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RESEARCH PAPER

USING LIDAR POINT CLOUDS IN DETERMINATION OF THE SCOTS PINE STANDS SPATIAL STRUCTURE MEANING IN THE CONSERVATION OF LICHEN COMMUNITIES IN "BORY TUCHOLSKIE" NATIONAL PARK

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KEY WORDS: LiDAR, point clouds, unmanned laser scanning, terrestrial laser scanning, Bory Tucholskie National Park, UAV.

ABSTRACT: The aim of the research carried out in 2018 and financed by the Forest Fund was the analysis of biometric features and parameters of pine stands in the area of the "Bory Tucholskie" National Park (PNBT), where a program of active protection of lichen was initiated in 2017. Environmental analyses were conducted in relation to selected biometric features of trees and stands using laser scanning (LiDAR), including ULS (Unmanned Laser Scanning; RIEGL VUX-1) and TLS (Terrestrial Laser Scanning; FARO FOCUS 3D; X130). Thanks to the application of LiDAR technology, the structure of pine stands was precisely determined by means of a series of descriptive statistics characterizing the 3D spatial structure of vegetation. Using the Trees Crown Model (CHM), the analysis of the volume of tree crowns and the volume of space under canopy was performed. For the analysed sub-compartments, GIS solar analyses were carried out for the solar energy reaching the canopy and the ground level due to active protection of lichen. Multispectral photos were obtained using a specialized RedEdge-M camera (MicaSense) mounted on the UAV multi rotor platform Typhoon H520 (Yuneec). Flights with a thermal camera were also performed in order to detect places on the ground with high temperature. Plant indices: NDVI, NDRE, GNDVI and GRVI were also calculated for sub-compartments. The data obtained in 2017 and 2018 were the basis for spatial and temporal analyses of 4-D changes in stands which were related to the removal of some trees and organic layer (litter, moss layer).

1. INTRODUCTION

The study has been developed as a result of the research project "Using LiDAR data to determine the significance of the spatial structure of pine stands in the maintenance of the lichen forest in the area of the Bory Tucholskie National Park (PNBT), commissioned by the Bory Tucholskie National Park (agreement no. 62/2018) and were financed from the Forest Fund 2018.

The strictly protected areas in the Bory Tucholskie National Park constitute a total of 324.30 ha, i.e. only 7% of the total area of the park. Forest communities cover as much as 79% of the total PNBT area, 98% of which are coniferous forests with pine (Banaszak, Tobolski, 2002). In a small part of the PNBT stands, very valuable complexes of *Cladonio-Pinetum* have been found, which is a community developing on dry and poor in biogas, sandy areas. The undergrowth in *Cladonio-Pinetum* is extremely scarce and the moss layer should be characterized by a high proportion of topsoil lichens, represented mainly by the species of the *Cladonia* genus and a low proportion of bryophytes. (Węgrzyn, Masłowska 2010; Węgrzyn, Wietrzyk 2017; Dingová Košuthová *et al*., 2013).

Due to the limited extent of the presence of lichen forests and the high sensitivity of terrestrial lichens to changes in habitat conditions (e.g. nitrogen deposition, better growth conditions for competitive trees), the community is under EU legal protection as an ESE Natura 2000 habitat (91T0 - Central European Common Pine Forests with lichens) under Council Directive 92/43/EEC on the conservation of natural habitats of wild fauna and flora.

The distribution of lichen forests is mainly limited to Central Europe: Czech Republic, Slovakia, Germany and Poland, however, the centre of occurrence of this plant community coincides with Natura 2000 sites located in Poland, including the Bory Tucholskie National Park. (Ermakov, Morozova 2011; Dingová Košuthová *et al*. 2013; Lipnicki, 2003; Matuszkiewicz, 1973).

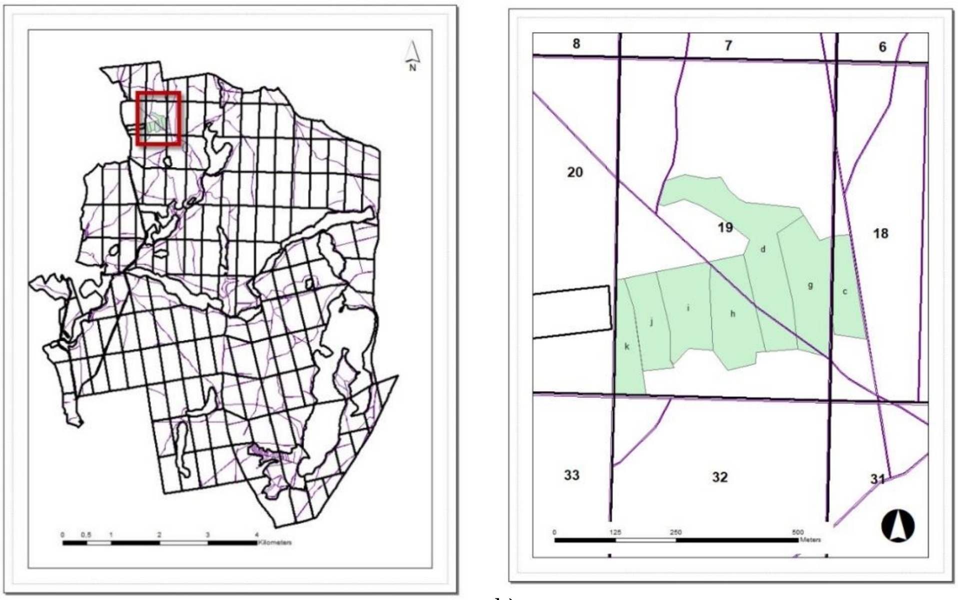
Unfortunately, in the last several years the process of slow degeneration of lichen forests has been observed (Danielewicz, Pawlaczyk 2004), both in the case of communities developed within the former commercial forests in the area of PNBT, and in the area of other forest districts of the Bory Tucholskie mesoregion.

In 2017, in several forest sub-compartments of the northern part of the PNBT, in which previously the lichen was found, an experimental program was initiated in the field of active protection consisting in lightning the cover of tree crowns (selective thinning) and removal of the bedding and layer of bryophytes competing with the lichen communities (experiment on about 2 ha). The main task of the research works carried out in the area of this experiment was to develop spatial and temporal analyses concerning changes in the value of the parameter of crowns' cover, quantitative solar analyses in selected PNBT stands and other parameters (e.g. top height, volume of crowns, etc.), which took place in the period of 2017-2018 as a result of active protection activities.

2. RESEARCH AREA

The research area was located in the north-west part of the PNBT and included Scots pine stands *(Pinus sylvestris L.)* with a very small addition of Silver Birch (*Betula pendula Roth),* in which *Cladonio-Pinetum* complex was found in the past.

The research was continued in two compartments selected in 2017 (Wężyk et al. 2018) in two forest divisions, i.e. sub-compartments: 18c, 19d, 19g, 19h, 19i, 19j and 19k (Fig. 1.).



a) b)

Fig. 1. Location of the research area: a) in the north-west part of the „Bory Tucholskie"; b) sub-compartments selected for active protection of the Cladonio-Pinetum complex (Wężyk et al. 2016; Wężyk et al. 2018).

3. METHODS

The project assumed the use of innovative solutions in the field of Unmanned Laser Scanning (ULS) technology in order to precisely determine the impact of selected elements of the 3D spatial structure of stands on the amount of solar radiation reaching directly the soil. During the works, the statistics of ULS point clouds were calculated automatically (Hyyppä *et al.* 2004; Maier 2008; Maltamo *et al.* 2014; Mcgaughey *et al.* 2014; Naesset 2002; Watt, Donoghue 2005; Wężyk *et al.* 2006; Wężyk *et al.* 2007; Wężyk *et al.* 2008; Wężyk *et al.* 2010; Zhen *et al.* 2016) in terms of changes in the structure of stands that occurred in the period 2017-2018, and which had an impact on the formation of conditions determining the presence of lichen.

The stages of works completed in 2018 included:

1) the analysis of the canopy based on data from the UAV (Unmanned Aerial Vehicle):

a) on the basis of a dense 3D LiDAR ULS point cloud and RGB orthophotography;

b) on the basis of high-resolution (GSD 5 cm) multispectral images (RedEdge-M camera MicaSense; bands: R, G, B, RedEdge, Near InfraRed).

2) the analysis of the sub-canopy space by terrestrial laser scanning method (TLS), based on:

a) LiDAR point clouds on circular surfaces (at least 100 TLS stations);

b) GNSS-RTK verification measurement of the survey network around the research area, stabilised in 2017;

c) integration of ALS and TLS point clouds;
d) developed biometric features of stands and point clouds statistics for the analysed sub-compartments;
e) the analysis of the microrelief (DEM) using TLS data.

3) 3D GIS spatial analyses of the impact of the canopy on the formation of microclimatic conditions in the understory, on the basis of :
a) solar analyses (insolation) for the crown layer (CHM level; Crown Height Model) and soil level with undergrowth vegetation (DTM level; Digital Terrain Model);
b) thermal and optical imaging from a low ceiling UAV platform (thermal camera+ RGB).

LiDAR point clouds were obtained on the basis of ULS platform of the RiCOPTER (RIEGL) multirotor equipped with VUX-1 (RIEGL) laser scanner. The ULS mission was carried out at an altitude of 100 m above the ground (AGL; approx. 242 m above sea level). The total area covered by ULS mission was about 32 ha, registering about 89 million returns of the laser beam. The average scanning density within 7 analysed sub-compartments exceeded 300 points/m2. The final ULS point cloud was classified according to the methodology adopted in the ISOK project (corresponding to ASPRS standards) based on algorithms implemented in TerraScan (Terrasolid) software. The ULS point cloud was limited to the range of developed sub-compartments (a new appropriate limit of sub-compartments was proposed), thus limiting it to about 38 million points. After the final classification of the ULS cloud, about 4.6 million points were recorded in the soil class (2) and 11.5 million in the low vegetation class (3), 471 thousand in the medium vegetation class (4) and 21.3 million in the high vegetation class (5). The ULS point cloud (VUX-1) was coloured on the basis of RGB imageries obtained simultaneously by 2 SONY Alfa 6000 oblique cameras mounted on RiCOPTER platform.

During the field work in 2018, a total of 172 clouds of TLS points were obtained from 148 sites located in 7 analysed forest sub-compartments and from 24 sites located around a prism of transported litter and moss layer originating from the analysis area. The FARO FOCUS 3D scanner of nominal range up to 130 meters was used for this purpose. Transections of TLS measurement lines were performed on the basis of the height matrix established in 2017 (Wężyk et al. 2018). The TLS point cloud was classified analogously to the adopted scheme for ULS data. TLS point clouds were connected with each other and limited to the boundaries of sub-compartments. In order to facilitate the use of large TLS data files, a grid of 10m polygons was created, into which individual point clouds were loaded (tiles).

DTM in two variants of spatial resolution, i.e. 0.5 m GDS and 1.0 m GDS, was generated on the basis of the ULS point cloud. As a result of TLS terrestrial scanning under the canopy, the point clouds were georeferenced, classified (ASPRS) and DTM (0.5 m GSD) was generated. The data were also limited to a circle with a radius of 15.0 m from the centre of the stand and presented in the form of detailed micro reliefs on which GIS hydrological analyses of (e.g. flow directions) were shown.

Analyses of biometric features and other stand parameters based on TLS point clouds (Bienert *et al.*, 2006; Hopkinson *et al.*, 2004; Maas *et al.*, 2008; Thies *et al.*, 2004; Watt & Donoghue, 2005; Wężyk & Tompalski, 2010; Wężyk *et al.*, 2007) were conducted in relation to selected biometric features of tree stands, i.e.: diameter at breast height (DBH), tree top height (H_w), crown base height (H_{pk}) , crown length, crown width, the mean area of breast height cross-section (g) and average number of trees pcs./ha.

Stand analyses conducted on the basis of ULS point clouds were aimed at determining a number of descriptive statistics characterizing the 3D spatial structure. Among other things, raster layers representing selected statistics were generated, i.e: *Elev.P95* (height corresponding to 95th percentile), *Elev.stddev* (standard deviation of height), *CRR* – Canopy relief ratio ((mean - min) / (max – min); relief of a stand canopy, *Cover* (cover with the assumed cut-off level of 0.5m AGL), modified crown cover (determined at the threshold of the tree crown height) and *Penetration* (penetration rate/penetration coefficient). In cover analyses, the threshold height corresponding to the tree crown base (Hpk) determined by the operator on TLS point clouds was tested. The analysis of the volume of tree crowns (V m3) and the volume of understory was also carried out. The histograms of vertical distribution of the number of ULS reflections in 1.0 m height intervals characterizing the vertical structure were also generated.

Insolation analyses for the level of crowns of remaining trees (CHM level) and soil level with undergrowth vegetation (DTM level) were performed for the analysed sub-compartments using ArcMap ArcGIS (Area Solar Radiation; Esri) software. The analyses were carried out in the following variants: for each month of the calendar year, for the vegetation period (May 1^{st} - October 31^{st}) and for the period of one year (12 months). Similar analyses were also limited for uncovered soil areas (DTM) with raked moss and litter layer (about 2 ha).

Thermal imaging of the research area was performed from the deck of UAV Typhoon H520 (Yuneec) using CGOET camera with two matrices: thermal imaging with increased recording sensitivity and RGB (1/3"; 2Mpix). The Uncooled Vox microbolometer sensor used in the thermal imaging camera shows the horizontal range: 71° and vertical range: 56°, with a refresh rate of 9 Hz. The average spectral resolution of the pixel is 12 µm (LWIR: 8-14 µm). The temperature in the photo was measured selectively and indicates relative temperature differences.

A very important stage of the work was to obtain multispectral UAV images (RedEdge-M camera; MicaSense) and to conduct analyses of the generated vegetation indices (VI) such as: NDVI, NDRE, GNDVI and GRVI. The photos were obtained from the BPS Typhoon H520 (Yuneec) platforms during the 80m AGL flight. The applied camera simultaneously acquires images in 5 spectral channels: Blue (B), Green (G), Red (R), RedEdge (RE) and Near InfraRed (NIR). During the flight, the camera was connected to its own GNSS receiver and sunlight sensor, which are mounted on top of the UAV case. A special calibration panel was photographed immediately before and after the flight mission in order to take into account the differences in sunlight intensity for individual UAV photos.

4. RESULTS

The results of measurement of selected characteristics and biometric parameters of stands based on LiDAR point analyses are presented in Table 1 below. Descriptive statistics characterizing the 3D spatial structure of vegetation generated solely on the basis of the standardized ULS point cloud are shown in Table 2.

Table 1. Results of measurements performed on TLS point clouds (n- number of trees in the circular area; n/ha – tree density index; DBH_m – diameter at breast height at 130 cm; P_DBH_m average cross-sectional area of the breast height on the surface [cm^2]; g - the sum of the breast section on the plot [m^2]; G – basal area m^2/ha; H_w [m] - tree top height; L_k - crown length, [m]; X – average crown length

Sub -comp.	n [items]	n/ha	DBH _m [cm]	P_DBH_m [cm^2]	g [m^2]	G [m^2/ha]	H_w [m]	L_k [m]	H_{pk} [m]	X [m]
18c	14	1377	15.48	206.6	0.2643	26.43	13.50	5.03	8.47	3.38
19d	14	1400	13.79	156.2	0.2177	21.77	10.56	4.72	5.84	3.00
19g	13	1307	14.32	166.4	0.2200	21.69	11.23	4.72	6.51	3.14
19h	20	2025	11.09	103.1	0.2068	20.67	9.56	3.91	5.66	2.62
19i	19	1881	10.34	88.6	0.1644	16.44	8.76	4.38	4.39	2.39
19j	12	1187	16.58	224.3	0.2574	25.74	14.06	5.16	8.98	3.59
19k	12	1228	13.27	145.3	0.1731	17.30	10.57	4.88	5.69	2.72
mean	15	1486	13.55	155.8	0.21	21.44	11.18	4.69	6.51	2.98

Selected map compositions for the analysed statistical parameters of the 3D structure of stands (ULS, 2018) are presented in Figure 2, i.e.: top height (95th percentile, Fig. 2a) and standard deviation of tree height – H_std_dev (GSD 5m; threshold value 2.0m, Fig.2b) as well as CRR – Canopy Relief Ratio (Fig. 2c) and Penetration coefficient (penetration rate/penetration coefficient for AGL = 0.5m; Fig.2d).

Table 2. ULS point cloud metrics characterizing the analysed stands in the PNBT.

Sub-comp.	Elev. max.	Elev. mean	Elev. std. dev.	Elev. variance	Elev. P99	Canopy relief. ratio	Cover [%] 5m	Penetration [%] 5m
18_c	19.25	6.61	5.23	27.37	14.49	0.35	80.90	19.10
19_d	21.14	4.38	4.43	19.67	15.33	0.22	69.29	30.71
19_g	20.85	4.88	4.65	21.59	14.52	0.24	71.37	28.63
19_h	22.19	4.02	4.05	16.44	14.21	0.19	69.84	30.16
19_i	16.89	3.35	3.33	11.11	10.75	0.21	71.83	28.17
19_j	18.57	6.33	5.58	31.13	15.25	0.35	72.93	27.07
19_k	15.12	4.74	4.25	18.07	11.97	0.32	75.46	24.54

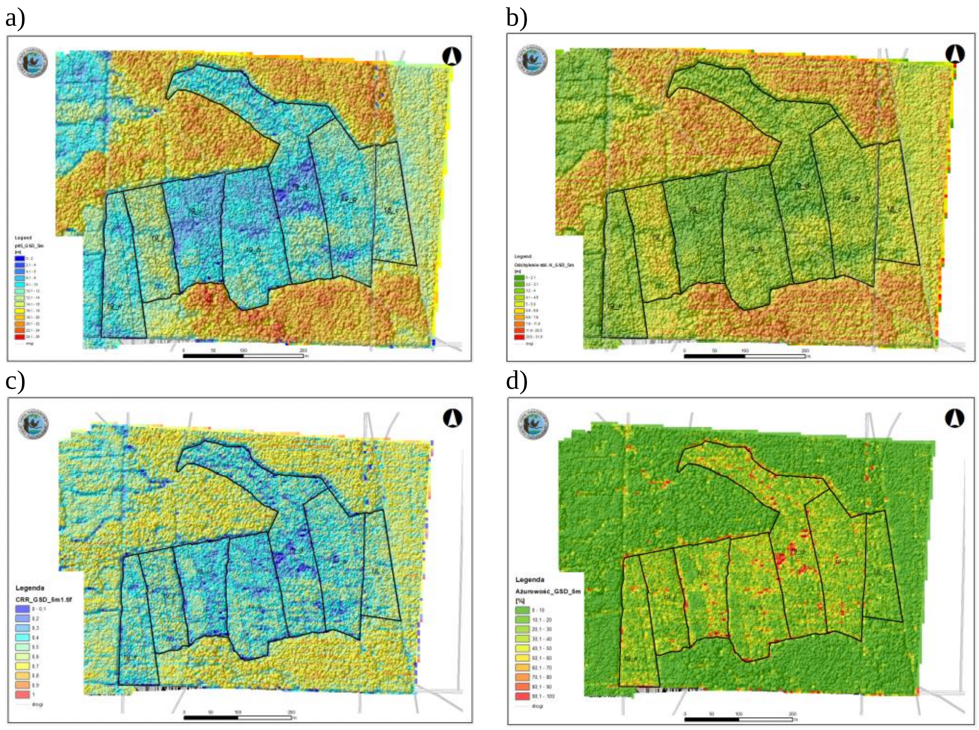


Fig. 2. Selected map compositions of analysed statistical parameters of 3D structure of stands generated from ULS point cloud: a) top height (P95); b) standard deviation of height; c) Canopy Relief Ratio; d) Penetration.

Table 3: Crown cover (0-100%) based on the ULS point cloud analyses
for GSD 1.0m and 5.0m.

Sub-compartment	Cover [%] GSD 1.0m	Cover [%] GSD 5.0m
18c	72.99	80.42
19d	57.58	66.80
19g	59.94	70.23
19h	59.71	69.21
19i	60.80	68.42
19j	60.77	71.51
19k	63.64	71.61

Percentage values of crown cover (0-100%) determined on the basis of the ULS points cloud, depending on the assumed size of 1.0 m and 5.0 m raster net are presented in Table 3. The results of the analysis of the tree crown volume (V m^3) and the volume of understory using the Tree Crown Model (CHM) generated on the basis of the standardized ULS point cloud (2018) are presented in Table 4.

Table 4: The volume of tree crown and understory in sub-compartments, determined on the basis of ULS data (2018).

Sub compartment	Crown V [m^3]	Sub-canopy space V [m^3]	Total V [m^3]	Proportion of the crown part [%]	Proportion of the sub-canopy space [%]
18c	34731	79466	114197	30.4	69.6
19d	88003	142338	230341	38.2	61.8
19g	66215	117948	184163	36.0	64.0
19h	56901	100550	157451	36.1	63.9
19i	41341	56346	97687	42.3	57.7
19j	37515	89486	127001	29.5	70.5
19k	46776	66875	113651	41.2	58.8

Based on ULS point clouds, histograms of vertical distribution of the number of returns in 1.0 m altitude intervals were generated for each of the analysed sub-compartments (Figure 3).

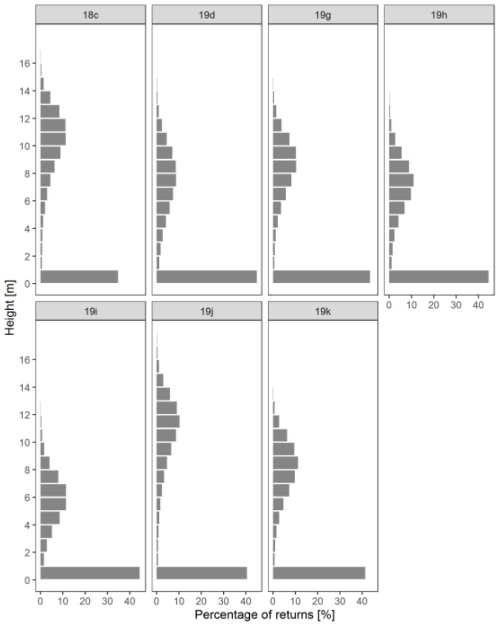


Figure 3: Diagram showing the histograms of the ULS vertical point distribution in selected sub-compartments.

The results of 3D-GIS analysis of light penetration and its potential influence on microclimatic conditions in the understory and the crown layer are presented below in Figure 4.

a) b)

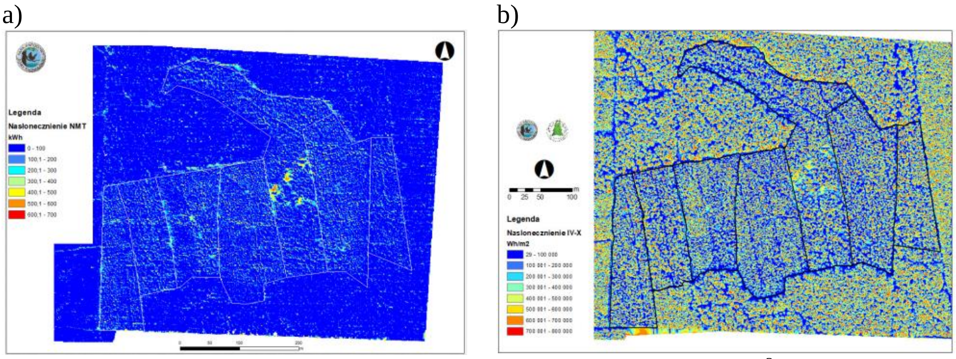


Fig. 4: 3D-GIS spatial analyses of light influence: a) insolation values (kWh/m^2) for the ground level taking into account the coefficient of tree crown penetration by sunlight; b) insolation values (Wh/m^2) for the vegetation period (Apr.-Oct.) for the tree crown layer.

The UAV flights with a thermal camera allowed to perform a mapping in terms of temperature distribution in crowns and on the ground. Below there is a video frame (Figure 5). On the day of the thermal flight mission, the air temperature was about 22˚ C, but on the ground we noticed radiation temperature of 47.9 ˚C emitted by black-brown lichens communities. This hot-spot indicates extreme conditions favouring the presence of lichens.

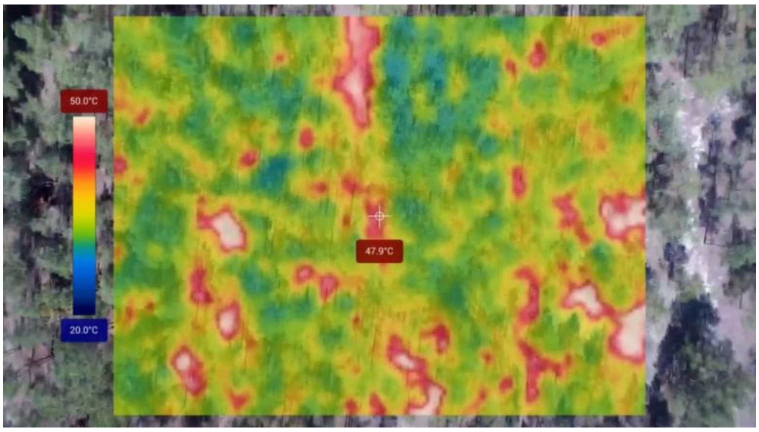


Fig. 5: Example of a thermal imaging from UAV (H520; CGOET). In background RGB image.

Orthophotomaps of vegetation indices (NDVI, NDRE, GNDVI and GRVI) were generated from UAV photos taken with the 5-bands RedEdge-M (MicaSense) during the flight mission and presented in Figure 6.

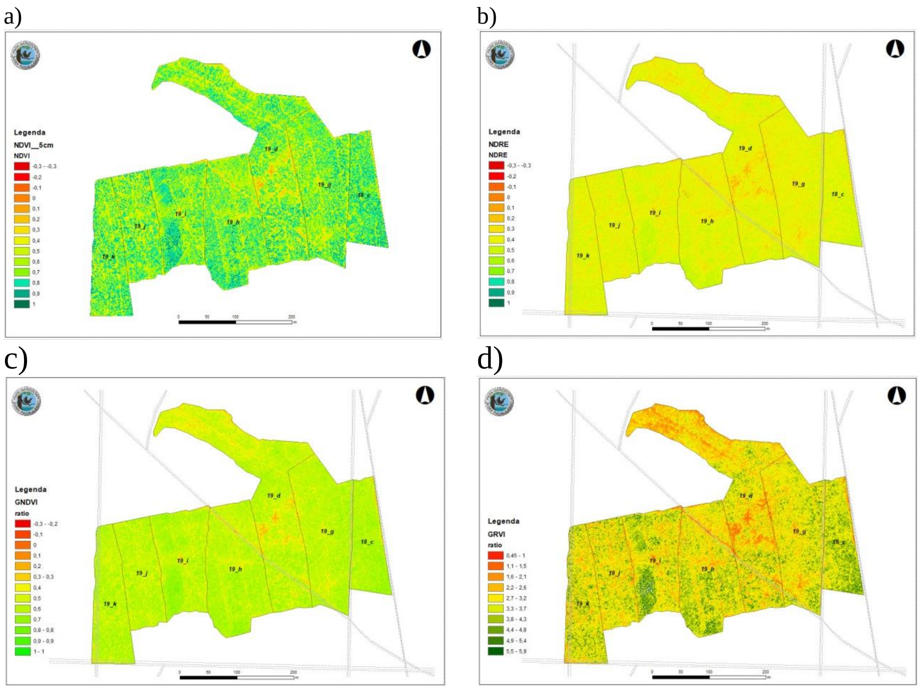


Figure 6: Vegetation indices a) NDVI; b) NDRE; c) GNDVI; d) GRVI.

Analyses of spatial and temporal changes (4-D) that occurred in the period 2017-2018 in the analysed pine stands subjected to active protection treatments were based on the processing of 2 sets of LiDAR point clouds: ALS (2017) and ULS (2018) and are presented in Figure 7. LiDAR returns from 2017 (removed trees) were marked in red, while white symbolizes the ULS cloud from 2018.

The changes in the number of trees in sub-compartments were traced in detail on the basis of TLS point cloud measurements and the resulting changes in parameters. Active protection measures (light thinning and exporting biomass) carried out in stands in 2017 resulted in a reduction in the number of trees by 65% on average. This high number, however, is due to the fact that mainly dead, silenced and co-dominant trees were removed. The highest intensity of thinning took place in the sub-compartment 19k (-72%; density decreased from 4342 trees per hectare to 1228 trees per hectare). It should be taken into account, however, that the research areas (100 m^2) were planted in different parts of stands in 2017 and 2018, which was caused by a very high density of trees (2017), which in many cases made it impossible to perform a proper TLS scan. The removal of trees caused (apart from the natural thickness gain) a change in the statistical value of the average diameter at breast height. Theoretically, the biggest change took place in the sub-compartment 19h (+112%), in which the DBH value moved from 5.22 cm to 11.09 cm. A similar situation occurred in the sub-compartment 19i (DBH from 5.94 cm to 10.34 cm; +74%). On average, the values of DBH in all the analysed areas increased from 9.39 cm (2017) to 13.55 cm (2018).

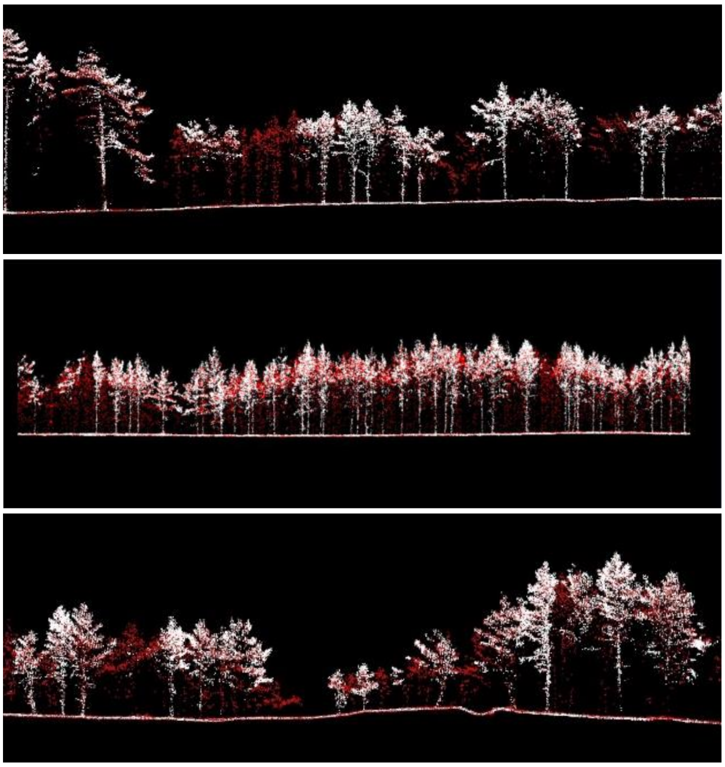


Figure 7: Cross-sections through the 2017 and 2018 point cloud

However, the removal of a relatively large number of supressed and dead trees during active protection procedures resulted in a decrease in the average breast height cross-section area (g) determined on circular areas (for all analysed areas by 32%). The greatest change was observed in the sub-compartments: 19k (-56%), 19d (-43%) and 19g (-43%). Accordingly, the value of the total basal area G (m^2/ha) decreased by -32% (from 31.72 to 21.44m^2/ha).

Detailed values of changes in the number of trees and average diameter at breast height (DBH) in the sub-compartments (2017 - 2018) are presented in Table 5. Changes in the value of average breast height cross-section area (g) on circular areas are shown in Table 6, whereas changes in the height and length of tree crown in Table 7.

Table 5: Changes in the number of trees and average diameter at breast height in the analysed sub-compartments, in which active protection procedures were carried out (2017-2018).

Sub-comp.	n [pcs.] on circular plots 100m^2		Change in the number on circular areas		Density n/ha		Change in the number of trees		DBH_m [cm]		Change in DBH	
	2017	2018	pcs.	%	2017	2018	pcs.	%	2017	2018	cm	%
18c	32	14	-18	-57	3188	1377	-1811	-57	10.91	15.48	4.57	42
19d	37	14	-23	-62	3717	1400	-2317	-62	11.48	13.79	2.31	20
19g	44	13	-31	-71	4423	1307	-3116	-70	10.07	14.32	4.25	42
19h	52	20	-32	-61	5238	2025	-3213	-61	5.22	11.09	5.87	112
19i	51	19	-32	-63	5113	1881	-3231	-63	5.94	10.34	4.40	74
19j	35	12	-23	-66	3463	1187	-2276	-66	11.98	16.58	4.60	38
19k	43	12	-31	-72	4342	1228	-3114	-72	10.09	13.27	3.18	31
Mean	42	15	-27	-65	4212	1486	-2725	-65	9.39	13.55	4.17	44%

Table 6: Changes in statistics in 2017-2018 for biometric parameters: P_DBH_m - values of the average cross-sectional area [cm^2], g- the sum of the breast height cross-section on the circular area [m^2] and G – basal area (m^2/ha).

Sub-comp.	P_DBH_m [cm^2]		Change in P_DBH_m		g [m^2]		Change in g (2017-18)		G [m^2/ha]		Change in G (2017-18)	
	2017	2018	cm^2	%	2017	2018	m^2	%	2017	2018	m^2	%
18c	105.2	206.6	101.4	96	0.3332	0.2643	-0.0688	-21	33.32	26.43	-6.88	-21
19d	108.4	156.2	47.9	44	0.3794	0.2177	-0.1617	-43	37.94	21.77	-16.17	-43
19g	89.5	166.4	76.8	86	0.3887	0.2200	-0.1687	-43	38.87	21.69	-17.18	-44
19h	25.0	103.1	78.1	313	0.1330	0.2068	0.0738	56	13.30	20.68	7.38	56
19i	32.5	88.6	56.1	173	0.1599	0.1644	0.0045	3	15.99	16.44	0.45	3
19j	125.6	224.3	98.7	79	0.4340	0.2574	-0.1766	-41	43.40	25.74	-17.66	-41
19k	89.7	145.3	55.6	62	0.3924	0.1731	-0.2193	-56	39.24	17.31	-21.93	-56
Mean	82.3	155.8	73.5	89	0.3172	0.2148	-0.1024	-32	31.72	21.44	-10.28	-32

Table 7: Changes in the height (H_w), length (L_k), base of crown (H_{pk}) and width (X) of tree crowns in the analysed sub-compartments in period of 2017-2018.

Sub-comp.	H_w [m]		Change in H_w	L_k [m]		Change in L_k	H_{pk} [m]		Change in H_{pk}	Width X [m]		Change in Width X
	2017	2018	m	2017	2018	m	2017	2018	m	2017	2018	m
18c	12.83	13.50	0.67	5.44	5.03	-0.42	7.33	8.47	1.14	2.01	3.38	1.37
19d	10.15	10.56	0.41	5.21	4.72	-0.49	5.00	5.84	0.84	2.11	3.00	0.89
19g	10.93	11.23	0.30	4.82	4.72	-0.10	6.09	6.51	0.42	1.68	3.14	1.46
19h	7.45	9.56	2.11	4.34	3.91	-0.43	3.05	5.66	2.61	1.68	2.62	0.95
19i	7.05	8.76	1.72	4.12	4.38	0.27	2.98	4.39	1.40	1.45	2.39	0.94
19j	12.38	14.06	1.69	4.53	5.16	0.63	7.87	8.98	1.12	2.24	3.59	1.35
19k	10.14	10.57	0.43	4.63	4.88	0.25	5.54	5.69	0.15	1.69	2.72	1.03
Mean	10.13	11.18	1.05	4.73	4.69	-0.04	5.41	6.51	1.10	1.84	2.98	1.14

Removal of some of the silenced and co-dominant trees in the analysed sub-compartments resulted in a decrease in the cover of tree crowns. The intensity of the change in crown cover depended mainly on the removal of trees with crowns located in the area of co-dominance (main level) and dominance. The removed silenced trees and dead branches whose reflections raised the value of cover by means of signal reflections were transported out of the research area. On average, in all the analysed sub-compartments the cover was reduced by 19.07 %, with the highest decrease recorded for the sub-compartment 19h (-23.02%) and the lowest for 18c (-11.27%). No significant changes were observed in the top height described by the 95th percentile (p95) of the ALS/ULS cloud. On average, in all analysed sub-compartments an increase of 0.38 m (4.02%) in the top height was observed. The greatest difference in height was recorded in the sub-compartment 19i (5.44%). It should be noted that in the period of 12 months (2017-2018) trees in the analysed stands also naturally increased in height (approx. 30-40 cm).

Table 8. Changes in tree crown cover in sub-compartments.

Sub-compartment	Tree crown cover [%]		Change in cover [%]
	2017	2018	
18c	91.69	80.42	-11.27
19d	86.80	66.86	-19.94
19g	92.12	70.23	-21.89
19h	92.50	69.48	-23.02
19i	86.33	70.03	-16.30
19j	92.22	70.84	-21.37
19k	92.68	72.97	-19.71
Mean	90.62	71.55	-19.07

Table 9. Change in the top height (p95) in sub-compartments.

Sub-compartment	Top height [m]		Change in the top height (2017-2018)	
	2017	2018	m	%
18c	11.89	12.29	0.40	3.37
19d	8.70	9.04	0.34	3.89
19g	9.95	10.25	0.30	3.05
19h	8.34	8.78	0.44	5.28
19i	7.16	7.55	0.39	5.44
19j	12.23	12.61	0.38	3.13
19k	9.50	9.87	0.37	3.95
Mean	9.68	10.06	0.38	4.02

Table 10. Changes in light conditions (insolation) in sub-compartments.

Sub-compartment	Insolation [Wh/m^2]		Change 2017-2018	
	2017	2018	Wh/m^2	%
18c	39752.89	73567.23	33814.34	85.06
19d	50473.06	102097.63	51624.57	102.28
19g	32742.16	93218.67	60476.51	184.71
19h	32543.62	87349.03	54805.41	168.41
19i	53449.20	91177.25	37728.05	70.59
19j	28653.46	100065.62	71412.16	249.23
19k	42460.29	88591.36	46131.07	108.65
mean	40010.67	90866.68	50856.02	138.42

Detailed values of changes in the crown cover in sub-compartments in the period 2017-2018 are presented in Table 8. Other parameters such as: top height (p95) are shown in Table 9 and changes in lighting conditions (insolation) in Table 10. The maps of changes in the crown cover of Scots pine stands after the application of active protection treatments (light thinning of stands) and changes in light conditions (insolation) in the analysed sub-compartments, are presented in Figure 8.

a) b)

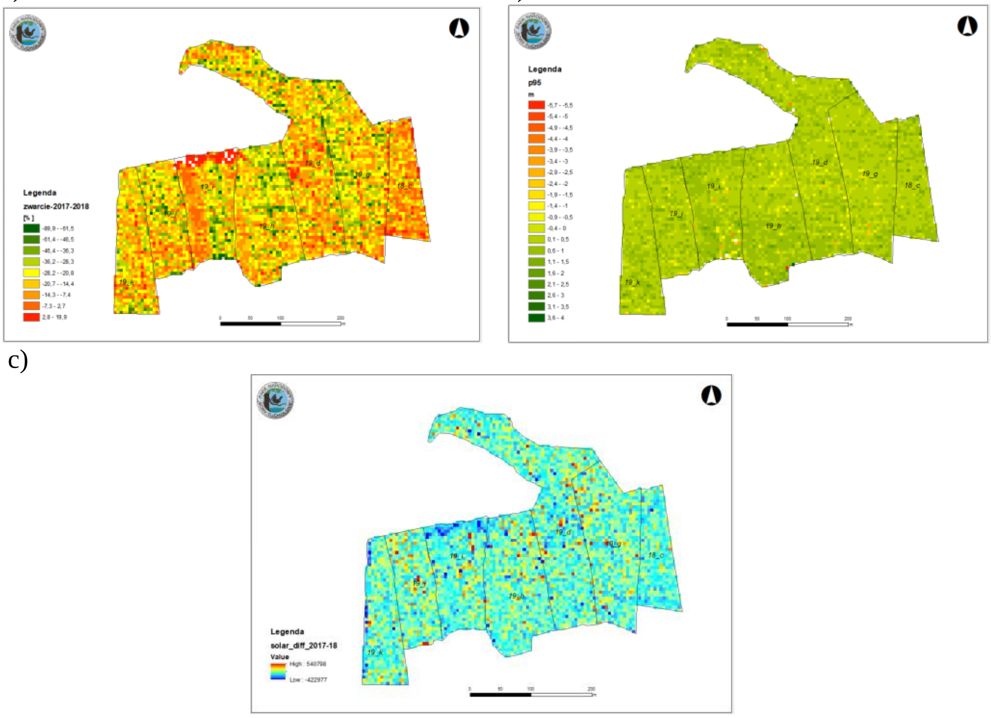


Fig. 8. Maps of changes in the analysed sub-compartments (2017–2018): a) change in the cover of stands; b) change in height; c) change in lighting conditions (insolation)

An example of a comparison of the height increment of individual trees on ALS point clouds (2017) and ULS (2018) is shown in Figure 9.

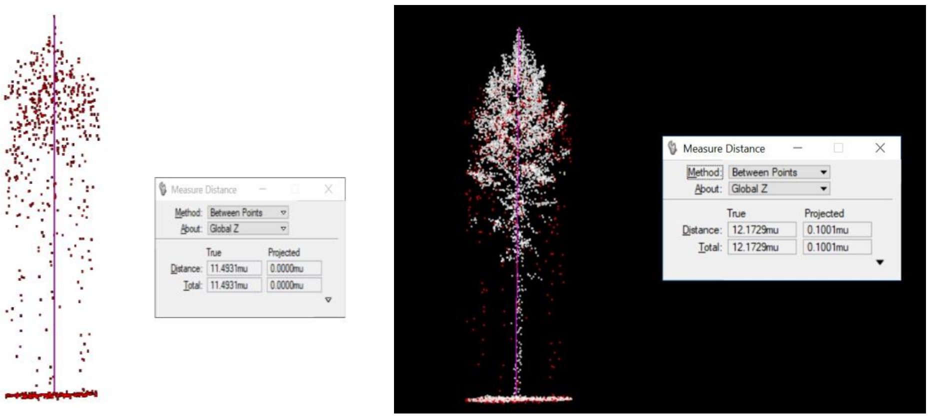


Fig. 9. Comparison of the height of individual trees on ALS point clouds from 2017 and ULS 2018

5. CONCLUSIONS

The conducted research shows unequivocally that the use of modern geoinformatics tools, including dense clouds of ULS and TLS LiDAR points, is the basis for performing objective research at present and is the basic material for future generations of researchers. 3D point clouds document with great precision the changes that have occurred in stands where the protection of lichens communities in the PNBT was initiated with the use of active protection measures. Light thinning carried out in autumn 2017 and spring 2018 by removing a significant number of trees from the analysed sub-compartments led to an increase in sunlight at the bottom of the stand and thus created more extreme conditions for plant development, which may favour the succession of these areas by the lichens (pioneering plants). A specially the process can be observed and monitor now at the areas with overburdened layer of litter and bryophytes removed partly from the sub-compartments.

The acquisition of ULS LiDAR point clouds with an average density of 300 points/m^2 in 2018 and the continuation of TLS scanning based on a locally established altitude reference system will be an excellent material and base for research of future inventories in terms of analysis of spatial conditions (filling the 3D space by tree crowns) and light inflow to the lower layer (lichens and competing bryophytes).

The research supported by additional measurements of meteorological conditions inside stands and UAV thermal images are undoubtedly unique in Poland and Europe and should be continued in the near future by adding new technologies for mapping e.g. hyperspectral cameras from the UAV or handheld laser scanners (HLS) as well the under canopy measurements using the spectro-radiometers or flux-tower as well.

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WYKORZYSTANIE DANYCH LIDAR DO OKREŚLENIA ZNACZENIA STRUKTURY PRZESTRZENNEJ DRZEWOSTANÓW SOSNOWYCH W ZACHOWANIU BORÓW CHROBOTKOWYCH NA TERENIE PARKU NARODOWEGO „BORY TUCHOLSKIE"

SŁOWA KLUCZOWE: chmury punktów LiDAR, bezzałogowe skanowanie laserowe ULS, naziemne skanowanie laserowe TLS, modelowanie 3D, Park Narodowy Bory Tucholskie

STRESZCZENIE: Celem badań realizowanych w roku 2018 finansowanych z Funduszu Leśnego, była analiza cech biometrycznych i parametrów drzewostanów sosnowych na terenie Parku Narodowego "Bory Tucholskie" (PNBT), w których w 2017 roku zainicjowano program ochronny czynnej borów chrobotkowych. Analizy środowiskowe prowadzono w odniesieniu do wybranych cech biometrycznych drzew i drzewostanów z wykorzystaniem chmur punktów ze skanowania laserowego (LiDAR), w tym bezzałogowych platform ULS (RiCopter + VUX-1 RIEGL) oraz naziemnych skanerów TLS (FARO FOCUS 3D; X130). Dzięki zastosowaniu technologii LiDAR, w precyzyjny sposób opisano strukturę drzewostanów sosnowych poprzez szeregi statystyk opisowych charakteryzujących strukturę przestrzenną 3D roślinności. Wykorzystując Model Koron Drzew (CHM) dokonano analizy objętości koron drzew oraz objętości przestrzeni podokapowej. Dla analizowanych wydzieleń przeprowadzono analizy solarne GIS pod kątem sumarycznej energii słonecznej docierającej do okapu drzewostanu oraz bezpośrednio do poziomu gruntu co ma duże znaczenie dla ochrony czynnej chrobotków. Dla celów projektu pozyskano także zdjęcia wielospektralne przy wykorzystaniu specjalistycznej kamery RedEdge-M (MiceSense) zamontowanej na platformie BSP wielowirnikowca Typhoon H520 (Yuneec). Przeprowadzono też naloty z kamerą termalną w celu detekcji miejsc z wysoką temperaturą na gruncie, odpowiednich na pionierskich gatunków porostów. Dla wydzieleń leśnych obliczono także wskaźniki roślinne: NDVI, NDRE, GNDVI oraz GRVI. Dane pozyskane w 2017 oraz 2018 roku były podstawą analiz przestrzenno-czasowych 4-D zmian w drzewostanach jakie miały związek z usunięciem części drzew oraz warstwy organicznej (ścioła, warstwa mszaków).

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