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Estimation of the stands' arithmetic mean diameter using manual method of digital photogrammetry

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Abstract

Background and Purpose: *The development of digital photogrammetry during the last twenty years has reopened the question of the possibility of its application in forest inventory. The focus of this paper is to research the potential of the manual method of digital photogrammetry for the estimation of diameter at breast height (DBH) at stand level.*

Material and Methods: *The results (stands' arithmetic mean diameter) obtained by classical terrestrial measurement and photogrammetric measurement were compared for the selected part of the 'Donja Kupčina – Pisarovina' management unit. Photogrammetric measurements of tree variables (height, crown diameter), necessary for DBH estimation, were carried out in the stereomodels of colour infrared digital images of 30 cm and 10 cm spatial resolution, i.e. ground sample distance (GSD) using digital photogrammetric workstation.*

Results: *The repeated measures ANOVA testing determined statistically significant differences between the results obtained by terrestrial and photogrammetric measurements (GSD 10 cm and GSD 30 cm) of the arithmetic mean DBH of subcompartments. Furthermore, the testing determined no statistically significant differences between the 'trends' of estimating DBH by different methods. In other words, a 'pattern of constant overestimation' of DBH, taken by the photogrammetric measurement in relation to terrestrial measurement, was noted for all subcompartments. The value of overestimation was lesser in case of aerial images of GSD 10 cm (1.45–3.90 cm) and greater in case of images of GSD 30 cm (2.55–5.29 cm).*

Conclusions: *Considering the obtained results, it can be concluded that the method used in this research may find its practical application primarily in forests of less intensive management (protective forests, forests with special purposes, privately-owned forests), where a compromise between the data collection costs and utilization value is necessary.*

INTRODUCTION

Although the use of aerial photographs for purposes of forest inventory has been studied since the 1920s *(1, 2)*, this method has not yet reached its full potential. Aerial photographs, however, are routinely used in the inventory of large forest areas in North America, Scandinavia and tropical forests, primarily in combination with two-phase sampling. In many other countries the usefulness of aerial photographs for forest inventories remains a controversial issue *(3)*.

The development of digital photogrammetry during the last twenty years, primarily the development of digital aerial cameras that capture digital aerial images of high spatial resolution, as well as the development of digital photogrammetric workstations (DPWs), has encouraged foresters to start researching the possibilities of its application in forestry *(4)*. Based on the review of the research on the application of digital photogrammetry in forest inventory, Benko and Balenović *(5)* distinguish: (a) *manual* and (b) *automated methods* of photogrammetric measurement and interpretation of digital aerial images using DPW. The application of each method has its advantages and disadvantages. Manual methods are more labor intensive, i.e. they require a much greater interpreter effort and knowledge, while with automated methods most of the work is done by computers. Thus, time saving is achieved with automated methods. Also, by using automated methods, the influence of the interpreter's subjectivity is eliminated *(6)*. However, despite these advantages, automated methods do not yet reach manual methods in terms of accuracy, e.g. in determining tree species and during the estimation of stand structure elements in mixed stands. Therefore, the practical application of automated methods is still questionable *(4, 5)*.

One of the earliest studies on the application of manual methods of digital photogrammetry in forest inventory was conducted by Magnusson *et al. (7)*. They evaluated the estimation accuracy of forest stem volume, tree height and tree species composition at stand level using DPW and aerial photo-interpretation of pansharpened colour infrared digital aerial images with the pixel size of 48 cm. Magnusson *et al. (7)* concluded that photo-interpretation of Z/I DMC images using a DPW may replace the photo-interpretation of film-based photographs using analogue or analytical photogrammetric workstations without a loss of accuracy. They also noted that the benefits of cost-savings on film and film processing, the ability to reproduce colour information and to automate triangulation, to make aerial photo-interpretation of digital images captured by digital aerial cameras, are efficient and suitable for use in forest inventory. Balenović *et al. (4)* developed two adapted methods of the manual digital photogrammetry for application in forest inventory, namely: the method for strata delineation (i.e. creation of forest management divisions), and the method for measuring stand structure elements. For that purpose Balenović *et al. (4)* used digital aerial images of spatial resolution, i.e. ground sample distance (GSD) of 10 cm, topographic maps, a digital terrain model (DTM) and a digital elevation model (DEM), as well as the DPW with the appropriate software (PHOTOMOD, Global Mapper). As a continuation of their study, Balenović et al. *(8)* researched the potential of the developed manual method in creating forest management divisions by comparing classical terrestrial stand mapping and the photointerpretation of digital aerial images of GSD 10 cm and of GSD 30 cm using DPW. Based on research results, they concluded that the photointerpretation of digital images of GSD 30 cm is the most suitable method for operational use in creating management divisions, i.e. the method that provides the most favorable ratio of costs and accuracy of obtained results.

The above presented research has emphasized the big potential for the application of manual digital photogrammetry in practical forest inventory. Therefore, more research of possible applications is necessary. One of the important forest variables that was less in the focus of previous research done with manual methods of digital photogrammetry is the diameter at breast height.

The diameter at breast height (DBH) is the most important measurement element in forest inventory and provides the basis for many other computations (e.g. basal area, volume) *(1, 9)*. Direct estimation of DBH from aerial images in most cases is not possible. Hence, the determination of DBH by the photogrammetric method is usually done by estimation models in which crown dimensions (diameter, area) and tree height are independent variables measured on images *(10)*.

The focus of this paper is to research the potential of the manual method of digital photogrammetry for DBH estimation at stand (subcompartment) level. The results (stands' arithmetic mean diameter) obtained by classical terrestrial measurement and photogrammetric measurement were compared for the selected part of the 'Donja Kupčina – Pisarovina' management unit. Photogrammetric measurements of tree variables (height, crown diameter), necessary for DBH estimation, were carried out in the stereomodels of colour infrared (CIR) digital images of 30 cm and 10 cm spatial resolution using DPW.

MATERIALS AND METHODS

Research Area

The research was carried out on the selected part of the privately-owned forest of »Donja Kupčina – Pisarovina« management unit. The selected part includes 6 compartments and 24 subcompartments and covers the total area of 480 ha (Figure 1). The main tree species are: Sessile oak (*Quercus petraea* L.), Common beech (*Fagus sylvatica* L.), Common hornbeam (*Carpinus betulus* L.) and Black alder (*Alnus glutinosa* (L.) Gaertn.). Other secondary species occurring are: poplars (*Populus* sp.), Wild cherry (*Prunus avium* L.), Black locust (*Robinia pseudoacacia* L.), European aspen (*Populus tremula* L.), Silver birch (*Betula pendula* Roth), etc. The above mentioned species form both the even-aged stands of the Sessile oak management class, as well as the multi-aged stands of the Common beech and Common hornbeam management classes. The multi-aged stands mostly consist of a series of even-aged stands in different development stages. Although these stands are privately-owned and were not managed according to the rules of forestry practice in the past, most of them are of good quality.

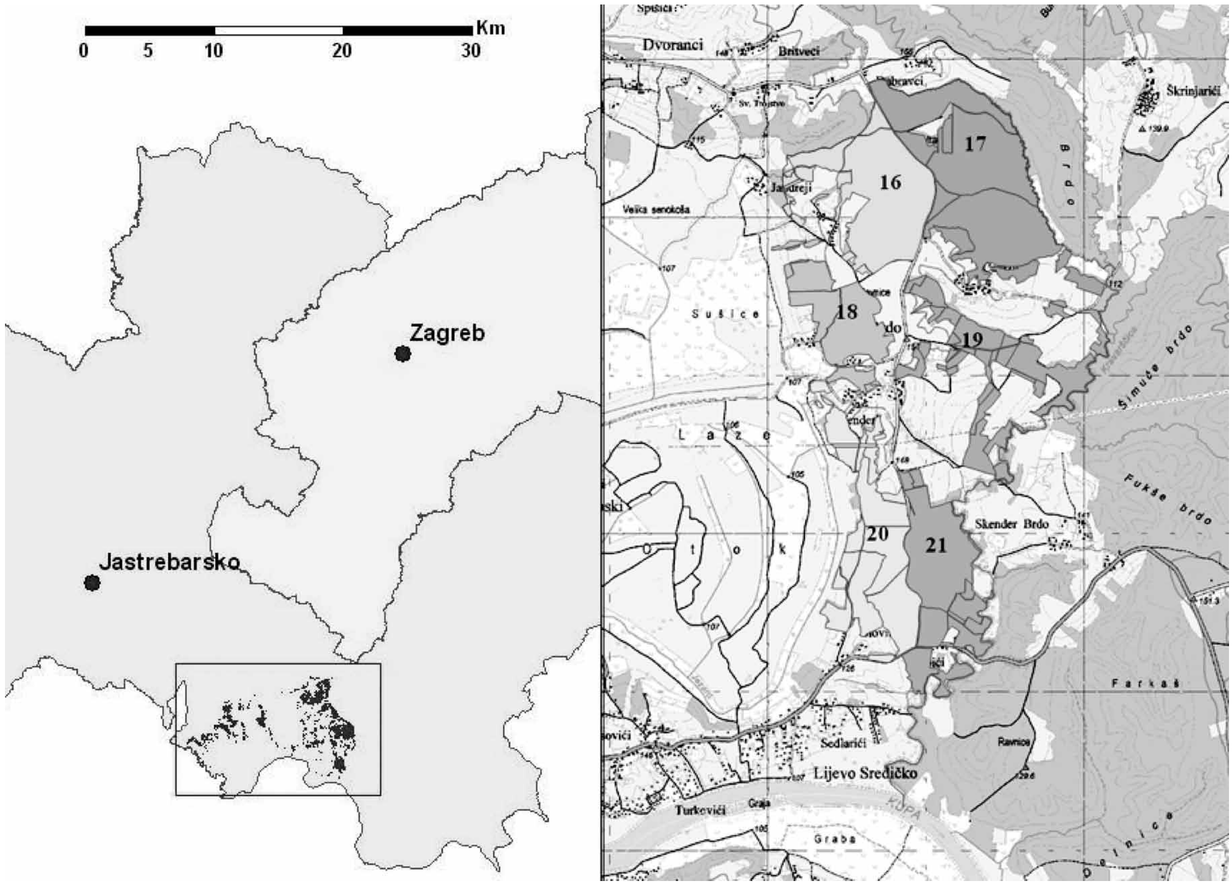

Figure 1. *Left: The Location of the »Donja Kupčina – Pisarovina« management unit in the Zagreb County. Right: The selected research area (compartments 16 to 21).*

Terrestrial Measurement

The terrestrial measurement of DBH was done according to the valid Regulation on Forest Management *(11, 12)* in June and July of 2009. A systematic pattern of circular sample plots was set up in the research area. Depending on the density and age of the stands, the radius of the plots was 8 or 12 m. A systematic pattern was set up in the form of a grid with 100×100 m, 100×200 m or 200×100 m points (plots), depending on the size and shape of subcompartments, as well as the plot size, all in order to satisfy the given intensity of sampling of the minimum 2%. In the 14 selected subcompartments (267.29 ha) 183 circular plots were set up, which makes the sampling area of 5.23 ha and the sampling intensity of 2.0%. The DBH of all trees on plots above the taxation limit of 10 cm were measured by a caliper with centimeter graduation. The position of the sampling plots, that is, the spatial coordinates (x, y) of the sampling plots' centers were recorded with a GPS (Global Position System) receiver in order to be found and 'overlaid' upon aerial images for photogrammetric measurement purposes.

Aerial Surveys

Two aerial surveys of the research area were conducted by Vexcel UltraCamX digital aerophotogrammetric camera in July 2009. The focal distance of camera lenses was 100.5 mm, while the radiometric resolution was 12 bit. The forward overlap (endlap) of images was 60%, while the lateral (sidelap) was 30%.

Firstly, the so-called »high« aerial survey was done at the flying height of about 4400 m above ground. Along two flight lines, 10 CIR digital aerial images of GSD 30 cm were acquired.

Secondly, the »low« aerial survey was done at the flying height of about 1400 m above ground, the product of which were 23 CIR digital aerial images of GSD 10 cm, acquired along two flight lines.

The aerial surveys of the research area and the post-processing of acquired digital aerial images were performed by Geofoto Ltd, Zagreb.

Photogrammetric Measurement

The photogrammetric measurement was carried out in the stereomodels of CIR digital images of GSD 30 cm and GSD 10 cm using DPW with PHOTOMOD Lite 4.4 photogrammetric software. Two modules of PHOTOMOD Lite software were used: (I) Montage Desktop – the core module of the digital photogrammetric system used to create and manage projects, as well as to operate different modules for further photogrammetric processing, and (II) StereoDraw – the module for 3D feature extraction, i.e. creating, editing and measuring 3D vector objects in stereomode. Additional data processing was performed using DEM and Global Mapper v11.01 software. A detailed description of tools (DPW), the software (PHOTOMOD Lite 4.4, Global Mapper v11.01), the creation of DEM and the manual method of photogrammetric measurement used in this research may be found in Balenović *et al. (4)*.

In brief, the first part of photogrammetric measurement and photointerpretation was done in the StereoDraw module. Photogrammetric plots were 'set up' based on the spatial coordinates (x, y) of centers of terrestrial plots recorded by the GPS receiver during terrestrial measurement. The determination of tree species and crown (tree) tops, as well as the crown delineation, was performed for each tree on each plot. Tree species were identified by a photogrammetry expert who had previously undergone training on stands with trees of known species. Species determination was done by visual interpretation based on the general appearance of tree crowns (form, structure and crown texture) and crown colour. Additionally, the findings from previous research *(13, 14, 15, 16, 17)* about the ways of mapping individual tree species on CIR aerial photographs were also helpful. The crown (tree top) of each tree, with its top falling inside the circular plot, was determined and marked by placing a stereo-marker on it and creating a 3D point object with x, y, z coordinates (where z is the height in meters above the sea level). Each point, representing a single tree top, was labeled with a unique code (e.g. 14_B_1 – plot number, tree species (beech), tree number). Finally, the crown area of each tree on the plot was manually delineated, represented by a polygon object and labeled with a unique code. The data collected with the StereoDraw module were recorded and stored in .dxf file format.

- The data from .dxf files were then uploaded as the »trees« layer into the Global Mapper software using the preloaded DEM as a background layer and a reference for obtaining necessary data to calculate the photogrammetric tree height (h_P) and crown area (CA_P). For that purpose, the following steps were taken:
- Selecting the »trees« layer and choosing the command *»Export Vector Data → Export CSV«* for exporting elevation coordinates of tree tops (h_T) into .csv format which is suitable for further processing with the Excel spreadsheet calculator;
- In order to obtain the elevations of the trees' »bottoms« (h_B; i.e. the elevation of the orthogonal projection of tree top points) from the associated tree top points and DEM, the command *»Apply Elevations from Terrain Layers to Selected Points«* was used. The obtained data were then exported into a .csv file;
- The polygons representing tree crowns were selected and the command *»Display Feature Measurements«* was used to show and subsequently export the areas of each polygon representing the orthogonal projection of the tree crown area (CA_P) into .csv format.

Data Processing and Analysis

The data from the terrestrial and photogrammetric measurements were entered into the MS Excell 2007 computer database for partial calculation. For the purpose of comparison between results obtained by different measurement methods, secondary tree species were grouped into other hardwood broadleaves (OHB) and other softwood broadleaves (OSB).

To calculate photogrammetric tree diameters at breast height (DBH_P), regression models built by Balenović *et al. (18)* were used (Table 1). Models were built for the main tree species of the research area using a multiple linear regression analysis with crown diameter (D) and tree height (h) as independent variables:

$$DBH = b_0 + b_1D + b_2h \qquad \text{(I)}$$

TABLE 1

The parameters of regression models for DBH estimation with crown diameter (D) and tree height (h) as independent variables (Balenović et al. (18)).

Species	N	Model, DBH =	R	R^2	SE_m	RMSE (cm)	p_m	Variable	SE_v	t	p_v
Sessile oak	103	–6.85 + 2.68·D + 1.13·h	0.90	0.80	5.09	5.01	< 0.01	D	0.21	12.50	< 0.01
								h	0.14	8.31	< 0.01
Common beech	103	–5.02 + 3.49·D + 0.73·h	0.96	0.92	4.16	4.10	< 0.01	D	0.19	18.04	< 0.01
								h	0.12	6.22	< 0.01
Common hornbeam	127	–3.80 + 2.82·D + 0.77·h	0.89	0.79	3.28	3.24	< 0.01	D	0.21	13.14	< 0.01
								h	0.09	8.85	< 0.01
Black alder	50	–7.98 + 3.19·D + 1.17·h	0.89	0.79	4.13	4.00	< 0.01	D	0.77	4.15	< 0.01
								h	0.20	5.83	< 0.01

N – number of trees in a sample, R – coefficient of correlation, R^2 – coefficient of determination, SE_m – standard error of model, RMSE – Root mean square error of model, p_m – p value of model, SE_v – standard error of variables, t – t value of variables, p_v – p value of variables where b_0 is the regression constant, b_1 and b_2 regression coefficients, h the terrestrially measured tree height, D the crown diameter calculated as the arithmetic mean from two terrestrially measured, mutually perpendicular diameters of the visible part of the crown, that is, two crown diameters vertically projected to the ground. Besides the aforementioned variables and for the purposes of model making, two perpendicular DBH were measured on trees in the terrestrial measurement sample, in order to calculate the arithmetic mean of the DBH, used in the regression analysis.

The obtained models were used also for the DBH estimation of the secondary tree species. To estimate the DBH of trees grouped in OHB, the estimation model for the Common hornbeam was used, while DBH of trees grouped in OSB were estimated by the Black alder model.

In order to estimate the photogrammetric diameter at breast height (DBH_P) using the equation (I), the photogrametrically estimated tree height (h_P) and crown diameter (D_P) were calculated for each tree on each plot.

The photogrammetric height (h_P) of each tree on each plot was calculated as:

$$h_P = h_T - h_B \quad \text{(II).}$$

The photogrammetric crown diameter (D_P) was calculated by applying the formula for circle surface area from the photogrammetrically measured crown surface area (CA_P):

$$D_p = \sqrt{\frac{CA_p}{\pi}} \times 2 \quad \text{(III).}$$

For purposes of statistical processing and data comparison, the arithmetic means of DBH for each plot were calculated, estimated by the terrestrial ($\overline{\mathrm{DBH}}_{T-\mathrm{pl}}$) and photogrammetric measurement on digital aerial images of GSD 30 cm ($\overline{\mathrm{DBH}}_{P30-\mathrm{pl}}$) and of GSD 10 cm ($\overline{\mathrm{DBH}}_{P10-\mathrm{pl}}$). Also, the arithmetic means of DBH for each subcompartment estimated by different methods were calculated: the terrestrial ($\overline{\mathrm{DBH}}_T$), and photogrammetric measurements on digital aerial images of GSD 30 cm ($\overline{\mathrm{DBH}}_{P30}$) and of GSD 10 cm ($\overline{\mathrm{DBH}}_{P10}$).

The statistical data processing was done using the program package STATISTICA 7.1 (*19*), with the 5% significance level taken as statistically significant. The differences in the arithmetic means of DBH of the plots, estimated by various methods, were tested by analyzing the variance of repeated measures (rANOVA) (*21*) for each subcompartment. Since rANOVA determined the existence of statistically significant differences between the results of DBH estimated by different methods, a *post hoc* test (Tukey HSD) was done in order to determine which methods produced statistically significant differences.

In order to evaluate the accuracy of photogrammetrically estimated DBH, deviations (Δ) of photogrammetrically estimated arithmetic means of DBH, in relation to the results obtained by terrestrial measurements, were calculated for each subcompartment. Thus, for aerial images of GSD 10 cm:

$$\Delta_{10} = \overline{\mathrm{DBH}}_T - \overline{\mathrm{DBH}}_{P10} \quad \text{(IV);}$$

and for aerial images of GSD 30 cm:

$$\Delta_{30} = \overline{\mathrm{DBH}}_T - \overline{\mathrm{DBH}}_{P30} \quad \text{(V).}$$

RESULTS WITH DISCUSSION

The terrestrial measurement on 183 sampling plots within 14 subcompartments provided DBH for total of 3135 trees. On the same sampling plots the photogrammetric measurement on digital aerial images of GSD 10 cm provided heights and delineated crowns of 2888 trees, while the photogrammetric measurement on aerial images of GSD 30 cm measured 2610 trees. As expected, the photogrammetric measurement produced a lesser number of trees, with underestimation greater on aerial images of the lower spatial resolution (GSD 30 cm). The underestimation in the number of trees when using photogrammetric measurement is usually caused by (a) the so-called 'clumped crowns', when two or more trees are interpreted as one, (b) the overshadowing on aerial images so some trees are not visible, and c) the overlapping preventing measurements (*3*).

The test (rANOVA) results of the differences between the subcompartments' arithmetic mean DBH estimated by different methods are shown in Table 2.

The testing determined statistically significant differences (Table 2, row »Method«) between the arithmetic means of the subcompartments' DBH estimated by terrestrial ($\overline{\mathrm{DBH}}_T$), and photogrammetric measurements on digital aerial images of GSD 10 cm ($\overline{\mathrm{DBH}}_{P10}$) and GSD 30 cm ($\overline{\mathrm{DBH}}_{P30}$). The Tukey HSD *post-hoc* test determined statistically significant differences between all measurement methods (Table 3).

TABLE 2

The rANOVA test of subcompartments' arithmetic mean DBH estimated by terrestrial ($\overline{\mathrm{DBH}}_T$) and photogrammetric measurement ($\overline{\mathrm{DBH}}_{P10}$, $\overline{\mathrm{DBH}}_{P30}$).

Source of variability	Sum of squares	Deegres of freedom	Mean square	F value	p value
Method	855.2	2	427.6	38.327	< 0.0001
Method*Subcompartment	77.6	26	3.0	0.267	0.9999
Error	3547.8	318	11.2		

TABLE 3

The Tukey HSD *post-hoc* test of differences between the subcompartments' arithmetic mean DBH estimated by terrestrial and photogrammetric measurement (GSD 10 cm and GSD 30 cm).

Error: Within MS = 11.157, df = 318.00			
Method	{1}	{2}	{3}
	20.194	22.518	23.603
Terrestrial measurement		0.000022	0.000022
Photogrammetric measurement GSD 10 cm	0.000022		0.003964
Photogrammetric measurement GSD 30 cm	0.000022	0.003964	

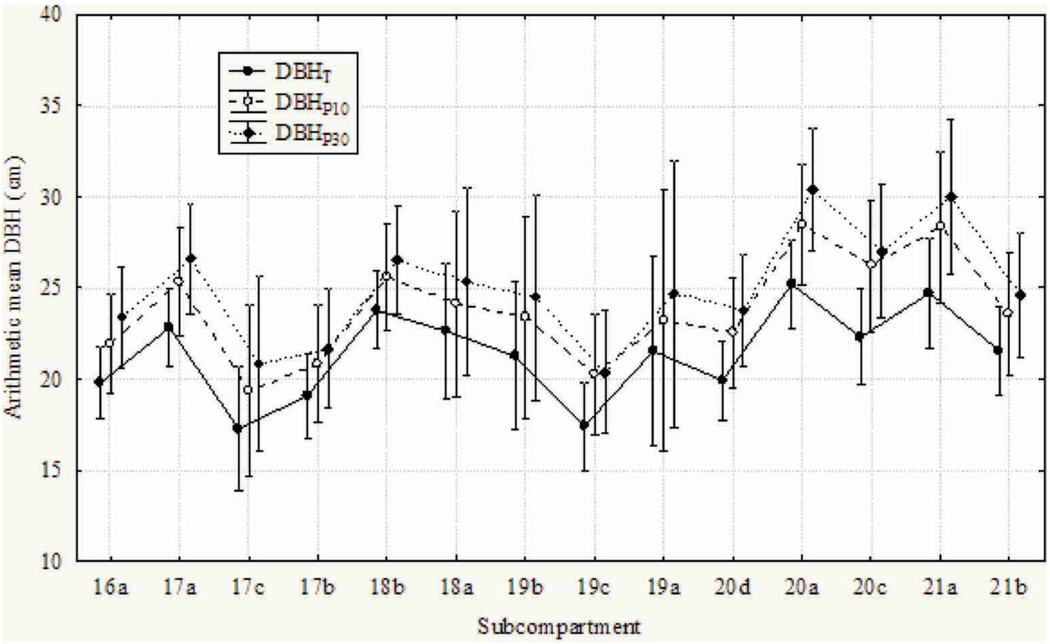

Figure 2. *The subcompartments' arithmetic mean DBH estimated by terrestrial and photogrammetric measurements (GSD 10 cm, GSD 30 cm). The dots are the estimated arithmetic mean DBHs and vertical lines present 95% confidence intervals.*

Furthermore, the rANOVA test results show that there are no statistically significant differences between the DBH estimation 'trend' by different methods (Table 2, row »Method*Subcompartment«), which is also evident from Figure 2 and Table 4. In other words, the constant overestimation of photogrammetrically estimated DBH in relation to terrestrial measurements is evident.

The errors of the photogrammetric estimation of the subcompartments' arithmetic mean DBH in relation to the terrestrial measurements are given through deviations (Δ_{10}, Δ_{30}), i.e., the differences which are shown in Table 4. In relation to the arithmetic means of DBH done by terrestrial measurement, the photogrammetric measurement on digital aerial images GSD 10 cm (Δ_{10}) show a constant overestimation of DBH in the range of 1.45 cm to 3.90 cm, i.e., in average 2.41 cm (6.4 – 17.5%. in average 11.3%). The photogrammetric measurement of aerial images of GSD 30 cm (Δ_{30}) shows an even greater overestimation of DBH in the range of 2.55 cm to 5.29 cm, i.e., in average 3.59 cm (11.7 – 21.4%. in average 16.8%).

'The pattern of constant overestimation' of DBH using the photogrammetric measurement in relation to the terrestrial measurement was noted for all subcompartments, with overestimation lesser on aerial images of GSD 10 cm and greater on aerial images of GSD 30 cm. Accordingly, we may conclude that the application of digital aerial images of lower spatial resolutions increases the error in estimating DBH. Naturally, the main reason is the lesser visibility of details on images of lower spatial resolutions, mainly the crown edges of individual trees. Hence, two or more so-called 'clumped' crowns of neighboring trees are often interpreted as a single tree crown, which leads to the overestimation of DBH. Therefore, the 'clumped' crowns cause an underestimated number of trees on one hand, and overestimated DBH on the other. If we compare the diameter distributions of all measurements (Figure 3), the greatest underestimation in the number of trees done by

TABLE 4

The subcompartments' arithmetic mean DBH estimated by terrestrial ($\overline{DBH}_T$) and photogrammetric measurement ($\overline{DBH}_{P10}$, $\overline{DBH}_{P30}$) with errors of photogrammetric measurements presented through deviation from terrestrial measurement (Δ_{10} i Δ_{30}).

Subcom-partment	Management class	$\overline{DBH}_T$	$\overline{DBH}_{P10}$	$\overline{DBH}_{P30}$	Δ_{10}		Δ_{30}	
		cm	cm	cm	cm	%	cm	%
16a	Common beech	19.79	21.91	23.38	2.12	10.7	3.59	18.1
17a	Common beech	22.83	25.33	26.57	2.50	11.0	3.74	16.4
17b	Common beech	19.10	20.87	21.65	1.77	9.3	2.55	13.4
17c	Common hornbeam	17.26	19.35	20.86	2.09	12.1	3.60	20.9
18a	Sessile oak	22.64	24.09	25.32	1.45	6.4	2.68	11.8
18b	Common beech	23.76	25.56	26.55	1.80	7.6	2.79	11.7
19a	Sessile oak	21.54	23.23	24.66	1.69	7.8	3.12	14.5
19b	Common beech	21.26	23.36	24.46	2.09	9.8	3.20	15.0
19c	Common hornbeam	17.41	20.25	20.39	2.84	16.3	2.98	17.1
20a	Sessile oak	25.20	28.47	30.38	3.27	13.0	5.18	20.6
20c	Common beech	22.32	26.22	27.01	3.90	17.5	4.70	21.0
20d	Common hornbeam	19.93	22.56	23.76	2.63	13.2	3.83	19.2
21a	Sessile oak	24.71	28.33	30.00	3.62	14.6	5.29	21.4
21b	Common hornbeam	21.57	23.58	24.60	2.00	9.3	3.03	14.0
Average					2.41	11.3	3.59	16.8

the photogrammetric measurement is evident in the lowest diameter class (III) with the mean of 12.5 cm. Such results were expected, because this diameter class is usually consisted of trees from understory level of a stand, often impossible to register on aerial images. Furthermore, both photogrammetric measurements show overestimation in the number of trees from the IV (17.5 cm) to VII (32.5 cm) diameter classes. The assumption is that due to the »clumping« of a certain number of crowns in these diameter classes, trees partially »migrate« from lower to higher diameter classes, that is, from III to IV, from IV to V, and so on.

The obtained results are in accordance with the results of previous research (*10, 14, 21*). For example, Tomašegović (*10*) quotes that the mean error in determining DBH of the mean stands' tree is between ±2 to ±6 cm if the image scale is larger than 1:20000.

Although it seems that the results of this research (Δ_{10} = 1.45 – 3.90 cm; Δ_{30} = 2.55 – 5.29 cm) do not significantly improve the accuracy of estimating DBH using the method of photogrammetric measurement, one should bear in mind that the research was, however, done in heterogeneous, multi-aged stands of privately-owned forests with no timely management activities in the past. This certainly means more difficult photogrammetric measurement and photointerpretation of these stands. Furthermore, due to the heterogenic structure of stands, it is questionable to what extent independent variables (crown diameter, tree height) of the used regression models for DBH estimation describe all the structural features of trees, that is, explain the variability of DBH for all measured trees (Table 1). Therefore, we may suppose that the photogrammetric measurement method on digital aerial images of high spatial resolutions may obtain satisfying results in managed state-owned forests, primarily in even-aged forests and forest cultures with a more regular distribution of trees, more regular crown shapes and significantly lesser share of trees in understory level.

Considering the obtained results that, after applying aerial images of GSD 30 cm, show slightly larger deviations of 5 cm in just two subcompartments, which is the width of a diameter class, the used method may find practical use in forests of less intensive management

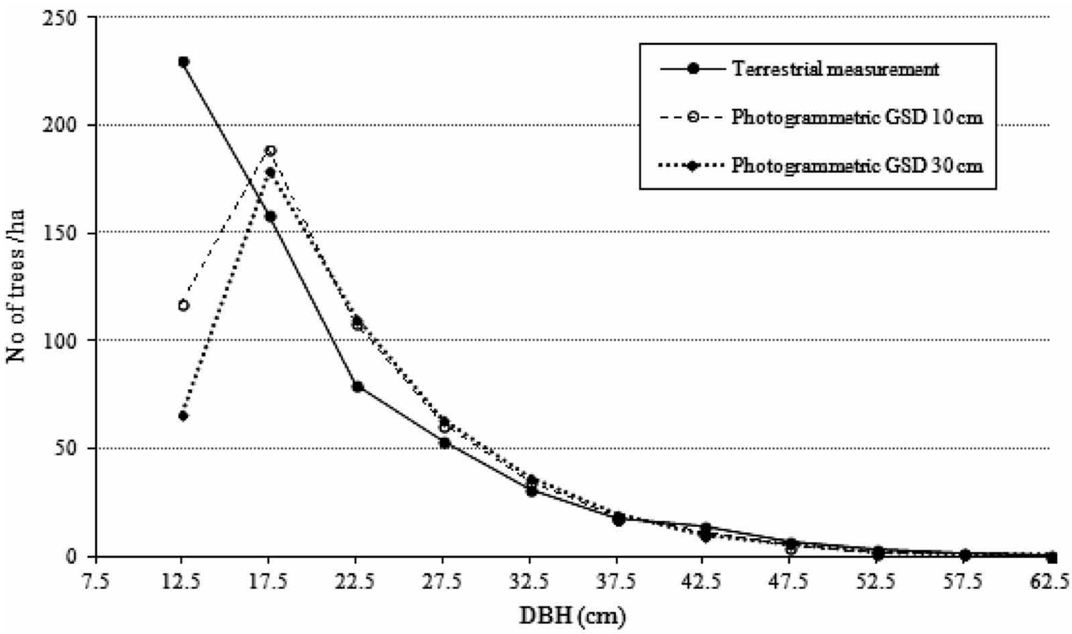

Figure 3. *The diameter distributions of whole research area obtained by terrestrial and photogrammetric measurement (GSD 10 cm, GSD 30 cm).*

(e.g. protective forests, forests with special purposes, privately-owned forests). Over the last five years privately-owned forests have been more intensively managed through management plans. For most of private forests this is the first time management; areas have been partially neglected, the terrain is inapproachable or difficult, forest stands are small or scattered (private forest lands cartulary units). All of the above significantly burdens field work, that is, increases costs and time necessary for field work (*22*). On the other hand, the intensity of management and applying regulations in the given management plans for private forests is very questionable. Accordingly, the purpose of the data collected in this way is also questionable. In their research Božić and Čavlović (*23*) claim the necessity to consider the cost of collecting data and their utilization value when managing privately-owned forests. According to them, the usefulness or the utilization value of such data in conditions of the expected weak implementation of management plans would be realized through the approach of less intensive forest measurement. Therefore, further research needs to examine the advisability of applying the manual method of digital photogrammetry when estimating other structural elements of stands, primarily their volume, but also when estimating elements of individual trees in privately-owned forests, as well as in state-owned (intensively managed) forests. Also, besides the accuracy of obtained results, the cost component of such application should be examined.

In relation to the classic photogrammetric measurement (analogue photogrammetry), the manual method of digital photogrammetry used in this research has many advantages. A series of photogrammetric processes is fully or partially automated, such as DTM or DEM production. The used PHOTOMOD Lite software enables creating projects in stereomodel of up to 10 images, while the commercial software version creates projects from an indefinite number of images. This significantly eases the manipulation with aerial images and reduces the interpreter's fatigue. Applying DEM enabled readings of the elevation above the sea level (tree 'bottom') in dense, clumped stands where the ground beside the trees is not visible, and that was the main disadvantage of analogue and analytical photogrammetry when measuring tree height. Aerial images of high spatial resolutions enable precise determination of tree tops, as well as crown edges. Measurement data, that is, vector objects remain permanently recorded in digital form which provides options for multiple measurement control. The collected vector objects are suitable for uploading and processing in other GIS software.

CONCLUSIONS

For the estimation of the arithmetic mean DBH of subcompartments the manual method of digital photogrammetry was used, which included the application of digital aerial images of high spatial resolutions (GSD 30 cm and GSD 10 cm), the application of DEM and DPW with the appropriate software (PHOTOMOD StereoDraw, Global Mapper). Obtained results were compared to results of classical terrestrial measurement. Based on this research, the following may be concluded:

The rANOVA testing determined statistically significant differences between the results obtained by terrestrial and photogrammetric measurements (GSD 10 cm and GSD 30 cm) of the subcompartments' arithmetic mean DBH. Subsequently, the Tukey HSD *post-hoc* test determined statistically significant differences between results of all measurement methods.

Furthermore, the testing determined no statistically significant differences between the 'trends' of estimating DBH by different methods. In other words, the 'pattern of constant overestimation' of DBH obtained by photogrammetric measurement in relation to terrestrial measurement was noted for all subcompartments. The value of overestimation was lesser in case of aerial images of GSD 10 cm (1.45 – 3.90 cm), and greater in case of aerial images of GSD 30 cm (2.55 – 5.29 cm). Therefore, it is obvius that the application of aerial images of lower spatial resolutions increases the error in estimating DBH.

As far as accuracy is concerned, the obtained results concur with the results of previous research. However, unlike previous research, this research was conductet in privately-owned forests of a rather heterogeneous structure, with no timely management actions in the past, which means a more demanding photogrammetric measurement and photointerpretation. Furthermore, due to the heterogenic structure of stands, it is questionable to what extent independent variables (crown diameter, tree height) of the used regression models for the estimation of DBH explain the variability of DBH of all measured trees. Therefore, we can assume that the photogrammetric measurement method on digital aerial images of high spatial resolutions may obtain satisfying results in managed forests, primarily in even-aged stands and forest cultures with a more regular distribution of trees, regular crown shapes and significantly lesser share of overlapping. Also, the applied method may find practical use in primarily in forests of less intensive management (e.g. protective forests, forests with special purposes, privately-owned forests) where a compromise between data collection costs and utilization value is necessary.

Therefore, further research is necessary to examine the results and the commercial validation of applying the manual method of digital photogrammetry when estimating other structural elements, primarily the volume, but also other elements of individual trees, both in privately-owned forests, as well as in state-owned (intensively managed) forests.

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