

**DETERMINATION OF THE NUMBER OF TREES IN THE BORY  
TUCHOLSKIE NATIONAL PARK USING CROWN DELINEATION OF  
THE CANOPY HEIGHT MODELS DERIVED FROM AERIAL PHOTOS  
MATCHING AND AIRBORNE LASER SCANNING DATA**

**OKREŚLANIE LICZBY DRZEW W PARKU NARODOWYM BORY  
TUCHOLSKIE METODĄ SEGMENTACJI KORON NA MODELACH  
WYSOKOŚCIOWYCH POCODZĄCYCH Z DOPASOWANIA ZDJĘĆ  
LOTNICZYCH ORAZ LOTNICZEGO SKANOWNIA LASEROWEGO**

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**KEY WORDS:** image segmentation, object classification, point clouds, stereomatching, airborne laser scanning, Bory Tucholskie National Park

**ABSTRACT:** In recent years the term "precise forestry" has been used more and more often, referring to a modern and sustainable model of forest management. Functioning of such management of wood biomass resources is based, among others, on precisely defined and long-term monitored selected forest taxation parameters of single trees and whole forest stands based on modern geoinformation technologies, including Airborne Laser Scanning (ALS) and digital photogrammetry. The purpose of the work was the analysis of the usefulness of the CHM (Canopy Height Model) generated from the image-based point cloud or ALS technology to define the number of trees using the method of the segmentation of single Scots pine (*Pinus sylvestris* L.) crowns. The study was carried out in the Scots pine stands located in the Bory Tucholskie National Park (Poland). Due to the intentional lack of certain silviculture treatments, over the recent decades, these forest stands have been characterized by relatively high tree density, compared to managed forests. The CHM was generated from digital airborne photos (CIR composition; GSD 0.15 m) and on the other hand - from the ALS point clouds (4 points/m<sup>2</sup>; ISOK project). To generate point clouds from airborne photos using stereomatching method, the PhotoScan Professional (Agisoft) software was applied. The CHM coming from the Image-Based Point Cloud (CHM\_IPC; GSD: 0.30 m) and ALS data (CHM\_ALS; GSD: 0.75 m) were generated using FUSION (USDA Forest Service) software. The segmentation of tree crowns was carried out in eCognition Developer (TRIMBLE GeoSpatial) software. Apart from height models, also spectral information was used (so-called true CIR orthophotomaps; GSD: 0.3 and 0.75 m). To assess the accuracy of the obtained results, the ground truth data from 248 reference areas were used. The carried out analyses showed that in forest stands of younger age classes (< 120 years) better results were achieved applying the method of image matching (CHM\_IPC), while in the case of older stands (> 120 years) the accuracy of the detection rate of tree crowns was the highest when CHM\_ALS model was applied. The mean percentage error (defined by the number of trees, based on the detection of single pine crowns), calculated based on 248 ground truth areas was 0.89%, which shows a great potential of digital photogrammetry (IPC) and GEOBIA. In case of almost full nationwide cover in Poland of airborne digital images (present IPC models) and ALS point clouds

(DTM and DSM), at almost 71% forest stands in the Polish State Forests National Forest Holding (PGL LP), one can assume wide application of geodata (available free of charge) in precise modelling of selected tree stand parameters all over Poland.

## 1. INTRODUCTION

Automation of the process of defining various features of forest ecosystems, based on geoinformation technologies is a very important issue of forests and protected areas management. It seems very important in the context of social and economic changes often causing the necessity of departing from traditional methods of forest inventory, which require large financial resources, related to the field work. In the latest decade more and more often, referring to the modern model of sustainable forest management function, the term "precise forestry" has been applied, in particular in the aspect of the carbon forest plantations formed by Polish State Forest National Holding. Functioning of such management model needs quick and reliable methods for estimation of forest stand and single tree parameters. Such automated methods of inventory and monitoring can be based on modern geoinformation technologies, in particular on Airborne Laser Scanning (ALS) point cloud data, innovative for forest areas and on (again competitive due to automated algorithms) - digital photogrammetry. Point clouds from airborne laser scanning, which make a valuable source of information on the height and vertical structure of the forest stands, are applied in the automation of the forest areas monitoring. Scientific research in this field, which has been carried out in Poland for nearly 10 years (Będkowski, Mikrut, 2006; Będkowski, Stereńczak, 2008; Marmol, Będkowski, 2008; Wężyk *et al.*, 2008; Wężyk *et al.*, 2010; Stereńczak, 2013) and practical implementations indicated the great usefulness of various taxation features and other parameters both for the whole tree stands and single trees as well. ALS data are used to describe the horizontal and vertical structure of a tree stand, to estimate horizontal crown cover, to define the upper height of tree stands and single trees, as well as to define the number of trees by the segmentation of crowns (Stereńczak, 2009; Będkowski, 2011; Stereńczak, 2012; Maltamo *et al.*, 2014).

In recent years the methods applying the Image-Based Point Clouds (IPC) have been gaining more and more popularity. Due to the technological development of the airborne cameras, it became possible to obtain airborne photographs of better and better spectral resolution (number of channels) and spatial (ground) resolution. At the same time the longitudinal and side overlap of the airborne photos strips was increased to almost fully enable the formed algorithms to work on the stereoscopic model. At the same time a dynamic development of algorithms for image analyses has been observed. They allow to obtain 3D representation of the actual reality in the form of point clouds with the methods of the automatic matching of airborne photographs (Leberl *et al.*, 2010; Dandois *et al.*, 2013; Stepper *et al.*, 2015). This new approach is now visible in digital photogrammetry, making this discipline again more competitive in the aspect of the automation of work, leading to further limitation of costs of the forest inventory and monitoring of the environment resources. One should, however remember to remove some disadvantages of the photogrammetric method, mainly considerable limitation in imaging the ground in the forested areas. Thus it is necessary to have a precise Digital Terrain Model (DTM) allowing the normalization of the point clouds (White *et al.*, 2013).

Among many applications of geoinformation technologies in the management of forest resources, an important place is taken by the issues of detecting single trees by the methods of the single tree crowns segmentation (Wulder, Franklin, 2003). Basically two main groups of methods can be applied in this context. The first group of methods is based on the raster analysis, mainly on Canopy Height Model (CHM), sometimes in combination with optical data (image). The second group of methods includes methods based on the analysis of 3D point clouds. Although both groups are applied, in case of IPC, the application of methods based on the cloud of points is very difficult in forest areas. This results from the fact that airborne photos usually register only the top layer of tree crowns, without the possibility of penetration to the ground inside crown canopy of dense horizontal cover.

In the group of methods based on raster layers, various algorithms and methods are applied, such as: the concept of local maximum, template matching, watershed segmentation, region growing, Geographic Object-Based Image Analysis (GEOBIA) and others (Zhen *et al.*, 2016).

The goal of this paper was the demonstration of the possibility of automatic tree counting with the methods of the crowns segmentation in Scots pine stands, based on processing of CHM and so-called true CIR orthophoto and the method of automatic Object Based Image Analysis (GEOBIA).

## **2. STUDY AREA**

The study was carried out in the area of the Bory Tucholskie National Park (Polish: *Park Narodowy „Bory Tucholskie”*– PNBT; Fig.1), situated in the Pomerania Voivodeship, in the area of the Chojnice Province, within the administrative borders of the communities: Chojnice and Brusy. The area of PNBT is relatively small: 4 613.04 ha. The priority task of PNBT is the preservation of natural biocenotic specifics of lakes, especially lobelia lakes, peat lands and dry Scots pine forests. Strict nature protection is imposed in PNBT, covering the areas characterized by the highest stability and resistance to the degradation of habitats. The areas of strict protection cover 324.30 ha, i.e. only 7% of the total NP area. Forests cover 79% of the PNBT, where as much as 98% are Scots pine forests (Banaszak, Tobolski, 2002).

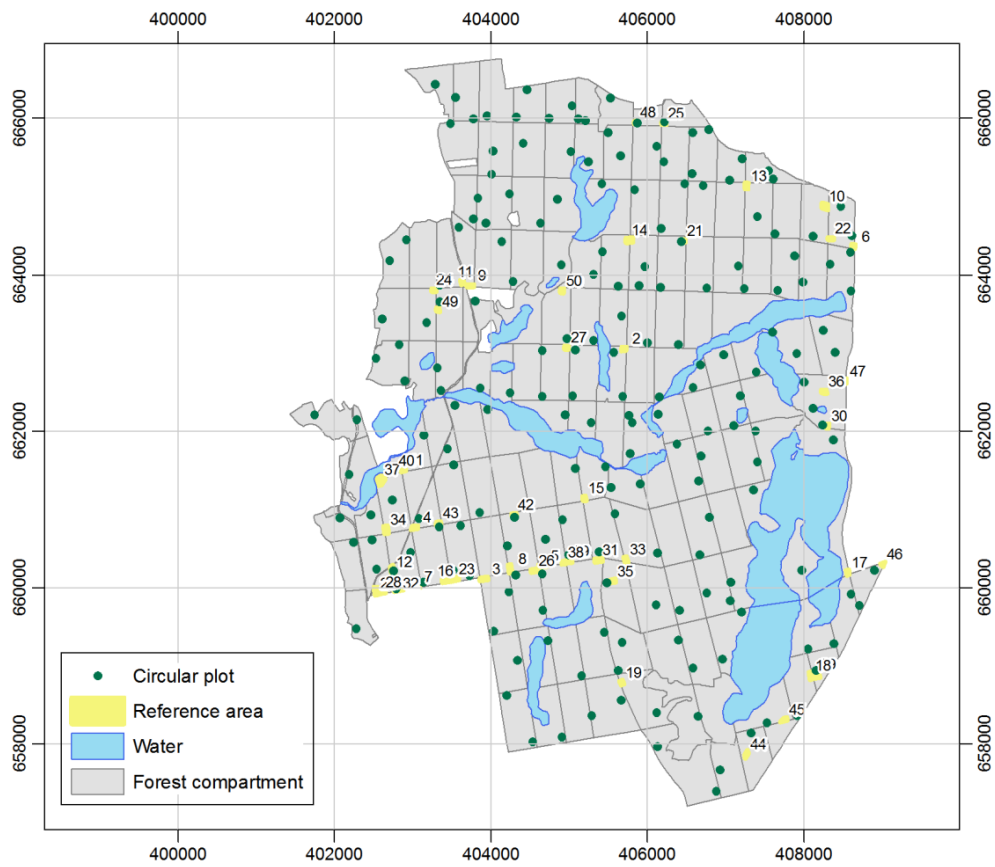


Fig. 1. The map of administrative borders (forest compartments) of the Bory Tucholskie National Park with the distribution of reference areas, established for this project and network of forest inventory circular plots.

Analysing the data collected in the PNB GIS database, it was established that the greatest percentage of the area is covered by the age class III (forest stands in age of: 41-60 years), IV (61-80 years) and VI (101-120 years), making almost 70% of the area (Tab.1). Small percentage of tree stands from class V (80-100 years) is very characteristic. It refers to the tree stands from the plantations shortly after WW I. Perhaps they were destroyed by the insect outbreaks or it was a great fire that destroyed the tree stands of that age or maybe simply there was not much tree planting in that time.

Table 1. The area and percentage of tree stands in PNBT according to the age classes.

Age Class	Area [ha]	Percentage [%]
I	43.66	1.11
II	402.34	10.27
III	958.61	24.46
IV	846.83	21.61
V	331.56	8.46
VI	925.19	23.61
VII	268.64	6.86
VIII	132.89	3.39
IX	7.76	0.20
X	0.99	0.03
Sum	3 918.47	100.00

### 3. METHODS

#### 3.1. Field work

To obtain the reference data on the number of trees in the stands of PNBT, in mid July 2015, forest inventory field work was carried out. Based on the descriptive database referring to tree stands and initial digital photointerpretation of the airborne orthophotomap (CIR composition) and ALS point clouds, the 50 reference areas were established (Fig.1). The tree crowns from the 50 plots were identifiable in the airborne true orthophotos. The mean area of the reference plot was about 0.3 ha. The plots were made in such a way that they represented Scots pine (*Pinus sylvestris* L.) of individual age classes. The board of PNBT was interested to perform this study only in the tree stands over 40 years old (from age class III). Reference areas were not established in tree stands where in the period between October 2012 and July 2015 cultivation activities were taken.

To determine the borders of reference areas, the receiver MobileMapper 120 (Spectra), equipped with the external antenna and special module to carry out the post-processing, was used. Counting the trees in the reference plots was carried out in such a way that trees of damaged and infested crowns (invisible from the aircraft) were eliminated. Counting on reference plots was carried out twice by the team of 5-6 persons, marking the trees (bark on trunk) that were already counted. Trunks, dead trees or seriously damaged trees were also counted (estimating the year of their death), but they were not taken into account in the final result making a reference. Additionally, on 30 reference plots the Terrestrial Laser Scanning (TLS) was carried out, with the use of scanner FARO Focus 3D. The obtained TLS point clouds were used in the further stage of work to define the relationship between the diameter of Scots pine crowns and the height of the trees. Then this parameter was implemented in the algorithm of the tree crowns segmentation.

### 3.2. Preparation of geodata

To fulfil the research project requirements, geodata given by PNBT were applied, i.e.:

- vector layers (Esri Shapefile), inter alia - the borders of forest compartments of PNBT,
- digital airborne photos obtained in 2013 and digital airborne orthophotomap (GSD: 0.15 m; composition CIR)
- ALS point cloud (density 4 pts/m<sup>2</sup>) obtained within project ISOK (Information System of the Protection of the Country from extraordinary threat); Standard I; airborne campaign at 09/10/2012.

Based on digital airborne images (altogether 498 images; longitudinal overlap  $p = 60\%$ ; side overlap  $q = 30\%$ ; the size of data sets 48.9 GB), using the method of automatic IPC generation, the 3D point cloud was constructed (11.2 GB) and so-called true aerial orthophoto GSD 0.3 m (5.06 GB). The processing was carried out on a PC (Intel Core i7-5820K; 6x3.3 GHz; 32 GB RAM) using PhotoScan Professional (Agisoft) software based on the Structure from Motion (SfM) approach. A detail description of the method was presented by Turner *et al.* (2012) and Dandois, Ellis (2013). Processing of images in PhotoScan was carried out in stages similar to the ones in the scheme described by Preuss (2014):

- uploading the images and defining the project;
- initial georeferencing by the image matching method;
- marking 13 Ground Control Points (GCPs) with the application of the existing aerial orthophotomap and DTM;
- optimization of georeference, using GCPs;
- making a dense 3D point cloud;
- reconstruction of a skeleton model of the object, and
- export of the final orthophotomosaic and 3D point cloud.

In a subsequent step, based on IPC and ALS point clouds digital height models representing tree crown canopy (CHM) were generated. Different values of spatial resolution of CHM were tested, in terms of their usefulness for the method of tree detection, based on the CHM segmentation. Finally, the optimal ground resolution was accepted as 0.75 m for CHM\_ALS and 0.3 m for CHM\_IPC (originated from photo matching). The height of points (Z) in IPC cloud had absolute values (a.s.l.) thus they underwent normalization based on the DTM, generated earlier basing on the class ground of ALS point clouds. The normalization of point clouds and generating the CHM versions were carried out in software FUSION (McGaughey, 2015).

### 3.3. Counting the number of trees using the crown segmentation method

The process of tree top detection and the crown segmentation were carried out in eCognition Developer (TRIMBLE Geospatial) software, using so-called GEographic Object-Based Image Analysis (GEOBIA), based on the input layers: CHM and true CIR aerial orthophoto. In case of Scots pine stands of 40-120 years old, the model of tree

crowns (CHM), generated with the aerial photo matching (called: CHM\_IPC, GSD: 0.3 m) approach was applied, while for forest stands older than 120 years, the CHM model was based on ALS point clouds (called: CHM\_ALS, GSD: 0.75m). The ground resolution of CHM models was selected empirically testing different input parameters of the filtration.

The processing of the geodata started from the classification of dead trees and damaged Scots pine crowns, because the segmentation algorithm in their case required small modifications. For this purpose, raster of the Normalized Difference Vegetation Index (NDVI) was applied. On the training areas located in forest with dGNSS measurement (post-processing using the ASG-EUPOS network; accuracy dm XY), the single dead trees, bio-groups of dead trees killed by the lightning or change of the ground water table, or trees destroyed by the pest gradation were mapped. Based on true orthophoto, the NDVI index value was measured and applied in semi-automatic GEOBIA approach. The next step after detecting dead and damaged trees was the classification of the preliminary class of "gaps between crowns", so these areas were excluded from the process of the tree crowns segmentation in the canopy. The gaps were classified based on the mean brightness of pixels in three spectral bands of the true orthophoto CIR and the values of the relative height (CHM). Shaded areas and the areas with relative height values below 5.0 m were classified as "gap".

To detect the tree tops, the concept of local maximum, implemented in the algorithm *find local extrema* was used. It allowed the detection of pixel with maximal values of CHM in mode of so-called moving window (with given size parameter). Based on manual measurements on 4 transects carried out in the TLS point cloud gathered with mainly 1 scanning station (FARO Focus 3D), and using the FugroViewer (Fugro) and TerraScan (Terrasolid) software - the width of Scots pine crowns and their height were elaborated. Based on those parameters the threshold value for maximal values of the radius of Scots pine crown in the process of tree tops detection was marked. In the subsequent step, applying the approach of so-called *region-growing*, the automatic segmentation of single pine crowns was performed. The segmentation algorithm, after the initial classification of potential tree tops, analysed each CHM pixel and attached it to a proper object (tree crown), to which it was most similar in height. With every iteration, the algorithm was looking for pixels of the highest value of CHM (algorithm *find domain extrema*), neighbouring with objects already detected on the existing tree crowns. The process of the increase of the single tree crown by the neighbouring pixels stopped in the moment of exceeding the assumed maximal radius of the crown (based on the measurements in TLS point clouds). After analysing all the pixels that potentially can fail to belong to the tree crown, generalization using the algorithms *pixel based object resizing* and *morphology* (meaning smoothing the shape of the polygon representing the range of the crown) was applied.

Results of the process of tree crown segmentation were shown in figure 2. At the very beginning (Fig. 2a) the small part of a true orthophoto CIR is given, for which subsequent stages of the carried out segmentation process were shown, i.e.: classification of shadows and pixels of height below 5.0 m (Fig. 2b), detection of the tree tops with the initial classification of the candidates for crowns (Fig. 2c) and the result of the crown segmentation (blue polygons) of crown based on the *region growing* method (Fig. 2d).

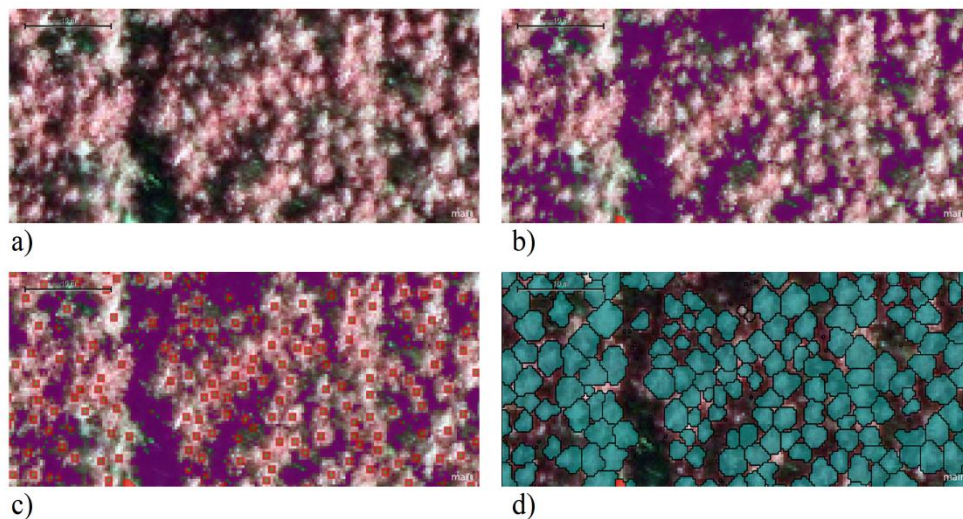


Fig. 2. The process of the tree crowns segmentation: a) enlarged part of the CIR true orthophoto; b) classification of shadows (purple) and pixels of height < 5.0 m; c) detection of tops (green dots) and initial classification of candidates for crowns (red box); d) results of the segmentation based on the *region growing* approach.

### 3.4. The accuracy assessment of the segmentation algorithm

The accuracy assessment of the presented method defining the number of trees was carried out based on the comparison to the reference data obtained during the field campaign in July 2015, that is nearly 3 years after ALS and 2 years after the photogrammetric flights. As it has already been mentioned in the section Methods, reference plots were marked by dGNSS method (post-processing measurement; ASG-EUPOS; GLONASS and NAVSTAR-GPS; accuracy XY in dm range) only in Scots pine stands, which did not have any signs of silviculture treatments (clearings) or strong insects breakout or trees broken by wind in years 2012-2015. The age of all the identified tree trunks or dead trees was estimated very accurately (the signs of shed bark or the structure of small dead twigs) so that the data collected in 2015 in the area corresponded with the number of pine crowns captured on the CIR aerial images from 2013.

To increase reference data from 50 plots, also the information coming from 198 stable (PNBT) circular inventory plots was used. Altogether the data from 31 plots of the area of 200 m<sup>2</sup> and 167 plots of the area of 400 m<sup>2</sup> were used. Based on the combined data of 248 reference plots (total = 50+31+167) the values of the following errors (1)-(4) were calculated:

- absolute error (AE),

$$AE = A - S \quad (1)$$



- mean error (ME),

$$ME = \frac{1}{n} \sum^n A - S \quad (2)$$

- mean percentage error (MPE),

$$MPE = \frac{100}{n} \sum^n \frac{a - s}{a} \quad (3)$$

- mean absolute percentage error (MAPE),

$$MAPE = \frac{100}{n} \sum^n \left| \frac{a - s}{a} \right| \quad (4)$$

where:

*A* - actual number of trees within all reference plots,

*S* - number of segmented trees within all reference plots,

*a* - actual number of trees within a single reference plot,

*s* - number of segmented trees within a single reference plot,

*n* - total number of reference plots.

#### 4. RESULTS

As a result of automatic process of detecting trees based on method of crown segmentation, run in the analysed Scots pine stands PNBТ (only above age class III), the 2 815 368 trees were detected in total. The obtained results, with distribution in the analysed age classes, were presented in table 2.

Among the total estimated number of trees as many as 1 163 294 trees (41.3%) belong to age class III, 876 865 trees (31.1%) belong to IV and 488 797 trees (17.4%) - to VI age class of the Scots pine stands. The trees from other analysed age classes altogether made up less than 10% of the total number of trees (~2.8 million). Figure 3 presents the results of the crown segmentation based on two tested CHM's, i.e.: CHM\_IPC and CHM\_ALS for two selected areas of PNBТ.

In the initial stage of construction of the algorithm, different options of the CHM to detecting and tree crowns segmentation were tested. Based on the analysis of reference data and initial trials of crown segmentation, it turns out that for stands up to 120 years old, more precise results were obtained and the model was generated by aerial photographs matching (CHM\_IPC), while for older stands, more adequate was the model originating from Airborne Laser Scanning (CHM\_ALS). The application CHM\_ALS in younger age classes caused a significant reduction in the number of trees defined by image segmentation (model). On the other hand, model CHM\_IPC turned out to be improper for older tree stands, because it caused significant overestimation of the number of detected trees (Fig. 4).

This can be the effect of arising of so-called "sub-crown" in one mature Scots pine tree. The threshold was assumed as age class VI (up to 120 years), for which the overestimation errors (+9.3%) in case of model CHM\_IPC were smaller than the underestimation errors (-23.1%) obtained using the CHM\_ALS model.

Table 2. Results of crown segmentation – number of trees in subsequent age classes of Scots pine forest stands in PNBT.

Age class of the stand (every 20 years)	Number of tree crowns defined by GEOBIA method	Percentage in the total number of trees [%]
III	1 163 294	41.3
IV	876 865	31.1
V	170 371	6.1
VI	488 797	17.4
VII	76 585	2.7
VIII	36 882	1.3
IX	2 331	0.1
X	243	0.0
Sum	2 815 368	100.0

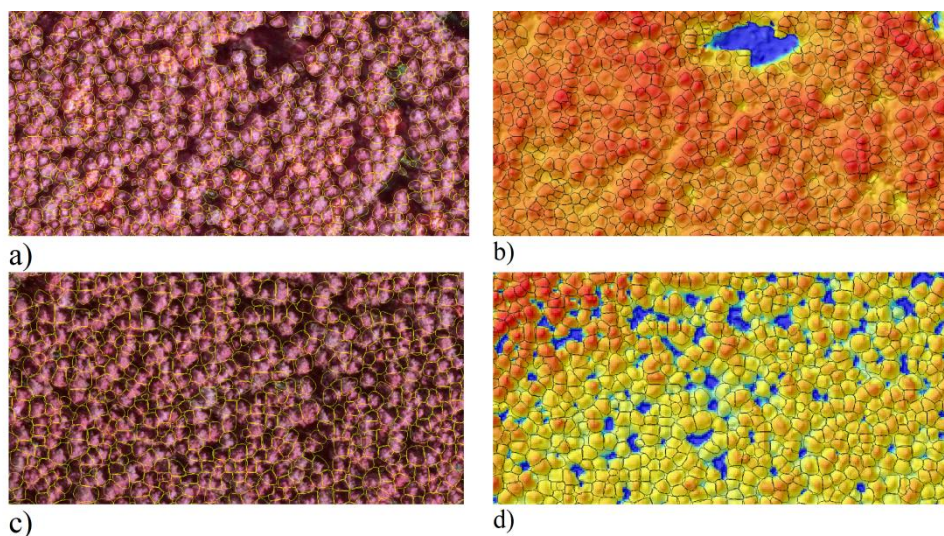


Fig. 3. Results of the tree crown segmentation process: a) yellow polygons on the background of the true CIR orthophoto (GSD: 0.3 m); b) black polygons on the background of CHM\_IPC; c) yellow polygons on the background of the true CIR orthophoto (GSD: 0.3 m); d) on the background of CHM\_ALS.

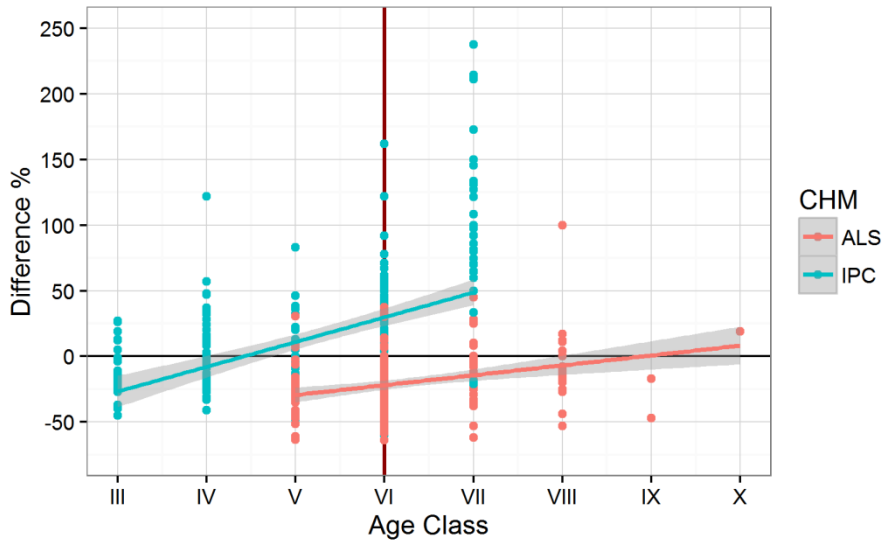


Fig. 4. Differences in the percentage of the resultant number of trees obtained by the crown segmentation method and reference data for analysed age classes for 2 tested CHM's (CHM\_ALS and CHM\_IPC).

The comparison between the number of trees obtained in the automatic way by GEOBIA method and the number of trees registered on the test areas (on 248 reference and inventory circular plots in total) allowed the calculation of the prediction error. In total, the reference set consisted of 15 125 trees. The number of tree crowns obtained as a result of the segmentation of CHM was 14 974, which results in absolute error on the level  $AE = 151$  trees. Mean error in defining the number of trees was only  $ME = 0.6$ . The calculated percentage errors in defining the number trees in Scots pine stands of the PNBT are the following:  $MPE = 0.89\%$ , and  $MAPE = 23.48\%$ . The number of trees and differences between the results of segmentation and ground truth data for individual age classes are presented below (Tab. 3). The distributions of the values of percentage differences between the results of segmentation and reference data (differences for single reference areas) grouped in age classes are presented in figure 5.

Table 3. Comparison of the number of trees in individual age classes of Scots pine stands in PNBT, obtained as a result of automatic GEOBIA approach, in the relation to reference data (248 reference plots).

Age Class [20 years]	The number of trees (ground truth) [items]	The number of detected trees (GEOBIA) [items]	Difference [items]	The accuracy of detected trees [%]	The number of plots [items]
III	3 880	3 472	-408	89.48	23
IV	4 518	4 684	166	103.67	48
V	1 538	1 523	-15	99.02	32
VI	3 209	3 412	203	106.33	95
VII	949	873	-76	91.99	31
VIII	701	664	-37	94.72	16
IX	115	90	-25	78.26	2
X	215	256	41	119.07	1
Sum	15 125	14 974	-151	-	248

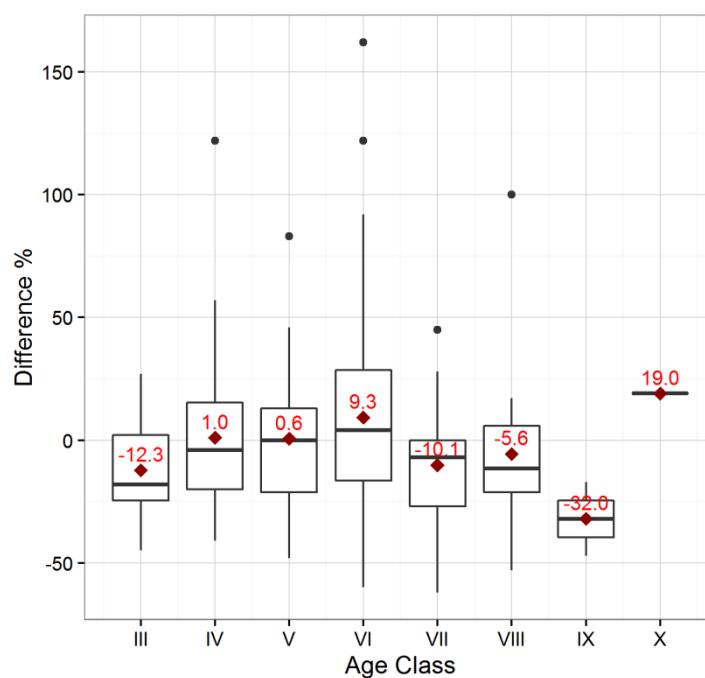


Fig. 5. The distribution of the number of trees percentage differences in subsequent age classes between the GEOBIA approach (CHM) and reference data.

The results obtained in quite a similar experiment conducted in Scots pine stands in the Forest District Milicz (Wężyk *et al.* 2010) based also on GEOBIA method with the

application of the segmentation of raster data CHM (ALS) and true orthophoto CIR (TopoSys line scanner) were shaped on the level of 104% of all the detected trees, including 72.6% of correctly classified crowns. The error of tree crowns underestimation was 16.4% and overestimation reached the level of 8.9%. Based only at the CHM segmentation (inverse watershed) approach the obtained results for detected crowns were at the level of 70.0% to 85.3% but the correctly classified trees were only 60.3% to 67.1%. The basic difference was that in the Milicz test area, the reference data sets were tree crowns interpreted by an operator on the CIR orthophoto, and not counted in the forest stands from the upper Scots pine storey. In the case of Scots pine stands, the assessment carried out in the field whether the infested crown will be visible or not in the aerial photo (in the same way on CHM) – is not able to consider a concrete light which was on the day of the airborne campaign, which additionally complicates the number of reference trees. In the studies in Milicz about 20% growth of accuracy of detected trees (from 85.3% CHM to 104.% GEOBIA: CIR+CHM) was achieved by the implementation of GEOBIA method to define the number of trees by adding to the process of segmentation the spectral information from CIR orthoimages.

Another team of authors (Wang et al. 2008), using the same point cloud for the tested area of Milicz (density about 14 pts/m<sup>2</sup>) and software TreesVis, in the case of Scots pine stands, obtained the results based on the accuracy level of only 50%. In the situation of pine-oak stands in the Forest District Głuchów (Poland), applying the ALS point cloud of similar parameters and the same software, Stereńczak et al. (2008) achieved slightly different results on the level of 52.5–81.5% of correctly detected segments, i.e. the number of trees. Reference data from 35 ground sample plots at Głuchów were used by Będkowski (2011) to test four methods of counting the number of trees. In the carried out experiment, the strength of the relationship between the crowns numbers obtained from segmentation of ALS data (N1-N4) and those from photogrammetric measurements (Nref) was evaluated. The highest correlation value ( $R^2 = 0.2728$ ) was found between number of crowns detected using an automatic algorithm detecting the location of so called locators and those from photogrammetric measurements performed on stereoimages. The second correlation value ( $R^2 = 0.1477$ ) was for visually detected crowns and reference.

The study performed by Stereńczak (2009) based on 325 test plots in Milicz and Rogów indicated the accuracy of tree counting on level of 77% ( $R^2 = 0.53$ ).

Based on the results obtained by Stereńczak (2013) with automatic (accuracy 70.9%) and semi-automatic (accuracy 77.8%) approach of crown segmentation run on 43 plots in Scots pine stands (automatic detection made up to 98.0% of all trees, crowns not detected 16.3%, crowns false detected 12.1%; semi-automatic detection: 104.1%, 14.3% and 8.2% respectively), the author justified the conclusions that the age of the tree stand and canopy cover are not statistically significant ( $p > 0.05$ ) in their influence on the count of trees in the tree stand. Semi-automatic method of segmentation gave the best results in the study (Stereńczak 2013) for trees in age class IVa (60-70 years), and totally automatic procedure was the best for age class IIIb (50-60 years).

In other studies performed by Maltamo *et al.*, (2004) the authors obtained the accuracy of tree counting in forest stands on the level of 94%.

Additionally, based on the obtained number of crown segments (50 reference plots) for each forest compartment of PNBT with Scots pine as dominant tree species (age > 60 years), the density parameter was calculated (Fig. 6). The value of the density is extremely interesting due to the fact that present Scots pine stands until recently (20 years ago) were a typical managed forest (Polish State Forest National Holding), in which the silviculture treatments were carried out, such as lighting, trimming, clearing or clear cutting. Nowadays forest stands have become unique research ground for the observations of natural ecosystem processes forming the tree density and 3D structure of stand. This trees density ranges in BTNP from 245 trees/ha (X age class) to 1 149 trees/ha (III age class; Fig. 7).

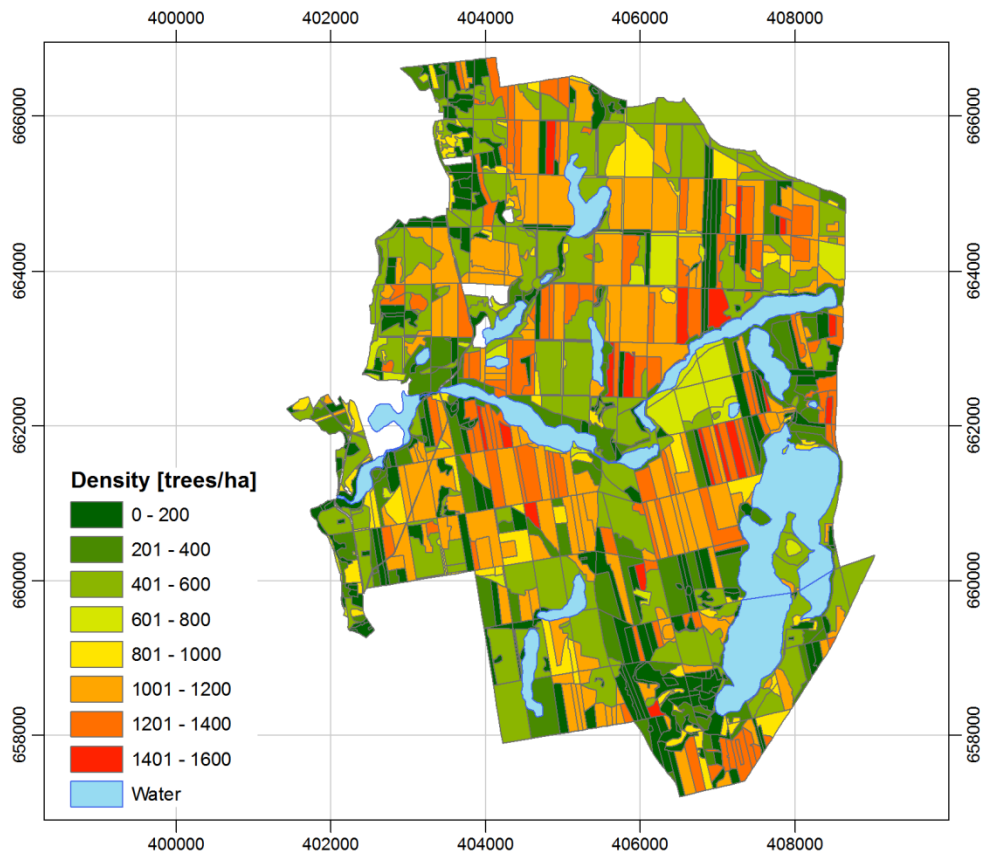


Fig. 6. Density of trees in Scots pine stands estimated from the results of the crown segmentation on CHM (IPC and ALS) and reference data obtained from the inventory plots.

It was found that in forest stands of age class VI the density was higher (509 trees/ha) than in class V (497 trees/ha) and it was bigger in class IX (314 trees/ha) than class VIII (268 trees/ha). Theoretically, the density of trees should decrease with the age of the forest stand. Untypical values of density can result from the silviculture treatments (e.g. clearing) carried out in the past or insects outbreaks common in the area. The presented studies did not cover the analyses of tree stand density in the historical aspect, where archive airborne photographs should definitely be applied (the aerial photo matching IPC approach or images taken in a proper scale), very high resolution satellite images (in the stereo-mode) or the forest inventory data giving the number of trees per ha within the periods of every 10 years.

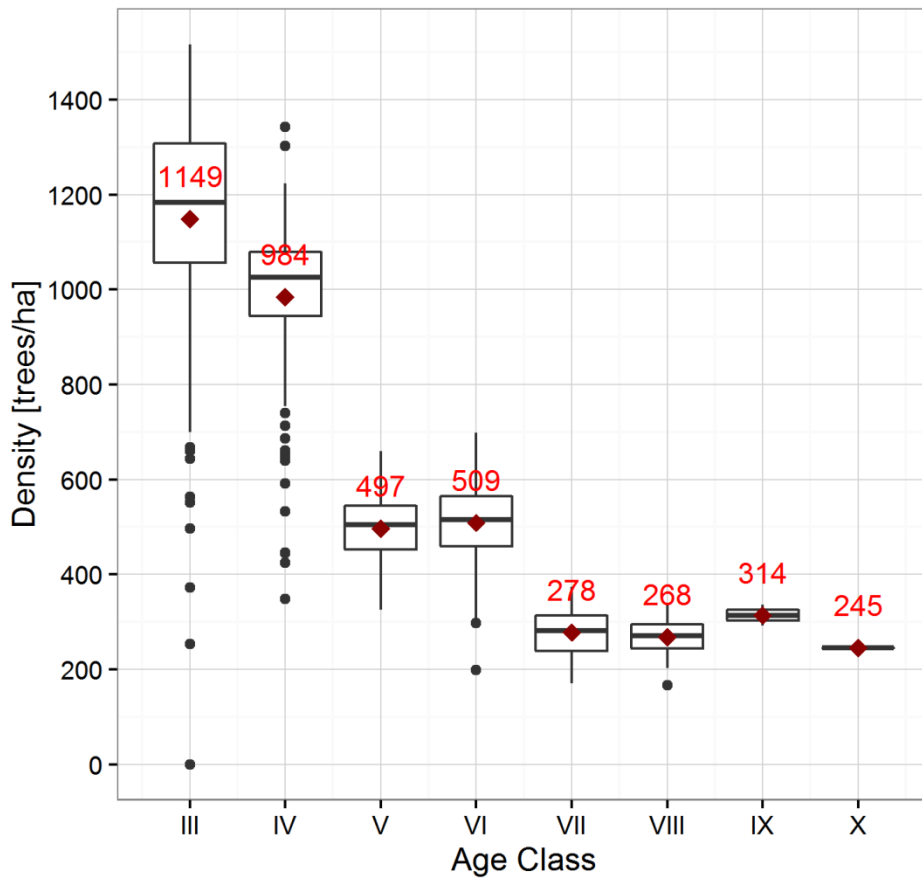


Fig. 7. The tree density of Scots pine stands in PNBT in 20-years range age classes.

## 5. CONCLUSIONS

The results obtained by the authors undoubtedly confirmed a great potential, both of once again appreciated digital photogrammetry (method of automatic aerial photographs matching) as well as the fast developing segment of Airborne Laser Scanning (ALS) in terms of forest inventory. The need for generating spatial models for the very complex forms, such as 3D plot of tree crowns, is ever-growing and is directly linked with a dynamic search for models used for the management and monitoring of biomass in forest ecosystems (e.g. the implemented concept of forests as "Carbon farms" in the Polish State Forests National Forest Holding (pl. PGL LP) or the carried out implementation of REMBIOFOR project) and consequently in the formation and implementation of policies connected with the climate protection.

The study proved that it is possible to count the number of trees in Scots pine stands with a very high accuracy, applying semi-automatic method GEOBIA, based (among others) on precise Canopy Height Model (CHM) generated from the high resolution digital aerial photographs (method of image matching; IPC) and Airborne Laser Scanning (ALS) point clouds – supported by the integration with spectral information, i.e. true digital orthophoto (CIR composition). Such a strongly automated method allows us to obtain reliable information on the number of trees in the case of the analyses carried out for larger areas, e.g., for forest stands in the whole National Park Bory Tucholskie (MPE = 0.89%) or other PGL LP units (like forest district). In the case of single forest stands, the errors of detecting crowns (underestimations or overestimations) can reach much bigger values (MAPE = 23.48%) resulting from the changeability of micro-habitats, even observed in one-species tree stands, infested e.g. by insects in the past.

In the case of analysed Scots pine stands in PNBT, it was stated that up to age class VI (40-120 years old) using of the CHM based on point clouds generated from matched aerial photos (IPC) is preferred. It allows obtaining more accurate results compared to the methods applying the CHM coming from the processing of ALS point clouds (mean density of 4 pts/m<sup>2</sup>). Probably in the case of the application of ALS point clouds characterised by higher nominal density of laser beams per the unit of area, it would be possible to obtain equally good results in the case of younger Scots pine stands. One should pay attention to the fact that the transparent structure of the Scots pine crown, in particular trees growing on extremely poor sandy soils (e.g. *Cladonio-Pinetum site*) cause that the CHM is not as correct as in the case of forest stands of dense canopy cover (the more healthy assimilation apparatus, significantly reflecting laser impulses). In this case, a great role is played by a proper selection of filters to achieve "smoothened" CHM, which, on the other hand carries a certain danger of removing local maxima to detect the top part of the trees, which in the case of Scots pine, is a complex problem, anyway (lack of a distinct top in case of older trees).

The application of algorithms matching the images to generate precise CHM models and true orthophotos applied in the process defining the number of trees by GEOBIA method seems particularly reasonable in the case of the areas of national parks (NP). Forests growing within the borders of the NP are usually not typical managed tree stands (although they fulfilled this function in the past) and are often characterised by greater density of trees per ha. As it can be concluded from the presented results of the study, in the



conditions of higher density of trees (younger age classes of forest stands), better results in the number of trees were obtained applying CHM segmentation, generated based on point clouds originating from image matching. One should bear in mind that although relatively expensive ALS data collection has been done for nearly the whole area of Poland (92% - state for 2015), the subsequent repetition of this would be quite difficult because of high financial costs. Fortunately, once well generated DTM, based on ALS point clouds for forest areas, usually do not change very much in time (apart from unusual cases of natural disasters, e.g. land slide). Proper regulations applied in PGL LP also order making digital orthophoto to make forest management plans every 10 years. The digital aerial images (4 channels) could be provided (free of charge) with the file of aero-triangulation and position of the ground control points (GCPs). At the same time, in Poland, every 3 years airborne campaigns providing aerial images (GSD 0.25 m) are regularly carried out (IACS UE). They are applied to generate up-to date aerial orthophotomaps for the purpose of agricultural policy of EU (the question of the control of direct subsidies for the farmers). More and more often these photos are stored at the Main Centre of the Geodetic and Cartographic Documentation (even with NIR channel) which makes it possible to use them free of charge in the proposed method of generating point clouds (IPC) e.g. to count the number of trees in the forest. Taking into account that the Scots pine makes up about 71% of total forest stands in Polish forests (PGL LP), and aerial photos and ALS data as well are free of charge available for the administration of PGL LP, it seems that a part of spatial information describing the 3D structure of forest stands, within the next years will support the model of precise forestry with a great chance to be implemented into daily practice.

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## **OKREŚLANIE LICZBY DRZEW W PARKU NARODOWYM BORY TUCHOLSKIE METODĄ SEGMENTACJI KORON NA MODELACH WYSOKOŚCIOWYCH POCHODZĄCYCH Z DOPASOWANIA ZDJĘĆ LOTNICZYCH ORAZ LOTNICZEGO SKANOWANIA LASEROWEGO**

SŁOWA KLUCZOWE: segmentacja obrazu, klasyfikacja obiektowa, chmury punktów, lotnicze skanowanie laserowe, PN Bory Tucholskie

### **Streszczenie**

W ostatnich latach coraz częściej w odniesieniu do nowoczesnej i zrównoważonej gospodarki leśnej używa się terminu "precyzyjne leśnictwo". Funkcjonowanie takiego modelu zarządzania zasobami biomasy drzewnej opiera się m.in. na dokładnie określonych i monitorowanych cyklicznie wybranych parametrach taksacyjnych drzewostanów i pojedynczych drzew w oparciu o nowoczesne technologie geoinformacyjne, w tym lotnicze skanowanie laserowe (ang. ALS) oraz fotogrametrię cyfrową. Celem pracy była analiza przydatności Modelu Koron Drzew (ang. CHM) generowanego z chmur punktów pochodzących z automatycznego dopasowania cyfrowych zdjęć lotniczych (ang.

Image-Based Point Cloud) lub z technologii ALS w celu określania liczby drzew metodą segmentacji pojedynczych koron sosen. Badania realizowano w drzewostanach sosnowych (*Pinus sylvestris* L.) na obszarze Parku Narodowego "Bory Tucholskie". Drzewostany te poprzez celowe zaniechanie w ostatnich dekadach pewnych zabiegów hodowlanych charakteryzowały się stosunkowo dużym zagęszczeniem drzew w porównaniu do drzewostanów gospodarczych. Model Koron Drzew wygenerowano w jednym wariancie ze zdjęć lotniczych CIR (GSD 0.15 m) a w drugim z chmur punktów ALS (4 pkt/m<sup>2</sup>; CODGiK ISOK). Do generowania chmur punktów ze zdjęć lotniczych metodą dopasowania zastosowano oprogramowanie Photoscan Professional (Agisoft). Modele Koron Drzew pochodzące z dopasowania zdjęć lotniczych (CHM\_IPC; GSD: 0.30 m) oraz z danych ALS (CHM\_ALS; GSD: 0.75 m) zostały wygenerowane w oprogramowaniu FUSION (USDA Forest Service). Segmentację koron prowadzono w oprogramowaniu eCognition Developer. Oprócz modeli wysokościowych wykorzystano także informację spektralną (tzw. prawdziwe ortofotomapy CIR; GSD: 0.3 i 0.75 m). Do oceny dokładności otrzymanych wyników wykorzystano dane pochodzące z 248 powierzchni referencyjnych. Przeprowadzona analiza wykazała, że w drzewostanach młodszych klas wieku (< 120 lat), lepsze wyniki można osiągnąć stosując metody dopasowania zdjęć (CHM\_IPC) natomiast w drzewostanach starszych (> 120 lat) dokładność wykrywania koron drzew jest najwyższa przy stosowaniu wariantu CHM\_ALS. Średni błąd procentowy określania liczby drzew w oparciu o detekcję pojedynczych koron sosen obliczony na podstawie 248 powierzchni referencyjnych wyniósł 0.89% co świadczy o ogromnym potencjale fotogrametrii cyfrowej (metod dopasowania zdjęć) oraz analizy obrazu (OBIA; Object-Based Image Analysis). W aspekcie niemal całkowitego pokrycia kraju danymi ALS oraz blisko 70% udziału drzewostanów sosnowych w Lasach Państwowych można założyć szerokie wykorzystanie tych nieodpłatnie dostępnych geodanych w celu zbudowania modelu precyzyjnego leśnictwa dla obszaru całego kraju.

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