, was determined according to the crown diameter.

The crown area of the trees and the crown diameter, respectively are variables that can be used in models to estimate the dendrometric characteristics of the trees and can be easily determined on the digital model. In the case of the 170-year-old sessile oak stands, the research showed that: cw was determined on the digital model with RMSE% values of 18.37%, the models based on the cw measured on the digital model estimated the tree diameter with an RMSE% of 0.32-0.89%, the models based on the height measured on the model estimated the tree height with an RMSE% of 11.70% and the volume, based on d and h estimated with an RMSE% of 9% [20], a value close to the results obtained in other research [14], [17]. As a result, digital images remain a source of information which by processing, can provide derived models necessary in dendrometric determinations.

This study included pine stands located in different site conditions, for which the site-index expressed by h_g has values between 18 and 25 m. The main characteristic was the crown diameters of the trees [20], measured in the field. Thusly determined, this variable can be used to calibrate the models obtained by digital image measurements for pine stands with similar structures in the researched area. At the stand level, the established subsampling plots are characterized by varied densities (0.41-1.17), which at the level of the SPs range between 0.65-0.93 (Table 1), as well as by a wide variation in tree sizes. However, no correlation was identified between the density of the plots and the average diameter (i.e., d_g) or average height (i.e., h_g) of the trees in the plots. Only at densities greater than 1.0 was there a slight increase in h_g in the plots. Research in this area needs to be continued on a larger number of sample plots. The generated models explain only 33-67% of the variation in the estimated dendrometric characteristics. The best estimate was made for the tree diameter, R^2 having values between 0.6 and 0.67. However, there might be a stronger link between the two variables if, instead of the crown diameter, the crown projection area was used [30]. From the variation of the tree height, the models explain only 32-55% and 50%-67% of the variation of the tree volume. The structural differences between the stands also led to high RMSE values in estimating the dendrometric characteristics with the general models. By adapting the models to the stand structure (i.e., generating models at the level of each stand), the reduction of RMSE was also achieved. The reduction of RMSE is especially evident in the case of the stands located in sites with different than average productivity (Figure 5) (e.g., in the case of SP2, which characterizes a stand with a h_g of 18.2 m, the RMSE% decreased from 28.9% to 3.7%).

The reduction of the RMSE% can be explained by the reduction of the amplitude of the variation of each characteristic. Even if there is a close correlation between the crown diameter and the tree diameter, the crown diameter should not remain the only variable in relation to which the tree volume is estimated. The field of variation of tree height, which is quite extensive in the conditions of different productivity sites, as well as of the other tree characteristics recommends the particularization of the models that have the crown diameter as an independent variable. As a result, stand structure shapes the size and geometry of trees and can be a criterion for differentiating models. Thus, the stratification of the forest in homogeneous areas in terms of structural conditions can become a condition for increasing the accuracy of determinations in the inventory and management planning of forests. As the average or dominant height is one of the indicators for estimating site productivity, it can become one of the criteria for differentiating stand structure.

5. Conclusions

Crown diameter is a good indicator of tree diameter. However, the relationship between the two variables is specific to each structure and the models that have the crown diameter as an independent variable likewise. The models thus obtained can only be generalized in conditions of similar structure such as stand age, site productivity, vertical distribution of the trees, and even tree density. Such models can be generated if measurements are made on as many trees as possible. Furthermore, they cannot be applied to individual trees, but to a sufficiently large number of trees ($N > 100$), as the errors increase if the number of trees is lower. In the case of the pine forest in this study, the generation of models at the level of each structure led to the reduction of the RMSE which was used to estimate the dendrometric characteristics of the trees. Thus, in the case of the stands located in different site conditions compared to the average productivity of the sample, the RMSE% when estimating the tree height based on the crown diameter was reduced by 49%. Using models specific to each structure ultimately led to a reduction in the estimation error of the forest volume from 20.1% to 2.8%. Crown diameter and tree height are variables that can be easily obtained by processing digital images taken from UAVs. Still, in the case of complex vertical structures, the use of other technologies should not be ruled out, as they could provide better digital models necessary in forestry applications.

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