SYLWAN 167 (7): 397-414, July 2023
https://doi.org/10.26202/sylwan.2023056
Journal homepage: https://sylwan-journal.pl

ORIGINAL PAPER

Assessment of long-term canopy height changes across the Białowieża Primeval Forest using historical stereoscopic images and aerial laser scanning data

Jarosław Janus✉, Piotr Bożek, Jarosław Taszakowski, Arkadiusz Doroż

Department of Agricultural Land Surveying, Cadastre and Photogrammetry, Faculty of Environmental Engineering and Land Surveying, University of Agriculture in Krakow, Mickiewicza 21, 31-120 Kraków, Poland

ABSTRACT

Both natural and man-made forest areas are subject to many changes, the observation of which is necessary to understand their causes, monitor current processes and precisely forecast further changes. Protected areas with preserved natural forests play a special role in research on long-term changes in forest cover height. The presented research presents the processes of changes in forest cover height over the last 30 years in the area of the Białowieża Primeval Forest, the last of the large, natural forest complexes that once covered the lowland part of Europe. For areas with different degrees of protection, data was obtained representing the spatial arrangement of tree crowns in the period between 1982 and 2012. The historical status was determined on the basis of point clouds obtained by processing panchromatic stereoscopic aerial photos. These data were compared with contemporary datasets resulting from airborne laser scanning measurements. This allowed for a precise definition of the range of changes, their dynamics and the nature of these changes in parts of the forest with different conservation regimes. The research demonstrated the usefulness of the proposed method for determining long-term changes affecting forested areas, including not only the range, but also the height structure of vegetation. This enables the identification of events affecting the structure of the forest, both due to normal forest management and to natural causes, along with the possibility of determining the location and approximate determination of the occurrence of a given event in time.

KEY WORDS

ALS, Białowieża Forest, historical photographs, LiDAR, natural forests, point clouds, protected areas, stereoscopic image processing

Introduction

Natural resources, both renewable and non-renewable, and the ecosystem services associated with them, are recognized as the true wealth of nations. Proper and sustainable management of these resources is an important contemporary challenge. This also applies to the monitoring of changes in these resources over time (Akay *et al.*, 2009) and the implementation of long-term environmental research (Karlson *et al.*, 2015). Monitoring changes in land cover has become an important

✉e-mail: j.janus@ur.krakow.pl

Received: 7 August 2023; Revised: 11 October 2023; Accepted: 17 October 2023; Available online: 14 November 2023

CC BY Open access ©2023 The Author(s). http://creativecommons.org/licenses/by/4.0

tool for forest management, especially in protected areas (Martinez del Castillo *et al.*, 2015). The primeval forests were cut down to create arable land and pastures and to enable the exploitation of forests for firewood and building materials, for centuries being the most important anthropogenic change to the natural environment (Kaplan *et al.*, 2009). There are few areas left in Europe where there are remnants of natural forests and they keep continuing to disappear (Sabatini *et al.*, 2021). Scattered remains of primeval forest still exist in remote areas, in mountain areas and wetlands, especially in the Balkans, the Alps and the Carpathians (Parviainen, 2005).

In Europe, forests cover approximately 180 Mha, which is more than 40% of land (Marin *et al.*, 2011). According to Sabatini *et al.* (2018), in Europe, primeval forests cover an area of 1.4 Mha located in 32 countries (0.7% of Europe's forest area), most of which are mountain or boreal forests. It is recognized that rare and sensitive remains of virgin forests can only be effectively protected by medium or large reserves (Parviainen, 2005). The global network of protected areas currently covers 11.5% of the planet's land area (Rodrigues *et al.*, 2004). Saving Europe's remaining natural forests is one of the main challenges of European environmental policy (Czerepko *et al.*, 2021). In the case of Europe, protected areas function mainly under the Natura 2000 network in combination with areas designated at the national level (Maiorano *et al.*, 2015). However, the area protected is still considered insufficient (Gaston *et al.*, 2008).

Both natural and human-transformed forested areas in Europe are subject to many changes, observation of which is essential to understand the processes behind these changes, prevent their negative effects, and create reliable forecasts of changes in the future. This also applies to the modelling of the possible effects of climate change, which allows the assessment of trends in disturbance regimes in different countries and at different time periods (Noszczyk *et al.*, 2020). Changes in forested areas occur mainly due to a number of anthropological factors related to the processes of deforestation and afforestation. These include both socio-economic and political processes, an example of which are changes in land use recorded in forest areas in many Eastern European countries in connection with the systemic transformation during the collapse of socialism (Munteanu *et al.*, 2014; Muchová and Tárníková, 2018; Cegielska *et al.*, 2019; Janus *et al.*, 2019). This transformation caused both a decrease in forest cover as a result of illegal logging and ownership changes (Kuemmerle *et al.*, 2009), as well as a successive increase in this cover related to the increasing phenomenon of abandoning land cultivation (Potapov *et al.*, 2015) and subsequent forest succession (Kolecka *et al.*, 2017). Planned afforestation of low-quality agricultural land (Kurowska *et al.*, 2020), often supported by appropriate programs encouraging these activities, has also played an important role in the increase in forest cover (Meyfroidt and Lambin, 2011; Liu *et al.*, 2019).

Understanding the characteristics of changes in European forests and the dynamics of these changes requires an interdisciplinary research program, integrated with monitoring networks and protection models (Lindner *et al.*, 2010). Knowledge of the dynamics of the forest ecosystem disturbance regime is also an important element of the process of managing these ecosystems (Zimble *et al.*, 2003). The usefulness of research on understanding the dynamics of forest canopy with different levels of human impact (managed, protected, strictly protected) is noted by Senf *et al.* (2017). However, some of the changes and their effects can only be observed in areas with natural forms of forest vegetation, because they are not visible in managed forests due to the significant impact of direct forest use by humans and the high degree of transformation of forest ecosystems (Cholewińska *et al.*, 2020).

A key role in the development of three-dimensional mapping techniques was played by photogrammetric techniques related to steroscopic processing of aerial photographs (Winterbotham *et al.*, 1921; Birdseye, 1940). The aforementioned methods (Piekarski, 1972, 1974), combined with the use of remote sensing techniques (Mozgawa, 1977, 1980) and progress in photointerpretation (Mozgawa, 1985), played an important role in the development of methods for obtaining modern information about forests (Piekarski and Będkowski, 1991).

Completely new analysis possibilities appeared with the spread of laser scanning technology. Airborne laser scanning data provide an extremely useful method for visualizing changes in forest vegetation cover. The very wide possibilities of using the LiDAR technique in forestry were quickly noticed (Zimble *et al.*, 2003; Będkowski, 2004; van Leeuwen and Nieuwenhuis, 2010; Bour *et al.*, 2021; Lenoir *et al.*, 2022, Prada *et al.*, 2022; Ørka *et al.*, 2022; Stereńczak, 2022). The most important feature that distinguishes the LiDAR technique from other methods is the ability to obtain a three-dimensional structure of vegetation (Będkowski, 2005; Wężyk *et al.*, 2013; Sverdrup--Thygeson *et al.*, 2018), including at the level of individual trees (Koch *et al.*, 2006; Stereńczak, 2009, 2014; Wężyk *et al.*, 2010; Kolendo and Ksepko, 2019), along with the simultaneous acquisition of data on topography (Akay *et al.*, 2009). Data of this type are now commonly used to study the height structure of forest cover (Sverdrup-Thygeson *et al.*, 2018; Farhadur Rahman *et al.*, 2022), tree species composition (Shi *et al.*, 2018), prediction of undergrowth yields (Bohlin *et al.*, 2021) or for fire monitoring (Wulder *et al.*, 2009; McCarley *et al.*, 2017).

Another of the main sources of information for the purposes of research on the long-term dynamics of changes in forest vegetation are aerial photographs (Fujita *et al.*, 2003; Harper *et al.*, 2007; Garzon-Lope *et al.*, 2013; Danneyrolles *et al.*, 2020). This form of data combines high spatial resolution, long range, and a longer possible time range compared to satellite imagery. Airborne data can be used in conjunction with spaceborne data (Varga *et al.*, 2015) or traditional cartographic studies (Cousins, 2001). Historical panchromatic photos are especially valuable in long-term analyses. They show the usage status from a time when no satellite imagery was available (Erener and Düzgün, 2009). Historical aerial photos can also be used as a data source to create point clouds (St-Onge *et al.*, 2015; Bożek *et al.*, 2019). Most often, motion-multi-view stereo (MVS) (Ishiguro *et al.*, 2016) or structure from motion (SfM) techniques are used for this purpose (Rodríguez-Vivancos *et al.*, 2022), which in addition to the analysis of tree crown coverage also allow for indirect monitoring of greenhouse gas emissions (Mlambo *et al.*, 2017) or above-ground biomass estimation (Ota *et al.*, 2015).

When highlighting laser scanning data and aerial photographs as the key data sources for the monitoring of forest areas, the development of the UAV technique should also be mentioned, which allows for faster and more accurate acquisition of both these types of data for the needs of detailed local research. Over the last dozen or so years, unmanned aerial vehicle (UAV) systems have been increasingly used in Europe to collect data for forest research (Torresan *et al.*, 2017). Due to the limited area of coverage, a large proportion of UAV-based applications in forest research are aimed at resource inventory, disease mapping, species classification (Hastings *et al.*, 2020), fire prevention (Fernández-Álvarez *et al.*, 2019) and quantification of spatial gaps (Torresan *et al.*, 2017). It seems that the use of UAVs in forestry will increase, which is likely to lead to regular use for small-scale monitoring purposes in Europe using hyperspectral sensors and LiDAR devices (Torresan *et al.*, 2017).

The presented research attempts to answer the question about the possibility of precisely depicting changes in the height structure of the stand in protected forested areas over a period of several dozen years, based on historic, stereoscopic aerial images and contemporary measurements made using the laser scanning technique. The possibility of diversifying forested areas due to the degree of their protection was assessed. An attempt was also made to answer the question whether the precision of depicting the height structure of an area practically entirely occupied by forest vegetation is sufficient to assess the dynamics of changes in forest cover and to record events resulting in the loss of this cover in the past. The presented research in the methodological part will present the process of processing historical photos into point clouds for the area of the Białowieża Primeval Forest, the largest area of lowland natural forests in Europe, divided into areas of strict protection and economically used forests. The processing of the obtained data sets into a frame of reference identical to modern height data sets made it possible to present a number of phenomena that have been observed in the Białowieża Primeval Forest over 30 years. The obtained results were the basis for a discussion on the observed changes in the afforestation structure by example of a few selected areas of the Białowieża Forest and, at the same time, on the possibilities and limitations of using the proposed technique in research on long-term changes in forested areas.

STUDY AREA. The research area is the Białowieża Primeval Forest (more precisely, six test areas with an area of 1 km^2 each), constituting a compact forest complex with an area of approximately 1500 km^2, located on the border of Poland and Belarus. It is considered a unique and very valuable forest object (Stereńczak, 2022). Some of the last large fragments of the primeval forest of the European lowlands have been preserved here within the Białowieża National Park. This area is one of those forests in Europe, where ecological processes have taken place since the last glaciation without direct human intervention (Cholewińska *et al.*, 2020), although some studies (Bobiec, 2012) indicate that the area is a remnant of an ecosystem to some extent shaped by man.

The area of the Białowieża Primeval Forest, regardless of its division by the border between countries, can be divided into areas of strict protection and active protection, as well as into economic forest lands that are not part of the Białowieża National Park. The location of the research area along with the breakdown according to the degree of protection is shown in Figure 1. The next two figures show the historical (1982, source: aerial photos, Fig. 2) and the current (2012, source: ALS data, Fig. 3) state of forest vegetation cover in selected test areas.

Despite the fact that only selected parts of the Białowieża Primeval Forest are under strict protection as a national park and nature reserves, the forest has been entirely recognized as

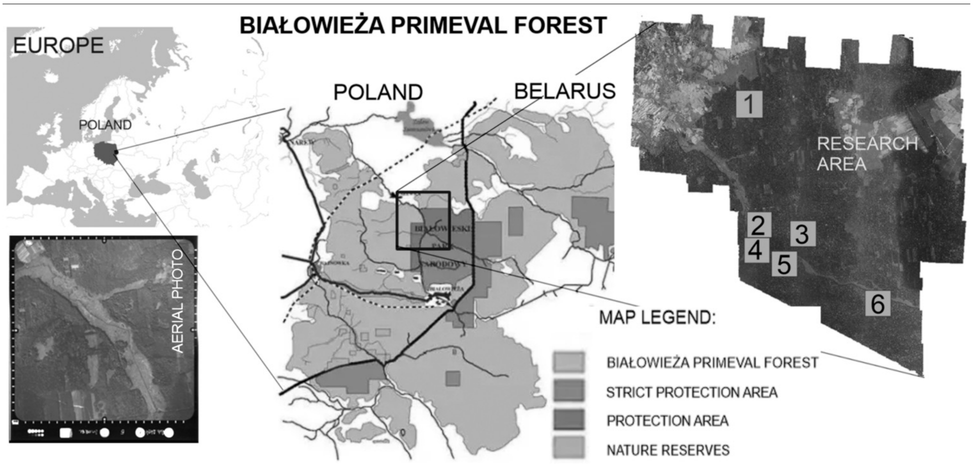

Fig. 1.
Location of the research area (Białowieża National Park) with a division into zones with different degrees of protection and location of the areas covered by detailed studies

a UNESCO natural heritage site since 1976, a biosphere reserve and an integrated Natura 2000 area (Kujawa *et al*., 2016). The Białowieża Primeval Forest is the only forest area in Europe with a temperate climate in which forest communities developed the natural structure of the stand (Bobiec, 2002; Mitchell and Cole, 1998). It is characterized by features related to the original

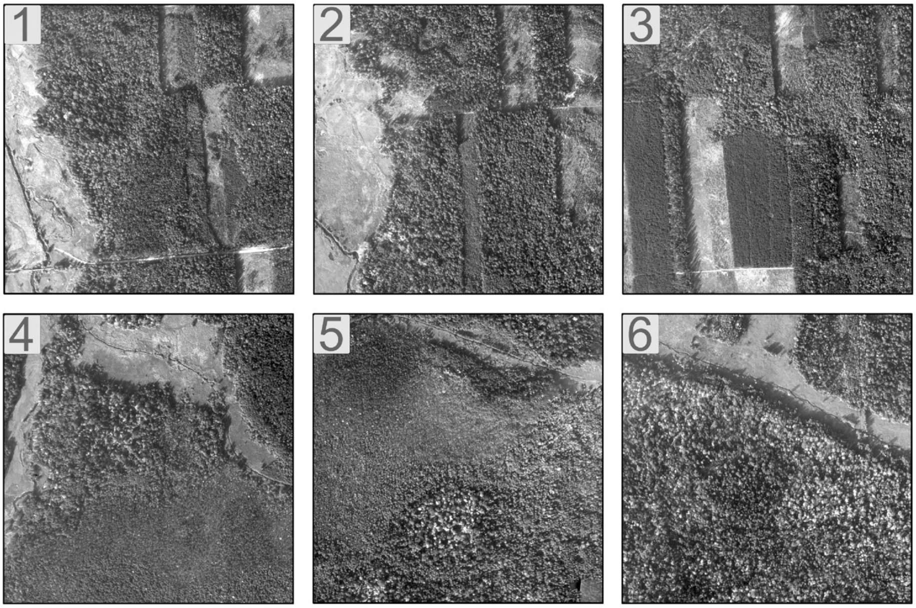

Fig. 2.
Historical aerial images which are the source of data for the year 1982 (size of each image: 1 km^2)

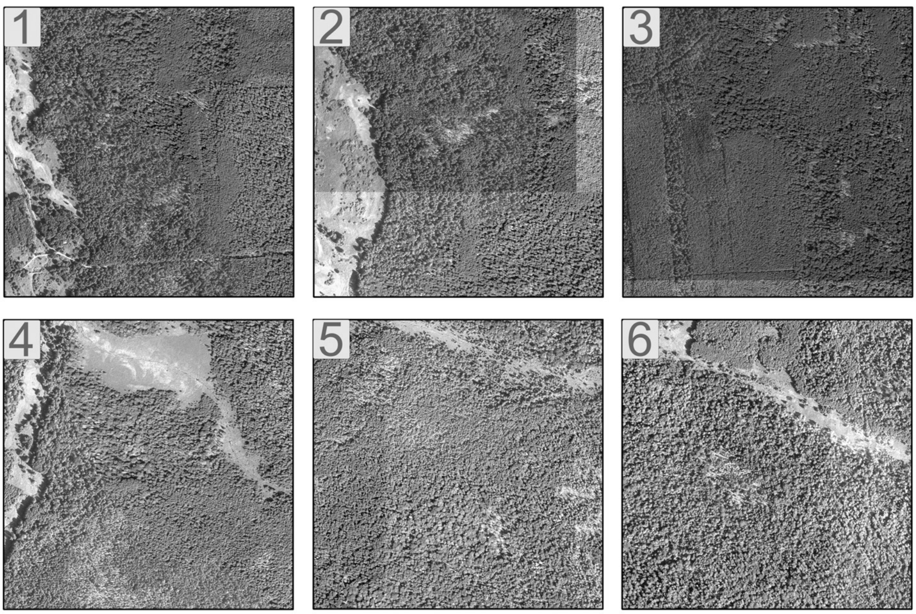

Fig. 3.
Contemporary images of the research area obtained in 2012 (size of each image: 1 km^2)

habitats, such as the stability of communities over time, high species richness, relatively low tree density (Czeszczewik and Walankiewicz, 2016; Brzeziecki *et al.*, 2020). The avifauna of the Białowieża Primeval Forest is also unique, mainly because it has retained most of its virgin features (Tomiałojć and Wesołowski, 2004). Therefore, it has the potential to present a model of forests that are unique in Europe and that are close to natural and require special protection

Methodology

The methodology used is based on the comparison of two point clouds: one set obtained from stereoscopic, historical aerial photos (photos taken in 1982) and a point cloud resulting from a modern measurement by airborne laser scanning (measurement made in 2012). However, in the final calculation process only information about the structure of the forest canopy was used, without data on the trees profile in the case of ALS data.

The main elements and stages of the data processing process are illustrated in Figure 4. The data used comes from publicly available collections managed by the Head Office of Land Surveying and Cartography in Poland (Polish abbreviation: GUGiK). In the process of generating the model based on archival photos, 55 photos were used, taken in 4 series in the north-south direction. The photos were taken on May 15, 1982. The flight altitude was 2200 m. The camera used during the flight had a lens with a focal length of 153.91 mm. The historical stereograms were digitized using a 2400-dots-per-inch (DPI) photogrammetric scanner, which resulted in a 14-μm pixel. For each photo, information about the approximate coordinates of the projection centres of the photos was also used.

The high-value data used in the presented study was acquired in 2012-2014 as part of the national ISOK project. For research, they were obtained from the Central Geodetic and Cartographic Documentation Center in the form of 1: 25,000 sheets (version 1.2 of the LAS format). The data received are georeferenced consistent with the PL-1992 (EPSG:2180) coordinate system and height reference frames PL-KRON86-NH. The density of point cloud was at least 4 points per m^2. The measurement was completed with the RIEGL LMS-Q680i laser scanner. Accuracy assessment of the point cloud geometry resulted in vertical (Z) and horizontal (XY) root mean square (RMS) errors of 0.15 m and 0.40 m, respectively. The given quantities were obtained from catalog data provided with LiDAR data from GUGiK. The minimum point density of SFM derived point cloud was 20 points per m^2.

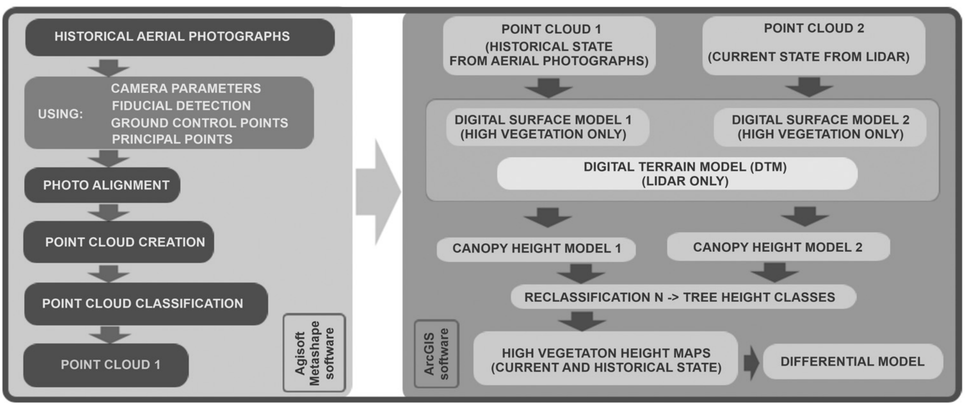

Fig. 4.

Diagram of data processing from the processing of historical aerial photos and modern data sets obtained by airborne laser scanning

Processing of historical photos was done using Agisoft Metashape™ software. In the first step, digitized historical images were imported. Then the known parameters of photos and cameras were introduced. The initial model building was performed using the Align Photos tool. The use of the Structure from Motion algorithm (Westoby *et al.*, 2012) allowed for the construction of a model illustrating the spatial extent of tree crowns. The created model was built in a local system, so it was transformed to the CS92 (EPSG 2180) coordinate system used in Poland using a set of ground control points with known coordinates (obtained on the basis of modern ALS data) which are identifiable in historical photos. GCP was used to orient the models to each other. 12 points were identified and used. The boundaries of cadastral plots and the boundaries of land use were used, which most likely have not changed over the years, based on the analysis of source data. 4 points were used in the model orientation process, 8 were used for control in the Agisoft Metashape™ program. XY coordinates were obtained from the vertices of the cadastral plots. Point heights were obtained from the DTM model from the LiDAR cloud. The obtained position errors did not exceed 0.3 m for the XY axis and 0.4 m for Z, both for the points involved in model alignment and for the control points.

On the basis of the obtained model, a point cloud representing the land cover was generated. The created point cloud from archival photos was classified, resulting in layers containing points representing the ground and woody vegetation, then a DTM raster model and a DSM raster model containing only woody vegetation were created. Then the difference of the two raster models created the CHM. For the LiDAR point cloud, the classification process was omitted because it was already classified. Then DSM and DTM were created, and the difference of the two models allowed for the creation of CHM. In the process of converting point clouds, an algorithm was used to generate meshes in a raster equal to 4 m^2, where the largest value from the mesh area assumes the value for it. As a result, only those points were left that represented vegetation over 2 m high, whose height relative to the ground was greater than 2 m. The result datasets were saved in the *.las format, and then used in the next steps carried out with ArcMap™ software (part of the ArcGIS ™ environment). Two point clouds from historical image processing and LiDAR measurement were used to create two Canopy Height Models (CHMs). This allowed for the determination of the contemporary and historical height structure of afforestation and the changes that took place during that period (the differential model). In each of the cases, the mesh size of the raster was 2 m (4 m^2).

Results

As a result of the application of the described methodology, a number of resulting data sets were obtained. The first of them, shown in Figure 5, represents the height structure of vegetation in 1982 obtained as a result of processing historical aerial photographs. The figure shows the division into areas 1, 2 and 3 located in the part of the Białowieża Forest with commercial forest management and areas 4, 5 and 6 located in the part under strict protection. This division will also be maintained at the stage of presenting the next described result sets. Figure 6 shows the contemporary height structure of vegetation obtained on the basis of airborne laser scanning data. The colour scale used is the same as in the case of the historical aerial photos.

The next resulting data set (differential model – Fig. 7) is the result of a comparison of changes in the height structure of the forest vegetation between the historical and present state.

The data that were used to generate historical and contemporary stand heights and to create a differential model can also be presented using a series of histograms representing the variability of the area covered by individual height categories of trees. Figure 8 shows these curves for each

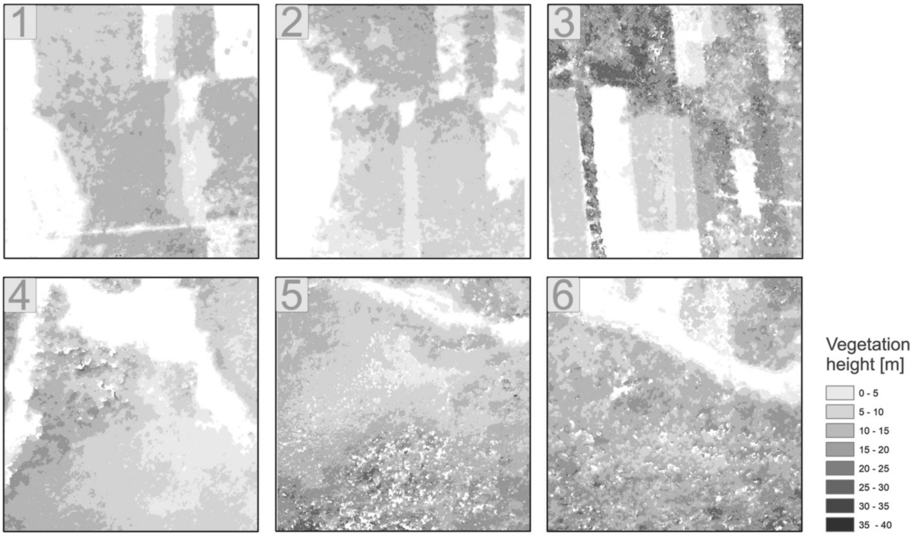

Fig. 5.
Map of the height of vegetation in the historical state obtained as a result of the processing aerial photographs (1982 year); size of each area: 1 km^2

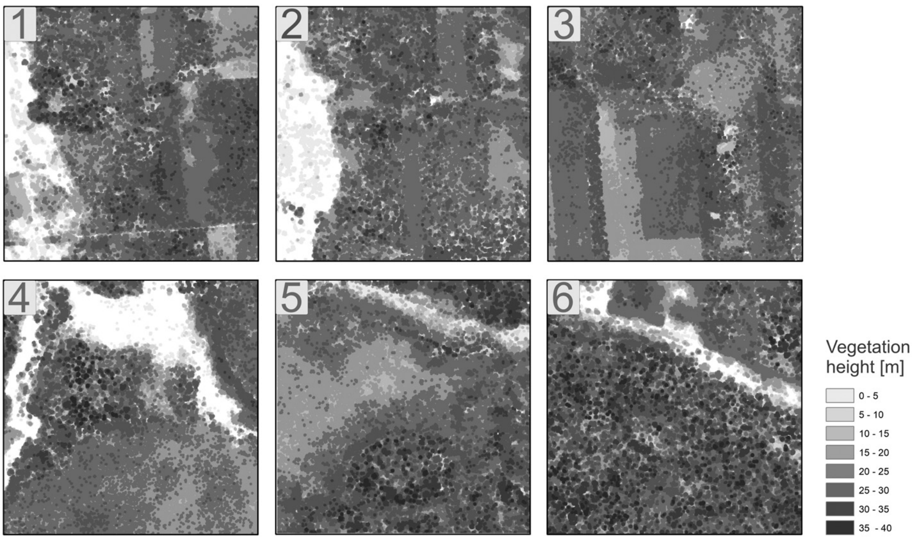

Fig. 6.
Map of vegetation height obtained by processing data sets produced by processing ALS data (2012 year); size of each area: 1 km^2

of the studied areas, including their courses for the historical and contemporary state and the differences between the two previous sets.

Discussion

The obtained results show a great potential for the use of historical aerial photographs in combination with modern laser scanning measurements for long-term analyses of changes in forest-covered areas. The ability to accurately reproduce the three-dimensional structure of vegetation

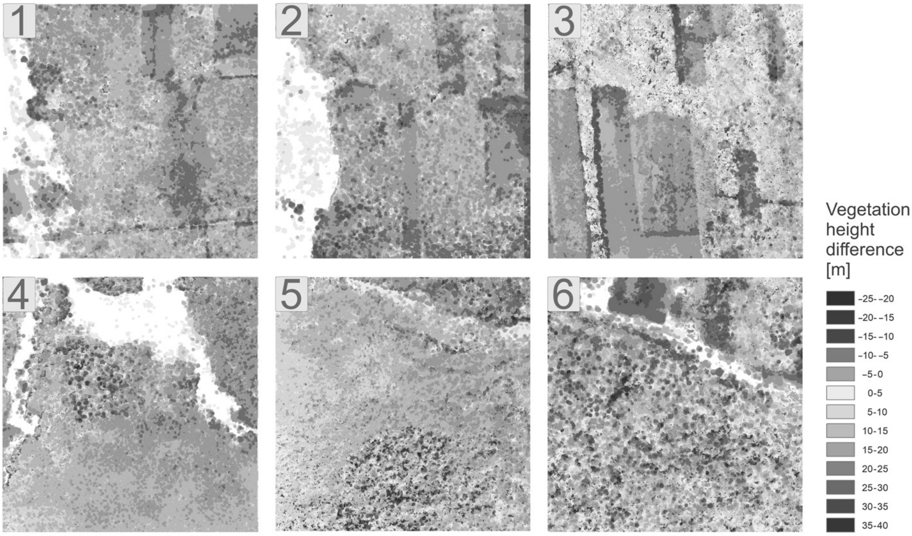

Fig. 7.

Height difference showing changes in the amount of afforestation recorded in the period 1982-2012; size of each area: 1 km^2

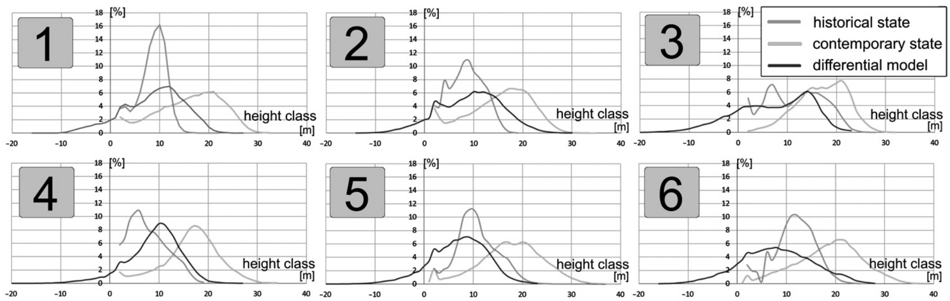

Fig. 8.

Curves showing the variability of the area occupied by individual height classes of vegetation: for the historical state, today, and with a differential approach

for a period reaching back several dozen years may be a valuable element of many studies, especially in areas with limited access due to the requirements of nature protection.

Both the attempt to recreate the historical state and the measurement of the current state are carried out in a way that does not require physical presence in the area under study, except for flights to conduct measurements with laser scanning with the use of traditional airplanes or with the use of UAV devices. The research area covered both the part of the Białowieża National Park under strict protection (sub-areas 1, 2, 3) and the part with the status of managed forests (sub-areas 4, 5 and 6). One of the objectives of the study was to verify the thesis that the characteristics of the height structure, and especially their changes over time, should differ depending on the degree of protection of a given area (although for the small areas studied, this thesis has not been positively verified). In both cases, the methodology used makes it possible to effectively monitor the increase in forest height over long periods of time, but also to monitor the occurrence of phenomena which reduce forest cover as a result of natural phenomena, planned logging or illegal logging.

The selection of test areas was designed in such a way as to cover both areas under long-term strict protection and those where ordinary forest management is carried out. The three-dimensional structure of afforestation shown in Figure 5, representing the state in 1982, shows the great potential of such a method even for densely afforested areas, as in the case of the Białowieża Primeval Forest. This makes it possible to create vegetation height maps, but also land use maps, taking into account the division into agricultural, forested or wooded areas, with an accuracy not available for methods using the first generation of satellite imagery.

The aim of the research was to present long-term changes in the height structure of tree crowns in the study area. The methodology used should therefore be adjusted to the assumed goal. Differences in the two result sets are an obstacle in the effective comparison of the height structure in historical and contemporary terms. The mapping of tree crown occupancy in the historical perspective, due to the oblique photographing of most trees within individual photos, is characterized by the lack of photographing of small gaps in the afforestation, an apparent increase in the height of the space between individual trees and an almost continuous coverage of the forested area with height data.

The second, modern data set, due to the technology used (LiDAR measurement), reflects even small gaps in the afforestation very well, so that the area covered by tree crowns seems to be much smaller than in the case of data from historical photos. In order to standardize the area covered by tree canopy in both height models, while maintaining the maximum height recorded in a specific, small area, it was decided to introduce an additional calculation step into LiDAR data processing. The principle of resampling performed (while maintaining the size of a single raster cell at 4 m^2, which results from the adopted size of the grid with sides of 2 m) is to determine the height of each cell on the basis of the maximum height value observed within a radius of 4 m from the centre of a given cell. This action led the LiDAR data to characteristics similar to those from historical photos, while maintaining the two most key parameters: crown occupancy and their local maximum height. The data on each of the three obtained afforestation models (historical, contemporary, differential) were also used to create a series of curves illustrating the distribution of individual height classes of a given model and their areas.

The charts presented in Figure 8 aims to reflect the characteristics of the afforestation structure in both analysed years, that is in 1982 and in 2012. This also applies to the changes that took place during this period. Based on the shapes of the selected curves, it is also possible to infer the type of the analysed area. The economically exploited areas are characterized by a more irregular shape of the afforestation height curve, which in some cases may have a larger number of local peaks. In such cases, there may also be fragments with steep curves. This is related to the periodic clear cut areas of the forest and subsequent plantings. The mutual shift of the curves representing the historical and contemporary states not only allows for conclusions about specific events from the past resulting in a change in forest cover, but also allows for the determination with some accuracy of the age (or rather the stage of development) of the stand at the time of recording of the historical and contemporary state. Knowledge of the variability of increases in tree height as a function of time is helpful in this. The curves representing this phenomenon are sigmoidal (Pödör *et al.*, 2014), which means that the height of trees increases approximately linearly with time only for the middle part of their life. In the initial period, the forest grows slower, but especially after it reaches maturity, the annual height increases of trees are smaller and smaller.

The differential model of afforestation showing changes recorded over a long period of time can be presented in the form of a spatial analysis and a graph presenting the balance of changes in individual height categories. However, the reliability of the information provided by the differential model depends most on the accuracy of the XY position of the output DSM models. Interpretation of both of these elements may have different applications. The graph shows the changes in occupancy by individual height categories, it can be used for an approximate balance of terrestrial biomass contained in wood, but also to assess the dynamics of changes in the structure of tall vegetation over time and to try to identify the nature of these changes. The spatial data of the differential model (Fig. 7) show the location of changes in the height of forest vegetation over the time covered by the study. In this way, it is possible to locate areas where no events were recorded, apart from the natural increase in the height of the forest cover (depending on its age at the beginning of the study, species composition and parameters of the habitat). It is also possible to indicate places where any changes other than natural ones in the structure of the forest took place, along with the determination of their area and nature.

The differential model (Fig. 7) shows places where the analysis shows a local decrease in the height of tree crowns. This may indicate events which resulted in the loss of forest cover in the past due to natural causes or deliberate human activity. The nature of these changes can be inferred from the size and shape of the observed gap. At the same time, based on the difference in height from the difference model and the height of trees from the modern model, it is also possible to ascertain the time of a specific event in the past with a certain accuracy. In the protected areas of the Białowieża Primeval Forest, most of the currently observed gaps in afforestation are a consequence of the dieback of spruce groups (Bobiec, 2007). A comprehensive inventory of such cases seems possible in this, and similar cases, using the proposed method.

Among the others potential applications of the method described, the possibility of identifying illegal logging in the past should also be indicated. The possibility of using remote sensing techniques in monitoring this type of change was indicated by Kuemmerle *et al.* (2009) in their research.

Existing monitoring systems for protected areas in Europe are still not sufficiently developed and can be significantly improved (Gaston *et al.*, 2008). This applies in particular to many countries in South-Eastern and Eastern Europe, where the importance of monitoring and protecting primeval forests was noticed often only in the early 1990s (Veen *et al.*, 2010). Having a model of changes in the structure of vegetation, which stretches back to the oldest available sources of stereoscopic aerial photos, through several intermediate stages, to measurements repeated cyclically every few years using the laser scanning method would fit well in the modern process of monitoring areas covered with forest vegetation. It also enables the construction of projection models determining changes in forest vegetation in the future (Lindner *et al.*, 2010), including those relating to natural forest communities (Hickler *et al.*, 2012). Undoubtedly, the use of UAVs equipped with traditional and multispectral cameras and laser scanners in research and monitoring of forested areas will increase (Torresan *et al.*, 2017), which is likely to lead to the regular use of this technique for small-scale monitoring purposes in Europe.

The proposed method of obtaining data also has its limitations. The first is the availability of historical data for specific areas, showing the structure of afforestation at a given time. Coverage with historical aerial photos varies greatly from region to region. These photos are characterized by high variability in terms of flight altitude, parameters of aerial cameras, as well as the photographic quality of the negatives. Adjacent areas may be covered by several series of photos taken in different years. Undoubtedly, obtaining a set of data useful for generating a point cloud representing the historical state of the data is not possible in every case.

The second disadvantage of the proposed data processing method is related to the process of recreating the three-dimensional structure of vegetation in a historical perspective. Aerial photos, especially those taken several dozen years ago, constitute a collection of data with a large variability of the parameters used at the time they were taken, only some of which are known at present. The quality of these materials also varies. In many cases, it is not possible to create three-dimensional models using traditional photogrammetry techniques. In such cases, it is possible to perform this task using other approaches, including the Structure from Motion (SfM) algorithm used in this case. However, in the case of areas covered mainly with dense forests, this is associated with a reduction in the orientation accuracy of the generated point cloud and the height model created using this cloud. It is not possible to obtain a sufficient number of control points with known XYZ coordinates, which are necessary for the correct orientation of the created point cloud in the absence of all data regarding the image acquisition process, such as flight parameters, aerial camera parameters and photos.

However, existing research indicates that the use of analogue classic aerial photos to determine the height of the forest canopy has certain limitations (Korpela and Anttila, 2004), mainly related to the uncertainty in the horizontal and altitudinal accuracy of the obtained results. The use of modern digital photographs allows us to obtain more accurate results (Balenović *et al.*, 2015). However, the key issue is the selection of appropriate points that enable appropriate placement of the created models in space. The best solution is to use points identified and measured directly in the field (Stepper *et al.*, 2014); however, this approach is significantly difficult (and sometimes impossible) when using historical photos.

As mentioned, the accuracy of the results obtained based on historical photos is largely dependent on the correct selection of appropriate control points and obtaining their correct parameters in terms of plane coordinates and heights. An additional difficulty is conducting the analysis in an area covered with forests, which makes it difficult to identify control points using appropriate parameters. A solution to this problem is the analysis carried out within measurement fields of 4 m^2, although adopting a larger field size could increase the reliability of the results (while reducing their spatial resolution). It is necessary to plan and perform research aimed at assessing the impact of the number, location, and accuracy of control points (including the possible occurrence of significant errors in the positions of these points) on the final results of both the single models of the historical forest canopy and the differential data between the historical state and data. obtained using modern measurement techniques, both ALS data and point clouds were obtained by processing the digital aerial photographs.

Conclusions

The obtained results indicate the possibility of precise monitoring of changes in forest cover, both in relation to its growth and loss of this cover caused by human activity or natural causes. The differential model and the interpretation of the family of curves representing the characteristics of historical and contemporary afforestation seem particularly useful for this purpose. The conducted studies, covering relatively small areas of the Białowieża Forest, are encouraging for wider attempts to use the proposed methodology for the study of long-term changes in forest cover covering much larger areas of protected forests and other forested areas with low accessibility. This method can also be used when trying to estimate long-term changes in carbon accumulation in wooded areas or changes in use associated with the abandonment of land cultivation in marginal areas.

The great advantage of using historical, stereoscopic aerial images is the ability to reproduce the three-dimensional structure of tree crowns for periods dating back to periods earlier than the first generation of observation satellites. The disadvantage of using historical aerial photos to create point clouds is the need to adjust the methodology to differentiate the quality of the input data, and the availability of data determining the parameters which applied when the photos were taken. Another limitation is the fact that the availability of source materials enabling the construction of an afforestation model is usually limited to a few selected periods over the last several dozen years.

The proposed method may be an element in improving the quality of models predicting future changes in forest cover. The presented method should also be an effective solution enabling the differentiation of natural areas from those affected by the human economy, although this requires further research into the analysis of the observed disorders and their classification.

Authors' contributions

J.J. – conceptualization, methodology, writing-original draft, writing-review & editing, formal analysis, project administration; P.B. – methodology, software, formal analysis, investigation; J.T. – resources, investigation; A.D. – resources, investigation.

Conflicts of interest/Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Funding

Research funding source Ministry of Science and Higher Education for the University of Agriculture in Krakow.

References

Akay, A.E., Oguz, H., Karas, I. R., Aruga, K., 2009. Using LiDAR technology in forestry activities. *Environmental Monitoring and Assessment*, 151: 117-125. DOI: https://doi.org/10.1007/s10661-008-0254-1.

Balenović, I., Seletković, A., Pernar, R., Jazbec, A., 2015. Estimation of the mean tree height of forest stands by photogrammetric measurement using digital aerial images of high spatial resolution. *Annals of Forest Research*, 58 (1): 125-143. DOI: https://doi.org/10.15287/afr.2015.300.

Będkowski, K., 2004. Skanowanie laserowe i jego zastosowanie w leśnictwie (Laser scanning and its application in forestry). *Roczniki Geomatyki*, 4: 33-40.

Będkowski, K., 2005. Fotogrametryczna metoda oceny stanu i zmian wysokościowej struktury warstwy koron w drzewostanach. (Photogrammetric method for the assessment of the forest canopy vertical structure condition and change). Rozprawy i Monografie Naukowe. Warszawa: Wydawnictwo SGGW, 208 pp.

Birdseye, C.H., 1940. Stereoscopic phototopographic mapping. *Annals of the Association of American Geographers*, 30 (1): 1-24. DOI: https://doi.org/10.1080/00045604009357193.

Bobiec, A., 2002. Living stands and dead wood in the Białowieża forest: Suggestions for restoration management. *Forest Ecology and Management*, 165 (1-3): 125-140. DOI: https://doi.org/10.1016/S0378-1127(01)00655-7.

Bobiec, A., 2007. The influence of gaps on tree regeneration: A case study of the mixed lime-hornbeam (Tilio-Carpinetum Tracz. 1962) communities in the Białowieża Primeval Forest. *Polish Journal of Ecology*, 55 (3): 441-455.

Bobiec, A., 2012. Białowieża Primeval Forest as a remnant of culturally modified ancient forest. *European Journal of Forest Research*, 131 (5): 1269-1285. DOI: https://doi.org/10.1007/s10342-012-0597-6.

Bohlin, I., Maltamo, M., HedenÍs, H., LämÍs, T., Dahlgren, J., Mehtätalo, L., 2021. Predicting bilberry and cowberry yields using airborne laser scanning and other auxiliary data combined with National Forest Inventory field plot data. *Forest Ecology and Management*, 502: 119737. DOI: https://doi.org/10.1016/j.foreco.2021.119737.

Bour, B., Danneyrolles, V., Boucher, Y., Fournier, R.A., Guindon, L., 2021. Modeling post-logging height growth of black spruce-dominated boreal forests by combining airborne LiDAR and time since harvest maps. *Forest Ecology and Management*, 502: 119697. DOI: https://doi.org/10.1016/j.foreco.2021.119697.

Bożek, P., Janus, J., Mitka, B., 2019. Analysis of changes in forest structure using point clouds from historical aerial photographs. *Remote Sensing*, 11 (19): 2259. DOI: https://doi.org/10.3390/rs11192259.

Brzeziecki, B., Woods, K., Bolibok, L., Zajączkowski, J., Drozdowski, S., Bielak, K., Żybura, H., 2020. Over 80 years without major disturbance, late-successional Białowieża woodlands exhibit complex dynamism, with coherent compositional shifts towards true old-growth conditions. *Journal of Ecology*, 108 (3): 1138-1154. DOI: https://doi.org/10.1111/1365-2745.13367.

Cegielska, K., Noszczyk, T., Kukulska, A., Szylar, M., Hernik, J., Dixon-Gough, R., Jombach, S., Valanszki, I., Filepné Kovács, K., 2018. Land use and land cover changes in post-socialist countries: Some observations from Hungary and Poland. *Land Use Policy*, 78: 1-18. DOI: https://doi.org/10.1016/j.landusepol.2018.06.017.

Cholewińska, O., Adamowski, W., Jaroszewicz, B., 2020. Homogenization of temperate mixed deciduous forests in Białowieża forest: Similar communities are becoming more similar. *Forests*, 11: 545. DOI: https://doi.org/10.3390/F11050545.

Cousins, S.A.O., 2001. Analysis of land-cover transitions based on 17th and 18th century cadastral maps and aerial photographs. *Landscape Ecology*, 16: 41-54. DOI: https://doi.org/10.1023/A:1008108704358.

Czerepko, J., Gawryś, R., Mańk, K., Janek, M., Tabor, J., Skalski, Ł., 2021. The influence of the forest management in the Białowieża forest on the species structure of the forest community. *Forest Ecology and Management*, 496: 119363. DOI: https://doi.org/10.1016/j.foreco.2021.119363.

Czeszczewik, D., Walankiewicz, W., 2016. Ecology and biology of birds in the Białowieża Forest: A 40-year perspective. *Forest Research Papers*, 77 (4): 332-340. DOI: https://doi.org/10.1515/frp-2016-0034.

Danneyrolles, V., Valeria, O., Djerboua, I., Gauthier, S., Bergeron, Y., 2020. How initial forest cover, site characteristics and fire severity drive the dynamics of the southern boreal forest. *Remote Sensing*, 12 (23): 3957. DOI: https://doi.org/10.3390/rs12233957.

Farhadur Rahman, M., Onoda, Y., Kitajima, K., 2022. Forest canopy height variation in relation to topography and forest types in central Japan with LiDAR. *Forest Ecology and Management*, 503: 119792. DOI: https://doi.org/10.1016/j.foreco.2021.119792.

Fernández-Álvarez, M., Armesto, J., Picos, J., 2019. LiDAR-based wildfire prevention in WUI: The automatic detection, measurement and evaluation of forest fuels. *Forests*, 10: 148. DOI: https://doi.org/10.3390/f10020148.

Fujita, T., Itaya, A., Miura, M., Manabe, T., Yamamoto, S.I., 2003. Long-term canopy dynamics analysed by aerial photographs in a temperate old-growth evergreen broad-leaved forest. *Journal of Ecology*, 91 (4): 686-693. DOI: https://doi.org/10.1046/j.1365-2745.2003.00796.x.

Garzon-Lopez, C.X., Bohlman, S.A., Olff, H., Jansen, P.A., 2013. Mapping tropical forest trees using high-resolution aerial digital photographs. *Biotropica*, 45 (3): 308-316. DOI: https://doi.org/10.1111/btp.12009.

Gaston, K.J., Jackson, S.F., Nagy, A., Cantú-Salazar, L., Johnson, M., 2008. Protected areas in Europe: Principle and practice. *Annals of the New York Academy of Sciences*, 1134 (1): 97-119. DOI: https://doi.org/10.1196/annals.1439.006.

Harper, G.J., Steininger, M.K., Tucker, C.J., Juhn, D., Hawkins, F., 2007. Fifty years of deforestation and forest fragmentation in Madagascar. *Environmental Conservation*, 34 (4): 325-333. DOI: https://doi.org/10.1017/S0376892907004262.

Hastings, J.H., Ollinger, S.V., Ouimette, A.P., Sanders-DeMott, R., Palace, M.W., Ducey, M.J., Sullivan, F.B., Basler, D., Orwig, D.A., 2020. Tree species traits determine the success of LiDAR-based crown mapping in a mixed temperate forest. *Remote Sensing*, 12: 309. DOI: https://doi.org/10.3390/rs12020309.

Hickler, T., Vohland, K., Feehan, J., Miller, P.A., Smith, B., Costa, L., Giesecke, T., Fronzek, S., Carter, T.R., Cramer, W., Kühn, I., Sykes, M.T., 2012. Projecting the future distribution of European potential natural vegetation zones with a generalized, tree species-based dynamic vegetation model. *Global Ecology and Biogeography*, 21 (1): 50-63. DOI: https://doi.org/10.1111/j.1466-8238.2010.00613.x.

Ishiguro, S., Yamano, H., Oguma, H., 2016. Evaluation of DSMs generated from multi-temporal aerial photographs using emerging structure from motion-multi-view stereo technology. *Geomorphology*, 268: 64-71. DOI: https://doi.org/10.1016/j.geomorph.2016.05.029.

Janus, J., Bozek, P., 2019. Land abandonment in Poland after the collapse of socialism: Over a quarter of a century of increasing tree cover on agricultural land. *Ecological Engineering*, 138: 106-117. DOI: https://doi.org/10.1016/j.ecoleng.2019.06.017.

Kaplan, J.O., Krumhardt, K.M., Zimmermann, N., 2009. The prehistoric and preindustrial deforestation of Europe. *Quaternary Science Reviews*, 28 (27-28): 3016-3034. DOI: https://doi.org/10.1016/j.quascirev.2009.09.028.

Koch, B., Heyder, U., Weinacker, H., 2006. Detection of individual tree crowns in airborne lidar data. *Photogrammetric Engineering and Remote Sensing*, 4: 357-363. DOI: https://doi.org/10.14358/PERS.72.4.357.

Kolecka, N., Kozak, J., Kaim, D., Dobosz, M., Ostafin, K., Ostapowicz, K., Price, B., 2017. Understanding farmland abandonment in the Polish Carpathians. *Applied Geography*, 88: 62-72. DOI: https://doi.org/10.1016/j.apgeog.2017.09.002.

Kolendo, Ł., Ksepko, M., 2019. Selection of optimal tree top detection parameters in a context of effective forest management. *Ekonomia i Środowisko*, 1 (68): 67-85. DOI: https://doi.org/10.34659/pjxd-gh10.

Korpela, I., Anttila, P., 2004. Appraisal of the mean height of trees by means of image matching of digitised aerial photographs. *Photogrammetric Journal of Finland*, 19: 23-36.

Kujawa, A., Orczewska, A., Falkowski, M., Blicharska, M., Bohdan, A., Buchholz, L., Chylarecki, P., Gutowski, J.M., Latałowa, M., Mysłajek, R.W., Nowak, S., Walankiewicz, W., Zalewska, A., 2016. The Białowieża Forest – a UNESCO Natural Heritage Site – protection priorities. *Forest Research Papers*, 77: 302-323. DOI: https://doi.org/10.1515/frp-2016-0032.

Kurowska, K., Kryszk, H., Marks-Bielska, R., Mika, M., Leń, P., 2020. Conversion of agricultural and forest land to other purposes in the context of land protection: Evidence from Polish experience. *Land Use Policy*, 95: 104614. DOI: https://doi.org/10.1016/j.landusepol.2020.104614.

van Leeuwen, M., Nieuwenhuis, M., 2010. Retrieval of forest structural parameters using LiDAR remote sensing. *European Journal of Forest Research*, 129: 749-770. DOI: https://doi.org/10.1007/s10342-010-0381-4.

Lenoir, J., Gril, E., Durrieu, S., Horen, H., Laslier, M., Lembrechts, J.J., Decocq, G., 2022. Unveil the unseen: Using LiDAR to capture time-lag dynamics in the herbaceous layer of European temperate forests. *Journal of Ecology*, 110 (2): 282-300. DOI: https://doi.org/10.1111/1365-2745.13837.

Lindner, M., Maroschek, M., Netherer, S., Kremer, A., Barbati, A., Garcia-Gonzalo, J., Machetti, M., 2010. Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems. *Forest Ecology and Management*, 259 (4): 698-709. DOI: https://doi.org/10.1016/j.foreco.2009.09.023.

Liu, Z., Zhang, T., Yu, J., Zhou, L., 2019. Determinants of rural households' afforestation program participation: Evidence from China's Ningxia and Sichuan provinces. *Global Ecology and Conservation*, 17: e00533. DOI: https://doi.org/10.1016/j.gecco.2019.e00533.

Maiorano, L., Amori, G., Montemaggiori, A., Rondinini, C., Santini, L., Saura, S., Boitani, L., 2015. On how much biodiversity is covered in Europe by national protected areas and by the Natura 2000 network: Insights from terrestrial vertebrates. *Conservation Biology*, 29 (4): 986-995. DOI: https://doi.org/10.1111/cobi.12535.

Marín, A.I., Abdul Malak, D., Bastrup-Birk, A., Chirici, G., Barbati, A., Kleeschulte, S., 2021. Mapping forest condition in Europe: Methodological developments in support to forest biodiversity assessments. *Ecological Indicators*, 128. 107839. DOI: https://doi.org/10.1016/j.ecolind.2021.107839.

Martinez del Castillo, E., García-Martin, A., Longares Aladrén, L.A., de Luis, M., 2015. Evaluation of forest cover change using remote sensing techniques and landscape metrics in Moncayo Natural Park (Spain). *Applied Geography*, 62: 247-255. DOI: https://doi.org/10.1016/j.apgeog.2015.05.002.

McCarley, T.R., Kolden, C.A., Vaillant, N.M., Hudak, A.T., Smith, A.M.S., Wing, B.M., Kellogg, B.S., Kreitler, J., 2017. Multi-temporal LiDAR and Landsat quantification of fire-induced changes to forest structure. *Remote Sensing of Environment*, 191: 419-432. DOI: https://doi.org/10.1016/j.rse.2016.12.022.

Meyfroidt, P., Lambin, E.F., 2011. Global forest transition: Prospects for an end to deforestation. *Annual Review of Environment and Resources*, 36: 343-371. DOI: https://doi.org/10.1146/annurev-environ-090710-143732.

Mitchell, F.J.G., Cole, E., 1998. Reconstruction of long-term successional dynamics of temperate woodland in Bialowieża Forest, Poland. *Journal of Ecology*, 86 (6): 1042-1059. DOI: https://doi.org/10.1046/j.1365-2745.1998.00323.x.

Mozgawa, J., 1977. Teledetekcyjna metoda badania obszarów leśnych. (Remote sensing for studying forest regions). *Sylwan*, 121 (5): 33-40.

Mozgawa, J., 1980. Lotnicze fotografie wielospektralne jako źródło informacji o obszarach leśnych. (Multispectral air photography as a source of information about forest regions). *Sylwan*, 124 (11): 11-20.

Mozgawa, J., 1985. Metodologiczne podstawy wykorzystania fotointerpretacji do modelowania systemowego w drzewostanach. Rozprawy naukowe i monografie. Warszawa: Wydawnictwo SGGW-AR, 67 pp.

Mlambo, R., Woodhouse, I.H., Gerard, F., Anderson, K., 2017. Structure from motion (SfM) photogrammetry with drone data: A low cost method for monitoring greenhouse gas emissions from forests in developing countries. *Forests*, 8 (3): 68. DOI: https://doi.org/10.3390/f8030068.

Muchová, Z., Tárníková, M., 2018. Land cover change and its influence on the assessment of the ecological stability. *Applied Ecology and Environmental Research*, 16 (3): 2169-2182. DOI: https://doi.org/10.15666/aeer/1603_21692182.

Munteanu, C., Kuemmerle, T., Boltiziar, M., Butsic, V., Gimmi, U., Halada L, Kaim, Kiraly, G., Konkoly-Gyuró, E., Kozak, J., Lieskovský, J., Moises, M., Müller, D., Ostafin, K., Ostapowicz, K., Shandra, O., Štych, P., Walker, S., Radeloff, V.C., 2014. Forest and agricultural land change in the Carpathian region – A meta-analysis of long-term patterns and drivers of change. *Land Use Policy*, 38: 685-697. DOI: https://doi.org/10.1016/j.landusepol.2014.01.012.

Niklasson, M., Zin, E., Zielonka, T., Feijen, M., Korczyk, A.F., Churski, M., Brzeziecki, B., 2010. A 350-year tree-ring fire record from Białowieża Primeval Forest, Poland: Implications for Central European lowland fire history. *Journal of Ecology*, 98 (6): 1319-1329. DOI: https://doi.org/10.1111/j.1365-2745.2010.01710.x.

Noszczyk, T., Rutkowska, A., Hernik, J., 2020. Exploring the land use changes in Eastern Poland: statistics-based modeling. *Human and Ecological Risk Assessment: An International Journal*, 26 (1): 255-282. DOI: https://doi.org/10.1080/10807039.2018.1506254.

OECD, 2011 The economic significance of natural resources: key points for reformers in Eastern Europe, Caucasus and Central Asia. Paris: OECD Publishing, 42 pp.

Ota, T., Ogawa, M., Shimizu, K., Kajisa, T., Mizoue, N., Yoshida, S., Ket, N., 2015. Aboveground biomass estimation using structure from motion approach with aerial photographs in a seasonal tropical forest. *Forests*, 6: 3882-3898. DOI: https://doi.org/10.3390/f6113882.

Ørka, H.O., Jutras-Perreault, M.C., Næsset, E., Gobakken, T., 2022. A framework for a forest ecological base map – An example from Norway. *Ecological Indicators*, 136: 108636. DOI: https://doi.org/10.1016/j.ecolind.2022.108636.

Parviainen, J., 2005. Virgin and natural forests in the temperate zone of Europe. *Forest Snow and Landscape Research*, 79 (1-2): 9-18.

Piekarski, E., 1972. Czynniki wpływające na dokładność określania wysokości drzew stereoskopowymi przyrządami fotogrametrycznymi. Zeszyty Naukowe SGGW, Leśnictwo, 17, pp. 135-153.

Piekarski, E., 1974. Niektóre fotogrametryczne metody określania wysokości drzew i drzewostanów. (Some photogrammetric techniques of the determination of tree and stand height). *Sylwan*, 118 (8): 46-53.

Piekarski, E., Będkowski, K., 1991. Fotografia lotnicza jako źródło informacji o lesie – fotogrametryczna taksacja drzewostanów i inwentaryzacja zapasu. In: *Metody oceny stanu i zmian zasobów leśnych*. Warszawa: Wydawnictwo SGGW-AR, pp. 105-118.

Pödör, Z., Manninger, M., Jereb, L., 2014. Application of sigmoid models for growth investigations of forest trees. In: T. Do, H.A.L. Thi, N.T. Nguyen, eds. *Advanced computational methods for knowledge engineering*, pp. 353-364. DOI: https://doi.org/10.1007/978-3-319-06569-4_26.

Rodrigues, A.S.L., Andelman, S.J., Bakan, M.I., Boitani, L., Brooks, T.M., Cowling, R.M., Yan, X., 2004. Effectiveness of the global protected area network in representing species diversity. *Nature*, 428: 640-643. DOI: https://doi.org/10.1038/nature02422.

Rodríguez-Vivancos, A., Manzanera, J.A., Martín-Fernández, S., García-Cimarras, A., García-Abril, A., 2022. Analysis of structure from motion and airborne laser scanning features for the evaluation of forest structure. *European Journal of Forest Research*, 141 (3): 447-465. DOI: https://doi.org/10.1007/s10342-022-01447-7.

Prada, M., Canga, E., Majada, J., Martínez-Alonso, C., 2022. Canopy characterization of sweet chestnut coppice in the north of Spain from lidar data. *European Journal of Forest Research*, 141 (2): 267-279. DOI: https://doi.org/10.1007/s10342-021-01436-2.

Sabatini, F.M., Bluhm, H., Kun, Z., Aksenov, D., Atauri, J.A., Buchwald, E., Kuemmerle, T., 2021. European primary forest database v2.0. *Scientific Data*, 8 (1): 220. DOI: https://doi.org/10.1038/s41597-021-00988-7.

Sabatini, F.M., Burrascano, S., Keeton, W.S., Levers, C., Lindner, M., Pötzschner, F., Kuemmerle, T., 2018. Where are Europe's last primary forests? *Diversity and Distributions*, 24 (10): 1426-1439. DOI: https://doi.org/10.1111/ddi.12778.

Shi, Y., Wang, T., Skidmore, A.K., Heurich, M., 2018. Important LiDAR metrics for discriminating forest tree species in Central Europe. *ISPRS Journal of Photogrammetry and Remote Sensing*, 137: 163-174. DOI: https://doi.org/10.1016/j.isprsjprs.2018.02.002.

Stepper, C., Straub, C., Pretzsch, H., 2014. Assessing height changes in a highly structured forest using regularly acquired aerial image data. *Forestry*, 88 (3). 304-316. DOI: https://doi.org/10.1093/forestry/cpu050.

Stereńczak, K., 2014. Factors influencing individual tree crowns detection based on airborne laser scanning data. *Forest Research Papers*, 74 (4): 323-333. DOI: https://doi.org/10.2478/frp-2013-0031.

Stereńczak, K., 2009. Single tree detection based on airborne LiDAR (ALS) data. *Annals of Geomatics*, 7 (2): 121-126.

Stereńczak, K., ed. 2022. Stan obecny Puszczy Białowieskiej na podstawie wyników projektu LIFE+ForBioSensing. (The current state of Białowieża Forest based on the results of the LIFE+ ForBioSensing project). Sękocin Stary: Instytut Badawczy Leśnictwa, 200 pp.

St-Onge, B., Audet, F.A., Bégin, J., 2015. Characterizing the height structure and composition of a boreal forest using an individual tree crown approach applied to photogrammetric point clouds. *Forests*, 6 (11): 3899-3922. DOI: https://doi.org/10.3390/f6113899.

Sverdrup-Thygeson, A., Ørka, H.O., Gobakken, T., Nćsset, E., 2016. Can airborne laser scanning assist in mapping and monitoring natural forests? *Forest Ecology and Management*, 369: 116-125. DOI: https://doi.org/10.1016/j.foreco.2016.03.035.

Tomiałojć, L., Wesołowski, T., 2004. Diversity of the Białowieża forest avifauna in space and time. *Journal of Ornithology*, 145: 81-92. DOI: https://doi.org/10.1007/s10336-003-0017-2.

Torresan, C., Berton, A., Carotenuto, F., Di Gennaro, S.F., Gioli, B., Matese, A., Wallace, L., 2017. Forestry applications of UAVs in Europe: a review. *International Journal of Remote Sensing*, 38 (8-10): 2427-2447. DOI: https://doi.org/10.1080/01431161.2016.1252477.

Varga, K., Szabó, S., Szabó, G., Dévai, G., Tóthmérész, B., 2015. Improved land cover mapping using aerial photographs and satellite images. *Open Geosciences*, 7 (1): 20150002. DOI: https://doi.org/10.1515/geo-2015-0002.

Veen, P., Fanta, J., Raev, I., Biriş, I.A., de Smidt, J., Maes, B., 2010. Virgin forests in Romania and Bulgaria: Results of two national inventory projects and their implications for protection. *Biodiversity and Conservation*, 19: 1805-1819. DOI: https://doi.org/10.1007/s10531-010-9804-2.

Westoby, M.J., Brasington, J., Glasser, N.F., Hambrey, M.J., Reynolds, J.M., 2012. 'Structure-from-Motion' photogrammetry: A low-cost, effective tool for geoscience applications. *Geomorphology*, 179: 300-314. DOI: https://doi.org/10.1016/j.geomorph.2012.08.021.

Wężyk, P., Szostak, M., Tompalski, P., 2013. Use of airborne laser scanning data for a revision and update of a digital forest map and its descriptive database: A case study from the Tatra National Park. In: J. Kozak, K. Ostapowicz, A. Bytnerowicz, B. Wyżga, eds. *The Carpathians: Integrating nature and society towards sustainability*. Environmental Science and Engineering, Berlin, Heidelberg: Springer, pp. 615-627. DOI: https://doi.org/10.1007/978-3-642-12725-0_43.

Wężyk, P., Tompalski, P., de Kok, R., Szostak, M., Kukawski, M., 2010. Metoda szacowania liczby drzew w drzewostanie z wykorzystaniem danych ALS i ortoobrazów (Method of the tree number estimation in the pine stand using ALS data and true orthoimages). *Sylwan*, 154 (11): 773-782. DOI: https://doi.org/10.26202/sylwan.2009230.

Winterbotham, H.S.L., Hugershoff, P., Cranz, P., 1921. Grundlagen der Photogrammetrie aus Luftfahrzeugen. *The Geographical Journal*, 57 (4): 304-305. DOI: https://doi.org/10.2307/1780576.

Wulder, M.A., White, J.C., Alvarez, F., Han, T., Rogan, J., Hawkes, B., 2009. Characterizing boreal forest wildfire with multi-temporal Landsat and LIDAR data. *Remote Sensing of Environment*, 113 (7): 1540-1555. DOI: https://doi.org/10.1016/j.rse.2009.03.004.

Zimble, D.A., Evans, D.L., Carlson, G.C., Parker, R.C., Grado, S.C., Gerard, P.D., 2003. Characterizing vertical forest structure using small-footprint airborne LiDAR. *Remote Sensing of Environment*, 87 (2-3): 171-182. DOI: https://doi.org/10.1016/S0034-4257(03)00139-1.

STRESZCZENIE

Ocena długoterminowych zmian wysokości koron drzew w Puszczy Białowieskiej z wykorzystaniem historycznych obrazów stereometrycznych i danych lotniczego skaningu laserowego

Zarówno obszary leśne pochodzenia naturalnego, jak i te stworzone przez człowieka podlegają wielu zmianom, których obserwacja jest niezbędna do zrozumienia ich przyczyn, monitorowania bieżących procesów oraz prognozowania dalszych zmian. Obszary chronione obejmujące lasy o charakterze pierwotnym odgrywają szczególną rolę w badaniach nad długoterminowymi zmianami w wysokości pokrywy leśnej. Przedstawione badania prezentują procesy zmian wysokości pokrywy leśnej w ciągu ostatnich 30 lat na terenie 6 różnych obszarów o powierzchni 1 km^2 położonych w Puszczy Białowieskiej, ostatnim dużym kompleksie lasów naturalnych, które w przeszłości pokrywały nizinne obszary Europy (ryc. 1). Dla obszarów o różnym stopniu ochrony uzyskano dane reprezentujące przestrzenny układ koron drzew w latach 1982 oraz 2012. Stan historyczny w roku 1982 został określony na podstawie chmur punktów uzyskanych poprzez przetworzenie monochromatycznych lotniczych zdjęć stereometrycznych (ryc. 2). Dane te zostały porównane ze współczesnymi danymi uzyskanymi z pomiarów wykonanych w roku 2012 techniką lotniczego skaningu laserowego w ramach rządowego projektu ISOK (Informatyczny System Osłony Kraju). Jako pomocnicze zbiory danych wykorzystano ortofotomapy z tego samego okresu co użyte chmury punktów. Rycina 3 przedstawia te same obszary co rycina 2, prezentuje jednak stan starszy o ponad 30 lat. Schemat przetwarzania danych został zamieszczony na rycinie 4.

Wykorzystanie odległych w czasie danych umożliwiających określenie struktury wysokościowej roślinności pozwoliło na przedstawienie zakresu zmian, ich dynamiki oraz wnioskowanie o ich charakterze w częściach lasu o różnych reżimach ochrony. Wyniki zostały zaprezentowane w kilku odmiennych formach. Pierwszą z nich są analizy przestrzenne (ryc. 5-7). Obejmują one mapy wysokości koron drzew w latach 1982 oraz 2012, jak również mapę przedstawiającą zmiany wysokości koron drzew w analizowanym okresie – związane zarówno z przyrostem drzewostanu na wysokość, jak i z lokalną utratą pokrywy leśnej w analizowanym okresie. Inną formą prezentacji danych są wykresy przedstawiające zmienność struktury wysokościowej roślinności na poszczególnych obszarach testowych (ryc. 8).

Badania wykazały przydatność proponowanej metody do określania długoterminowych zmian wpływających na obszary leśne, obejmujących nie tylko zakres, ale także strukturę wysokościową roślinności. Za szczególnie cenne należy uznać wykorzystanie do określania struktury

wysokościowej pokrywy leśnej stereoskopowych zdjęć lotniczych, które dla obszaru Polski dostępne są od lat 50. ubiegłego wieku. Pozwala to na precyzyjne analizy zdarzeń wpływających na strukturę wysokościową lasów, będących zarówno efektem gospodarki leśnej, jak i przyczyn naturalnych, wraz z możliwością określenia lokalizacji i przybliżonego ustalenia wystąpienia danego zdarzenia w czasie.