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SELECTION OF OPTIMAL TREE TOP DETECTION PARAMETERS IN A CONTEXT OF EFFECTIVE FOREST MANAGEMENT

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ABSTRACT: In the process of tree stand parameter estimation based on data from airborne laser scanning ALS, the detection of a single tree is an important starting point.
The aim of this work is to develop optimal values of parameters in the process of detection of tops and segmentation of stands on the basis of ALS data analysis. The research was carried out on the basis of ALS data from raids carried out in 2007 and 2017 on a fragment of the Zajma forest district in the Zednia forest inspectorate (north-eastern Poland). Parameters analyzed included: Ground Sampling Distance [m], the level of smoothing of the Canopy Height Model (CHM) with the Gaussian filter (the size of the moving window, the value of standard deviation), the filtration of the output point cloud, as well as the application of the additional interpolation algorithm CHM based on the analysis of raster cells neighborhood.
The research has shown that it is possible to indicate detection parameters that ensure a very high correlation between the number of automatically detected treetops and the number of trunks found during fieldwork. Importantly, the optimal detection parameters developed for remote-sensing materials from the years 2007 and 2017 differ slightly, which ensures generally high accuracy of ALS data and the possibility of implementing the values of these parameters in other research objects.

KEY WORDS: ALS, forest inventory, treetop detections, and crown segmentation parameters

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Introduction

Forest management as a field of science deals with the knowledge of environmental and economic features of forest production – combining the achievements and knowledge of forest management, forest protection, and use as well as geomatics, nowadays strongly supported by remote sensing. In the area of practical applications, forest management deals with the organization of the production process in a forest holding and the development of forms that ensure a constant increase in the productivity and social utility of forests. In the area of practical applications, forest management deals with the organization of the production process in a forest holding and the development of forms that ensure a constant increase in the productivity and social utility of forests. Forest management serves to improve the technique of organizing production over usually ten-year periods and includes it synthetically for each forest inspectorate in a project for all economic activities, known as the Forest Management Plan (FMP) (Molenda, 1980).

The key issue in the management planning process, and especially in forecasting the development of resources in a very long period of time, is the accuracy of estimation of several dozen stand parameters, and among them, the most important – forest stand volume and their growth in the period under study. The accuracy of their determination directly influences the results of modeling the development of resources in the planning period and thus the possibility of using forests in the scope safe for their sustainability (Dawidziuk, Zajączkowski, 2013). The current inventory of forest resources supported by remote-sensing techniques is based on the use of traditional methods based on instrumental measurements and visual estimation aimed at collecting information on each stand (stand description) in the basic spatial unit, which is the forest division (or subdivision). In this context, particular importance shall be attached to the obtaining of as precise data as possible on stand volume in any spatial unit e.g. division or forest area (growing stock) or unit of area e.g. 1 ha (volume). Especially in recent years, in the area of instrumental methods of measuring environmental features, technological progress provides modern tools enabling remote and very fast measurement of many features of forest phytocenosis. These include Airborne Laser Scanning (ALS), which makes it possible to collect information in a short time and for very vast areas, which corresponds to the production conditions in the State Forests holding SF and the needs of forest management in Poland. The confirmation of this fact is reflected in the national (Zawiła-Niedźwiecki et al., 2008; Myszkowski, Ksepko, 2010; Zasada et al., 2011; Stereńczak et al., 2018) and foreign literature (Hyyppä et al., 2006; Vastaranta et al., 2011; Yao et al., 2012; Hayashi et al., 2015). At the same time, the availability of tools for data acquisition, analysis and ready-made sets of data collected for other purposes (IT System of the Country's Protection against extreme hazards, ISOK) is constantly improving on the domestic market. In the current Forest Management Manual (IUL, 2012) there are no provisions regulating the possibility and method of using ALS data for the estimation of selected stand features. Therefore, it is necessary to conduct intensive research on the possibility of using the data obtained remotely in the forest practice in Poland, which allows to optimize the economic aspect of forest management work and to conclude on the impact of the use of objective instrumental data on the planning of human activity and the quality of functioning of the forest environment in the country.

Precise determination of selected stand features allows for more precise planning of their use or protection. This is important for all strategic decisions related to forest environment management in Poland and worldwide, including those directly related to their economic dimensions. The aim of this work is to develop optimal values of parameters in the process of detection of tops and segmentation of stands on the basis of ALS data analysis.

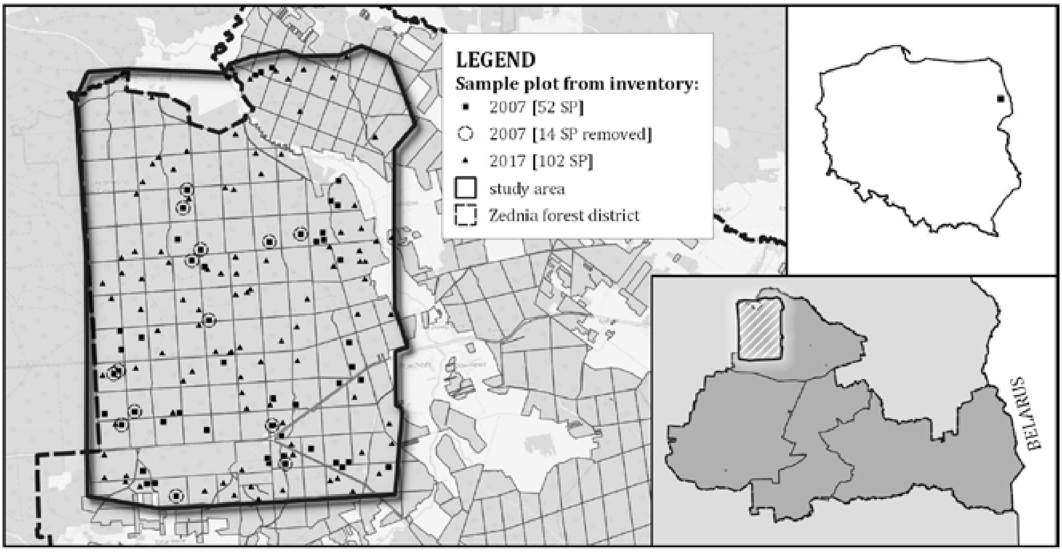

Figure 1. The location of the studied area and location of sample circular surfaces inventoried during field works of stages I and II of the experiment

Source: author's own elaboration based on Open Street Data.

Study area

The research was carried out on a selected fragment of the Zajma forest district in the Zednia forest inspectorate, located in north-eastern Poland and within the range of the Regional Directorate of SF in Bialystok. The research area is located within the range of a large forest complex of the Knyszyn Forest and covers a total area of 51 km^2, which constitutes more than half of the area of the forest district. The location of the research area against the background of the administrative division of the SF is presented in figure 1 together with the location of sample plots SP from field inventory part of experiment. The characterized area was the subject of a 2-stage scientific experiment aimed at determining the possibility of remote acquisition of data on forest environment, including information on the growing stock volume and growth of stands. In 2007 the first stage of the experiment was carried out, which was then continued in 2017 (stage II).

Research methods

The study used remote sensing materials and other spatial data, as well as data collected during the field inventory works carried out within the two stages of the project. The main source material in this analysis were ALS point acquired in 2007 and 2017 (table 1). The remote data acquisition was carried out twice at an interval of ten years and there was a significant technological progress within this period of time, but result point clouds are characterized by similar high density. However point cloud density of remote-sensing material used can have reflection in differences in optimal values of tree detection parameters.

Table 1. The comparison of selected characteristics of ALS data from 2007 and 2017

Feature	Point cloud – 2007	Point cloud – 2017
Flight date	August 2007	August 2017
Scanner model	Optech ALTM 3100	Riegl LMS-Q680i
Plane model	Cessna 404	Cessna 402
Number of registered returns	820,97 mln pts	1178,27 mln pts
Scanning density	14,08 pts/m2	19,64 pts/m2
Number of registered returns	4 discrete returns	Full-waveform registration

Source: author's own work.

In both missions, simultaneously with scanning, aerial photos in the visible and spectro-zone range were obtained, from which orthophoto maps in CIR (ColorInfraRed) and RGB (RedGreenBlue) compositions were generated. The intensity of laser beam reflection (intensity channel) was also recorded and RGB values were assigned to points in the point cloud on the basis of CIR photos. The obtained point clouds, apart from the different character of the return wave recording, also differ in scanning density (table 1). The raw LAS data has been classified using Terrascan software from TerraSolid package in accordance with the ASPRS standard. Apart from remote sensing materials, the study also used data collected in the SILP SF system (LAS module), as well as data from a soil and settlement study by BfFMaG in Bialystok concerning trophic differentiation of habitats and forest soils of the studied area.

In the context of research carried out in this work, reference data collected on SPs during the fieldwork of stages I and II of the experiment are the carrier of, particularly important information. In this respect, a wide range of information has been collected on individual trees located within circular SPs, such as the location of trees (x, y coordinates), species, diameter at breast height DBH, height relative to the ground, height of the base of the crown, visibility, health and other additional information. Among these key parameters for the survey are: GPS stabilized geodetic location of the plot center and coordinates of individual tree trunks, their species affiliation, visibility of the tree top, as well as natural disturbances observed on the sample plot, i.e. tree crowns with multiple tops, which may result in an incorrect number of trees detected by the algorithm on the SP.

In the first stage of the experiment (2007), a total of 52 circular SP with a radius of r=20 m (n=7) and r=25m (n=45) were established. On 47 Sps the dominant species was the pine, while on 5 SPs the dominant component was the spruce. The determinants for the selection of the size of SP were the vertical structure and age of the stand, as well as the possibility of the measuring equipment used, based on the use of the ultrasonic signal. On the analyzed 52 plots a total of 5485 trees were measured, of which 4268 were a component of the upper floor (trees with visible tops) (Myszkowski et al., 2009).

In the period from January to the end of March 2018, field works of stage II of the experiment were carried out. The SPs established during the stage I of the project have been revisited (38 z 52 SPs on which no treatments, e.g. thinning, were carried out in the last 10 years). Pine pine in subclasses IIb to VIIa was the dominant species on 37 SPs, while spruce in the age of VIIa dominated on 1 SP. Apart from the repeated 38 SPs from of stage I of the experiment, additional 102 SPs were selected. The main criteria in the selection of their location were the prevailing species and its bonitation (as an indicator of the use of trophic properties of habitats). The aim was to locate circular areas in groups of the most numerous stands, characteristic for the Zajma forest district in the Zednia forest inspectorate. Among these areas, the most numerous representations are the areas where the dominant species was pine (53 SPs). The next position is taken by SP with the dominant spruce (24 SPs). The remaining 25 SPs included stands not included in the stage I of the project (with black alde., birch and oak.), including stands typically for hydrogenic habitats (alder trees of I and II class of bonitation). In stage II a reduced radius of SP was adopted (in relation to stage I). The radius was calculated according to the methodology contained in the IUL, by one age class upwards than according to SILP-LAS data.

Out of 38 SPs from the first stage of the experiment with a radius of 20-25 m, a total of 5149 trees were inventoried, of which 929 (18.04%) were removed as a result of economic operations and natural phenomena, while 964 objects (18.72%) are trees which in the last decade reached the minimum DBH of 70 mm, adopted in the IUL (ingrowth). Out of the 4220 trees of the 38 SPs of stage I, 2699 (63,95%) were classified as trees with a visible top. On 102 sample plots established additionally in the second stage of the experiment, a total of 2357 trees were inventoried, of which the most numerous group was spruce in the number of 1159 occurrences (49.17%) and pine in the number of 682 trees (28.94%). In this case of trees with full top visibility, 1425 trees were recorded, which constitutes 60.46% of all observations. To sum up, the total number of trees with top visible in remote sensing, on 140 circular plots of the first stage was 4124 (62.70% of trees).

Selection of optimal (closest to field observations) parameters for tree crown segmentation and tree top detection process depends on selected features of stands, which include the dominant species and its age class. Taking into account the characteristics of data collected during the fieldwork of stages I and II of the experiment, it was decided to list 7 species-age categories for which the optimal range of detection parameters will be indicated:

- category 1 a – pine in age classes up to IIIb (< 60 years),
- category 1 b – pine trees in age classes IV-V (61-100 years),
- category 1 c – pine in age classes VI and above (>100 years),
- category 2 a – spruce in age classes up to IV (< 80 years),
- category 2 b – spruce in age classes V and above (>80 years),
- category 3 a – deciduous species in age classes up to IV (< 80 years),
- category 3 b – deciduous species of age classes V and above (>80 years).

This automatic procedure was performed within 52 SPs of stage I with the use of the point cloud obtained in 2007, while the remote-sensing material from 2017 became the basis for the implementation of the process within 140 SPs of stage II, in accordance with the diagram in figure 2. The selection of optimal parameters consisted in consideration of the influence of various conditions having a potential impact on the correctness of tree crown segmentation and tree top detection, to which they were included: Ground Sampling Distance GSD [0.3-0.7 m, with a pitch of 0.05 m], the level of smoothing of the Canopy Height Model (CHM) with the Gaussian filter depending on the size of the moving window (1×1, 2×2, 3×3, 4×4 pixels) ang the standard deviation value (1, 2, 3), the filtration of the output point cloud (the filtration of single or first of many returns or all returns), as well as the conducting additional 2-stage interpolation of empty cells within the CHM on the basis of raster cell neighborhood analysis. In the case of Gauss filter smoothing, option 0, assuming no smoothing, was also considered.

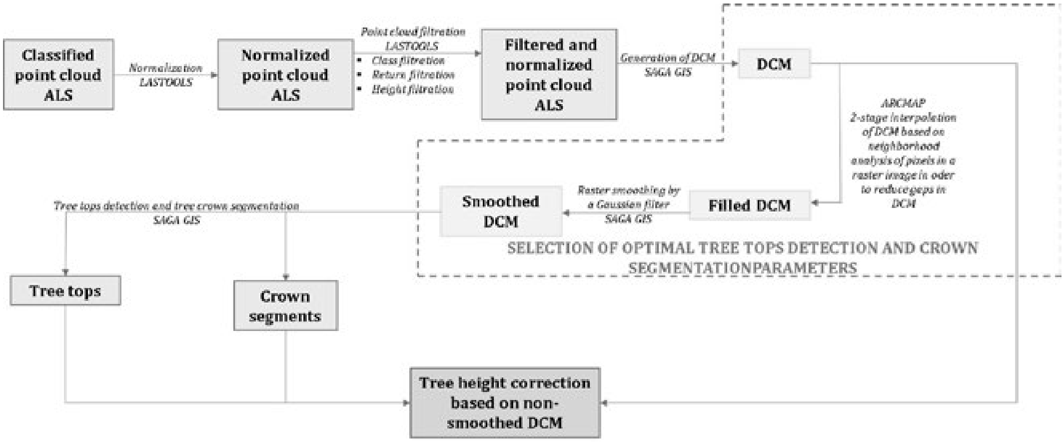

Figure 2. The flow chart of tree tops detection and tree crown segmentation with input data and with the indication of calculation environments

Source: author's own work.

The procedure considered a total of 351 parameter configurations within each species-age category, in three variants:

- Variant I – consideration of all point returns with the use of single empty cell filling within CHM.
- Variant II – consideration of single or first of many point returns with the use of a proprietary algorithm of 2-stage interpolation of empty cells within CHM on the basis of pixel neighborhood analysis.
- Variant III – consideration of all point returns with the use of the proprietary algorithm of 2-stage interpolation of empty cells within CHM on the basis of neighborhood analysis.

The starting point for this analysis was the extraction from a point cloud within the range of SPs. The point cloud was cut with polygons representing circular surfaces with a radius of 1.5 times the radius of individual SPs. This approach was aimed at minimizing the boundary effect and avoiding errors in the segmentation process in the boundary zone of SPs. Remote sensing material prepared in this way was subjected to the process of normalization of height in relation to the ground surface. The calculations were performed directly on the input point cloud in RapidLasso's LASTOOLS software, which allowed the transformation of above sea level coordinates to relative altitudes (relative to the ground surface, the height of which was reduced to 0) (figure 3).

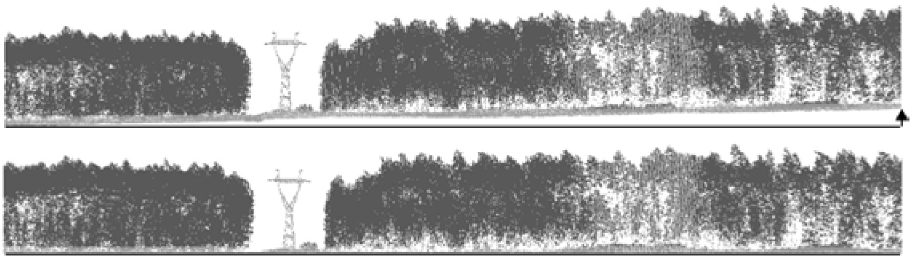

Figure 3. The cross-section through point cloud before (top) and after normalization process

Source: author's own work.

In the next step, the normalized point cloud was filtered in order to optimize the tree detection process by removing the redundant output data for further calculations. It was assumed that the threshold height for distinguishing the tree layer from the lower vegetation layer is 2 m. The remaining points were removed from the cloud.

The next stage was the construction of CHM as a result of the conversion of points height in the cloud to a raster with a spatial resolution appropriate for the considered species-age tree stand category. The resulting picture element value was assigned a relative altitude value based on the point representing the maximum height. In such CHM, empty cells may appear (without altitude value) in the absence of at least one point return. This phenomenon occurs in areas where the point cloud is characterized by a lower density parameter and in stands with visible defoliation due to pathogenic factors. In this paper, two ways of solving this problem have been applied. The first one is to fill single empty cells with the average height of its closest 8 neighbors. The second method is the application of a computational model developed in the Model Builder ESRI environment for the needs of the presented method, consisting of 2-stage interpolation of CHM on the basis of an in-depth analysis of the neighborhood (figure 4). The main assumption in the construction of the calculation model was to avoid the phenomenon of artificial "growth" of tree crowns in the edge zone of the crown. This is particularly important in the case of the later use of the developed crown models for the analysis of gaps in stands or in the calculation of tree crown biomass for the purpose of forest fire protection (Inan et al., 2017).

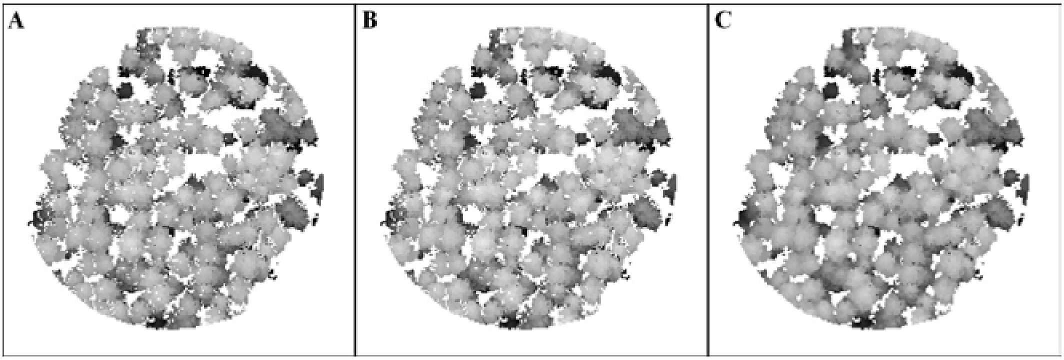

Figure 4. The comparison of CHM on a selected surface: A – non-interpolated model; B – CHM with closed single cells; CHM – subject to 2-stage interpolation

Source: author's own work.

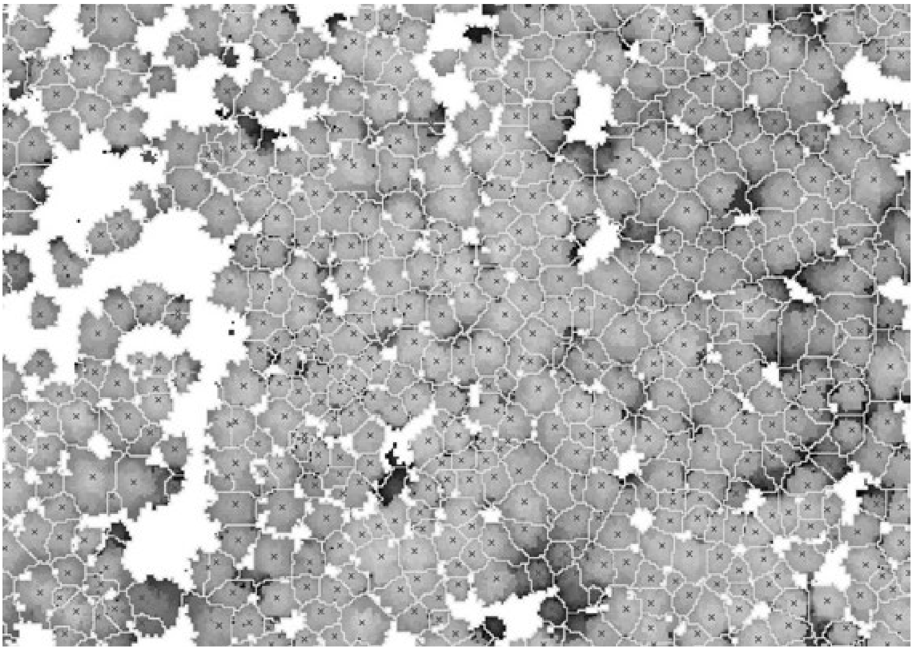

Figure 5. The result of the automatic process of crown segmentation and detection of tops in stands with common pine in age class (IV-V)

Source: author's own work.

Crown models without empty cells were smoothed with a Gaussian filter. They were then subjected to the process of tree crown segmentation and tree tops detection with the use of an inverted watershed algorithm. The result of this operation is a vector layer of local extremes of the height of the crowns model (identified with tree tops) and a raster image presenting the range of crowns. At the final stage, on the basis of the CHM generated directly from the filtered and normalized point cloud, the height values assigned to the tops of trees from the smoothed CHM were corrected. The aim was to avoid underestimation of the height of individual trees in further analyses, e.g. related to estimating the growing stand volume. The result of an exemplary, automatic tree detection and crown segmentation in a stand with pine trees in age classes 60-100 years is presented in figure 5.

Results of the research

The selection of optimal parameters of tree crown segmentation and single tree detection was carried out through comparative analysis of the number of detected treetops in relation to the actual number of trunks in the field inventory. The criteria for the selection of optimal parameters were: the ratio of the number of tree tops identified remotely to the number of tree trunks with a visible top within the range of the sample plots [%], as well as the coefficient of determination of the model of relations between these values within each of the analyzed species-age categories. The analysis assumes that the optimal solution will be characterized by no more than 10% absolute detectability of the number of trees.

Analyzing the results of the automatic detection process on the basis of remote sensing data from stage I of the experiment, where only categories representing coniferous stands were analyzed (categories 1 a, 1 b, 1 c, 2 b), it can be concluded that 15.81% of the detection variants are optimal solutions. The highest number of optimal occurrences was found in categories 1 b (23.08%) and 2 b (17.66%), while the lowest number of such solutions was found in category 1 c (9.40%). Considering the variants including initial filtration of the point cloud and additional interpolation of the crown model, it can be stated that in the case of stands with the prevailing pine trees, automatic detection was the most effective when using variants III (38.13%) and II (36.88%). In relation to stands with the prevailing spruce, the highest number of occurrences of the optimal solution was recorded with the use of variant II (41.94%).

In addition, it can be concluded from the results obtained that, in general, the highest number of optimal solutions occurs in the pixel size range of

0.40-0.55 m (figure 6), although these relations are less pronounced than in the case of stage II data. In the case of the smoothing level with the Gaussian filter, there is a clear decrease in the number of optimal solutions as the size of the smoothing window increases. This trend is particularly noticeable in the case of pine in category 1 a, where optimal solutions are only found in the size range of the smoothing window 1×1 and 2×2 (figure 7).

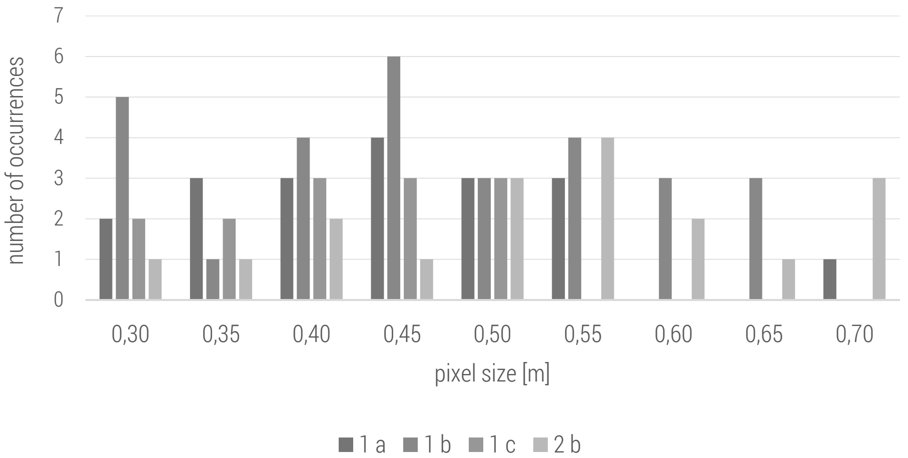

Figure 6. The number of occurrences of the optimal solution in particular species-age categories depending on the pixel size based on data from stage I

Source: author's own work.

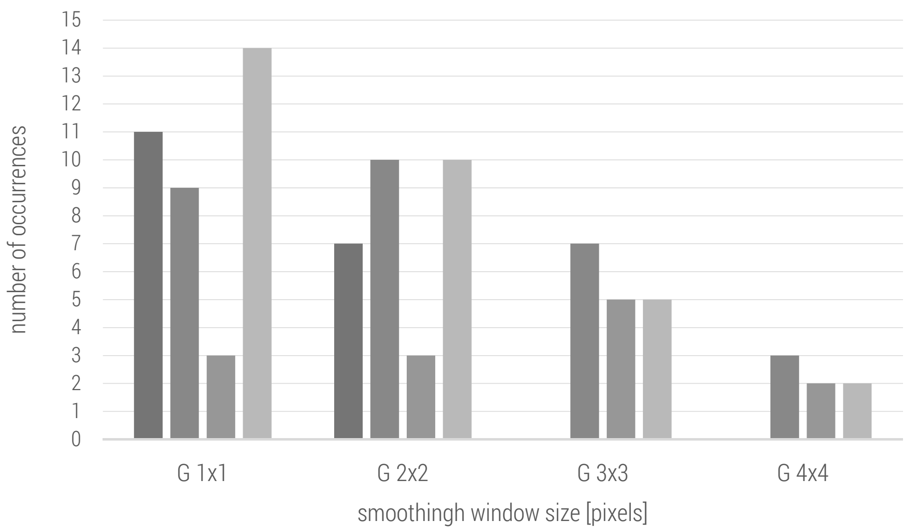

Figure 7. The number of occurrences of the optimal solution in particular species-age categories depending on the smoothing level with the Gaussian filter on the basis of data from stage II

Source: author's own work.

On the basis of the analysis of the results of the segmentation process, carried out on the basis of LiDAR data from stage II of the experiment, it was found that the total number of optimal solutions constitutes 13.31% of all cases. The highest percentage of optimal solution occurrence was recorded in categories 1 b (21.65%) and 3 a (17.09%), while the lowest number of such occurrences was recorded in the case of the category representing younger age classes with the prevailing spruce (category 2 a – 4.84%). On the other hand, comparing three variants related to point cloud output filtration and the application of different approaches to additional interpolation within the CHM, it can be stated that in the context of the applied data, the best results were obtained using the proprietary algorithm of 2-stage CHM interpolation. Of all optimal solutions, 39.14% concern this variant. A large number of occurrences at the level of 34.86% was also noted in the case of the variant assuming no filtration of the reflection character and filling of single empty cells in the crown model. In the case of variant II, assuming filtration of single or first point returns with the use of 2-stage interpolation, 85 optimal solutions (25.99%) were obtained. This can be explained by a lower density of points from which the CHM is built, which results in worse detection results as a result of the presence of empty spaces in the CHM.

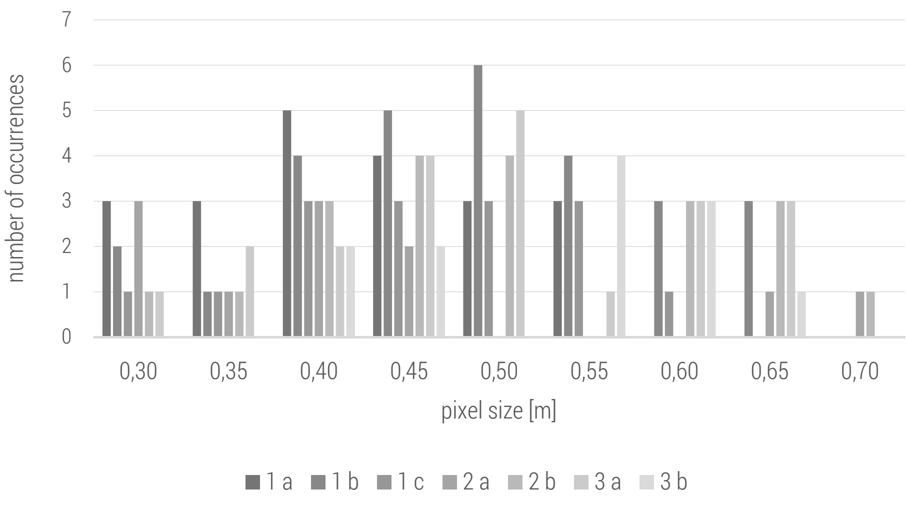

Figure 8. The number of occurrences of an optimal solution in particular species-age categories depending on the pixel size based on data from stage II

Source: author's own work.

Figure 8 presents a comparison of the number of occurrences of the optimal solution in particular species-age categories of the analyzed stands depending on the used pixel size. On the basis of the analysis of the contents presented in this figure, it can be stated that the highest number of optimal solutions occurs in the pixel size range of 0.40-0.55 m, while characteristic relations can be noticed.

Larger pixel sizes (especially in the case of coniferous stands) cause the underestimation of the total number of trees, which is caused by the over-generalization of CHM. On the other hand, pixels in the 0.30-0.35 m range require a high-density point cloud (>25 points/m2), otherwise, these sizes tend to overestimate the results. Another characteristic feature of the presented distribution is the tendency to increase the pixel size with the age of the stand, as well as the fact that in the case of deciduous stands the use of a larger pixel size gives better results (≥0.60 m), while coniferous stands have different characteristics. On the other hand, when analyzing the influence of the smoothing level with the Gaussian filter on the correctness of detection, it can be stated that the variant assuming no smoothing is definitely not applicable, leading to a significant (max. 400%) overestimation of the obtained results. Moreover, a general tendency can be stated that with the increase in the degree of smoothing expressed by the size of the window in pixels, the quality of detection decreases in the case of coniferous stands. The opposite is true for the analysis of deciduous stands in higher age classes (figure 9).

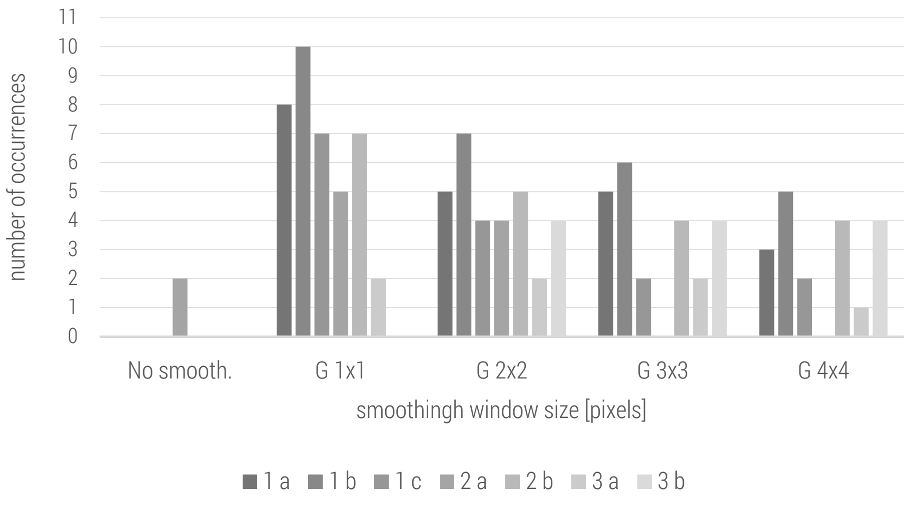

Figure 9. The number of occurrences of the optimal solution in particular species-age categories depending on the degree of smoothing with the Gaussian filter on the basis of data from stage II

Source: author's work.

A total analysis of all variants of automatic detection parameters allowed to indicate proposals for specific sets of parameters on the basis of which the final process of crown segmentation and tree tops detection is the closest to the data obtained directly in the field. When selecting these parameters, apart from the degree of tree detection [%], the values of the determination coefficient determined on the basis of comparison of the number of tops detected automatically to the number of trunks inventoried in the field in the SPs for particular species-age categories (table 2) were also taken into account. The indicated optimal detection parameters reflect the previously indicated conditions concerning the influence of the species (coniferous and deciduous stands) and its age on the selection of these parameters. On the basis of the comparison of the selection of optimal detection parameters developed for the data from the first and second stage of the experiment, it is characteristic that in the case of the data from the stage I, a larger raster cell of the CHM and a lower smoothing level is generally recommended. This trend may be justified by a lower point cloud density in 2007.

Table 2. Summary of proposed (optimal/expected) sets of detection parameters, taking into account the specificity of ALS data from Stage I and II of the experiment

Cat.	Point cloud EI		Point cloud EII	
	Detection parameters	R2/detection of trees [%]	Detection parameters	R2/detection of trees [%]
1 a	Variant I; 0,50 m; G1x1; std 1	0,96/100,06	Variant III; 0,40 m; G2x2; std 1	0,98/100,31
1 b	Variant III; 0,55 m; G1x1; std 2	089/100,07	Variant III 0,45 m; G2x2; std 1	0,98/101,65
1 c	Variant III; 0,50 m; G1x1; std 3	096/101,84	Variant III 0,55 m; G1x1; std 3	0,94/96,26
2 a	-	-	Variant III 0,45 m; G1x1; std 2	0,77/91,43
2 b	Variant III; 0,55 m; G3x3; std 1	0,88/97,06	Variant III 0,45 m; G3x3; std 1	0,78/99,48
3 a	-	-	Variant III 0,45 m; G4x4; std 1	0,79/99,49
3 b	-	-	Variant III 0,55 m; G4x4; std 1	0,21/106,43

Source: author's own work.

Taking into account the data presented in table 2, the process of treetop detection and crown segmentation within 140 SPs on remote-sensing material from stage II was again performed. The results are very promising. On 4124 trunks inventoried on trial surfaces in the field, the automatic segmentation algorithm indicated the occurrence of 4125 tops. Figure 10 compares the number of tops detected remotely with the number of trunks measured in the field.

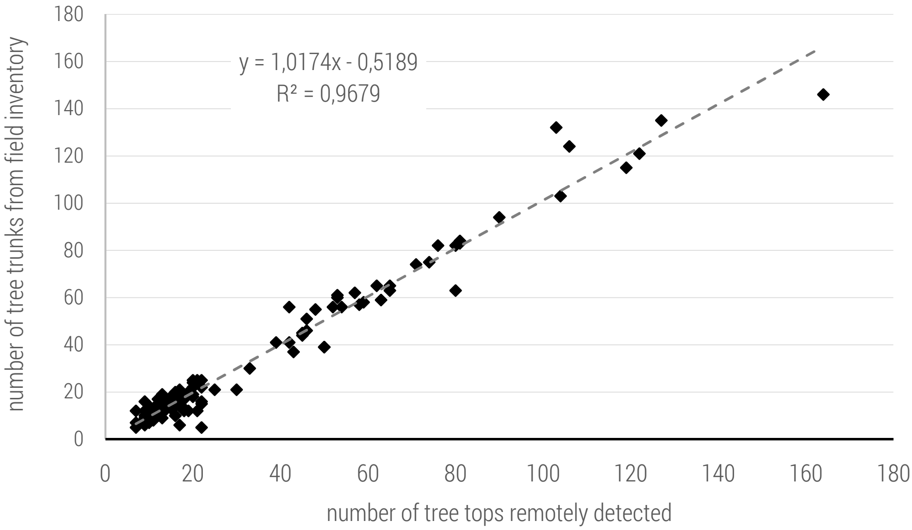

Figure 10. Comparison of the remotely detected number of treetops against the number of tree trunks from field inventory in the spatial extent of 140 circular plots from stage 2 of an experiment

Source: author's own work.

Comparing the results obtained on all 140 SP, the determination coefficient is very high at the level of R2 (0.97), which indicates a very high matching of automatic detection results with empirical data collected on SPs. Slightly weaker relationships were observed within 102 circular surfaces established in the second stage of the experiment (surfaces with a radius r in the range of 5.64-12.62 m). In this case, the determination coefficient R2=0.42 was obtained and after the rejection of areas with the prevailing deciduous species the coefficient increases to 0.49. The mean absolute MAPE (Mean Absolute Percentage Error) was recorded at the level of 22.17% (102 areas of stage II) and 8.26% (38 areas of stage I) (table 3). It can be concluded that the detection algorithm was wrong by an average of 6 tops (with the average number of trees detected in the field at the level of 70) within 38 circular sample plots of stage I and by an average of 3 tops (the average number of trees on the plot – 14 items) in relation to 102 plots.

The highest absolute percentage error was obtained at the level of 340%, (22 tops detected automatically in relation to 5 trunks found in the field) on the circular surface with the prevailing pedunculate oak in the age class Vb. It was a specific area on which spreading crowns formed a heterogeneous, very variable area, extremely difficult for the segmenting algorithm. On other plots with oak (in younger age classes) the results obtained were much better, with an average absolute percentage error of 22.80%.

Table 3. The summary of basic metrics showing the conformity of the automatic detection process in the different trial categories of circular surfaces

Metric	sample plot category					
	all	EI 38	EII 102	E102 (coniferous)	coniferous	decidious
Minimum absolute percentage error	0,00	0,00	0,00	0,00	0,00	0,00
Maximum absolute percentage error	340,00	28,21	340,00	183,33	183,33	340,00
Mean absolute percentage error	18,39	8,26	22,17	19,48	15,67	29,29
R2	0,97	0,92	0,42	0,49	0,97	0,51
Mean tree count (field inventory)	29,46	69,68	14,48	14,78	33,00	13,68
Mean detection error [tree tops]	5,42	5,75	3,21	2,88	5,17	4,01

Source: author's own work.

Conclusions

On the basis of the results obtained, it can be concluded that laser scanning techniques (LiDAR) are very useful in detecting trees with visible tops (trees of the upper floor and visible trees of the lower floors), which confirms the results of the work of other research teams. Precise determination of the number of trees in the upper floor is a key element in the economic use of stands, as practically the entire volume of wood is concentrated in this part (Stereńczak, 2013). The purpose of this work has been achieved. The results obtained indicate that it is possible to select a set of detection parameters that provides a very high fit to empirical data, with a coefficient of determination greater than 0.90, which in general is a better result compared to similar studies conducted in this field (Hyyppä et al., 2001; Persson et al., 2002; Koch et al., 2006; Kaartinen, Hyyppä, 2008; Tompalski et al., 2009; Wang et al., 2008; Myszkowski et al., 2009; Wężyk et al., 2010; Stereńczak, 2013). It has been shown that there is more than one optimal solution from the point of view of the selection of several important parameters, which reduces the risk of errors resulting from not carrying out earlier calibration works and uncritical assumption of parameter values. The conducted research also indicates that the optimal values of detection parameters differ slightly depending on the characteristics of the remote-sensing material used. In this case, the higher density of the point cloud makes it possible to use a smaller cell size of the raster cell for the construction of CHM. This fact significantly extends the possibility of using laser scanning data in historical analyses (data reanalysis) or in studies based on data of unknown accuracy.

The conducted research also indicates some solutions from the point of view of the problem of selecting the size of the sample area so as to minimize the cost of fieldwork and at the same time ensure the representativeness of the research. It is worth mentioning that apart from increasing the radius of analysis (1.5 radius), no special measures were taken in the study to reduce the impact of the boundary effect. Such a state of affairs may be influenced by several factors of different nature. The first factor is the significantly reduced size of test surfaces (in comparison to the inventory from stage I), which means that the accuracy of the obtained results is more influenced by the boundary effect resulting from the higher values of the ratio of circumference to test surfaces of circular surfaces (figure 11). In addition, on smaller circular areas, far fewer observations are recorded (sample size), due to a drastic increase in the circular area from a radius of approx. 15 m. With a smaller circular area, the effect of the measurement error of the position of the centre of the circular area may be more pronounced.

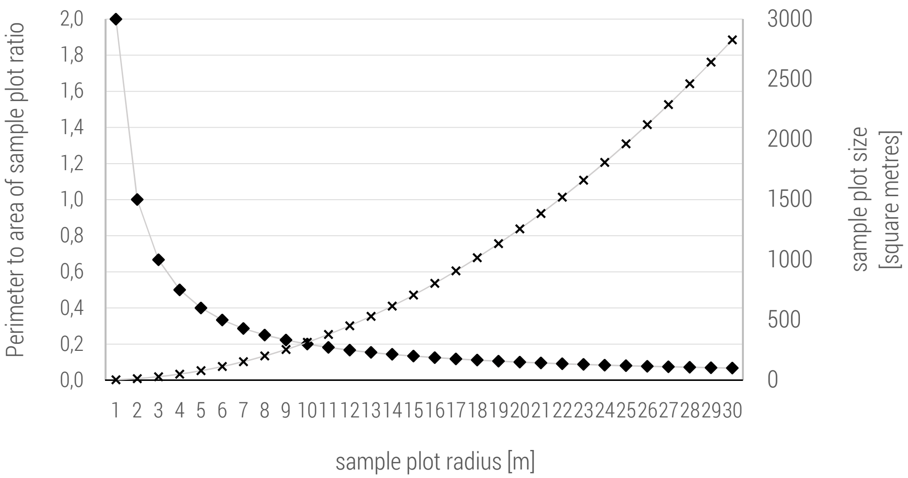

Figure 11. The relationship between the ratio of circumference and surface values on circular surfaces depending on the size of the radius of the circular surface

Source: author's own work.

The proposed methodology can be successfully applied for the automatic detection of treetops and crown segmentation in large areas (e.g. a range of the entire forest inspectorate covered by the forest management plan). The results obtained in this way can be an important starting point for other studies of different aspects of forest management, including those related to its economic, social or protective dimension.

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The contribution of the authors

Łukasz Kolendo – 50%.
Marek Ksepko – 50%.

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