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Comparative Analysis of Ice Break Damage in Two Börzsöny Mountain Valleys in Hungary in 2014 Based on Airborne Laser Scanning

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Abstract – Severe mechanical damage from frost and ice on trees occurred in the Börzsöny Mountains in Northern Hungary during 1–2 December 2014. The frost and ice affected 10,000 hectares overall; however, the two examined valleys suffered conspicuously different extents of damage. While the Rakottyás Valley study area had severe damage, the Pogány-Rózsás Forest Reserve suffered only moderate damage. Airborne Laser Scanning (ALS) and a field survey were utilised to assess the damage. Digital Surface Modell (DSM), Digital Terrain Model (DTM), and Normalised Digital Surface Modell (nDSM) were calculated from the dense point cloud in 3D. Elevation, slope and aspect were derived to describe site conditions. Damage thresholds were set for the ALS data (tree height < 5 m) and the ground-based damage (frequency > 90%). These were compared in a confusion matrix on a pixel scale, which showed partial agreement due to different sampling methods and ranges but also indicated that Rakottyás was more damaged (54.35% of the area) than Pogány-Rózsás (36.7%). The Total Accuracy was 0.54.

forest damage / airborne laser scanning / digital terrain model / icing

Kivonat – A 2014-es börzsönyi jégtörés által érintett völgyek összehasonlító elemzése légi lézeres letapogatás segítségével. 2014 december 1-2. között súlyos jégkár károsította a Börzsöny hegységet. A 10 000 hektárt érintő kár a Börzsöny hegység vizsgált két völgyét eltérő mértékben érintette. Amíg a Rakottyás-völgy nagy mértékben károsodott, addig a Pogány-Rózsás erdőrezervátum völgye kevésbé. A károk mértékét légi lézeres letapogatással és terepi felméréssel vizsgáltuk. A felméréshez 3D-s borított felszínmodellt (BFM), digitális domborzatmodellt (DDM) és normalizált borított felszínmodellt (nBFM) állítottunk elő nagysűrűségű pontfelhőből, melyből tengerszint feletti magasságot, lejtést és kitettséget számítottunk a termőhelyi adatok leírásához. A távérzékelt és a terepi adatokat károsodási határértékek meghatározása után képpont szinten hasonlítottuk össze egy hibamátrixban, ami részleges egyezést mutatott az eltérő mintavételi módszerek és a területi lefedettségek között. Kimutattuk továbbá, hogy a Rakottyás völgy súlyosabban sérült (a terület 54,35%-a), mint a Pogány-Rózsás rezervátum (36,7%).

erdőkár / légi lézeres letapogatás / digitális terepmodell / jégkár

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1 INTRODUCTION

The Börzsöny Mountains experienced the most severe abiotic forest damage in Hungary in the last half-century (Hirka 2015). The damaged areas include the two study areas this article covers. Sleet combined with frost characterised the weather during the damage event. Sleet fell continuously for 48 hours and froze when the temperature dropped and remained between - 0.5 – -1 ℃. The ice break caused 10,000 hectares of severe forest damage in the form of mechanical damage to branches, tops, and trunks from the ice burden on the trees. The combination of sleet and frost turned to ice and gradually accumulated on the trees over several hours. The 4–5 cm thick additional rime layer on the 3–5 cm thick ice layer, deposited from the 20–50 mm sleet, caused the most damage (Nagy 2015a). The severe top-breakage and forest reclamation triggered 100,000 m^3 of sanitary logging (Nagy 2015b).

Laser scanning technologies include terrestrial (TLS), airborne (ALS), and spaceborne (SLS) solutions. All can be efficiently applied for forest mapping and monitoring, but ALS by aeroplane is the most suitable (Király – Brolly 2006). The advantages of this method are the flexibility of flight lines, time, and sensors, and the rapidly created dense point cloud in 3D. ALS can survey several thousands of hectares in a single day within a possible accuracy of a few centimetres for elevation (Dahlqvist et al. 2011) and half a meter for tree height (or canopy height) (Kaartinen et al. 2012). ALS is ideal for measuring these two essential attributes for forest damage surveys, especially in barely accessible, mountainous areas where fieldwork is often problematic. Vastaranta et al. (2011) monitored canopy height change in Finland and reported ALS as a promising tool for snow damage surveys; however, high omission errors and acquisition costs were also experienced. Other biophysical parameters like crown diameter, biomass, or Leaf Area Index (LAI) can also be used for forest damage detection as part of forest inventory creation (Hyyppä et al. 2012).

According to previous studies, the homogenous stands in the Börzsöny Mountains with active management for economic gain suffered more crown breakage and fall damage than the forest reserve that had been unmanaged for several decades (Zoltán – Standovár 2018). With ALS data, it was possible to compare these two areas to show the difference in damage distribution in the two Börzsöny Mountain valleys. This article did not investigate discrepancies between management modes since both sites contained large damaged areas, triggering large-scale sanitary logging, which made it impossible to show differences in forest structure.

The main goal of this article was to survey ice damage in Börzsöny Mountains based on ALS and ground-based datasets. The post-event method is used to compare two valleys in the mountains that were damaged to different extents. We measured the damage via tree height and the forest damage frequency of field-based damage reports. The other goal was to investigate the site conditions (elevation, slope, aspect derived from ALS data) of the two sites, which showed similarities and dissimilarities in some geographical-ecological attributes. The reasons for the divergent observed damage intensities in the two valleys could be due to particular forest structures, management and site conditions. However, the objective of this study was to show the applicability of ALS data on forest damage sites using a post-event method on the example of the two valleys, not management surveying. The ALS survey and the field survey were both conducted after the damage, and we aimed to test if these datasets made with different methods can be compared. We also investigated possible disparities between the valleys based on the combined dataset.

2 MATERIALS AND METHODS

2.1 Study area

The study areas are located in the central part of the Börzsöny Mountains (*Figure 1a*) in Northern Hungary, belonging to Kemence and Diósjenő-Királyrét forest administrative units, more specifically, the Kemence and Diósjenő village boundaries on the borderline of Pest and Nógrád counties. The local forest manager here is Ipolyerdő Forestry Corporation. The whole of Börzsöny is protected and is part of the NATURA 2000 Network, and the Pogány-Rózsás area has further restrictions on management by belonging to the network of forest reserves (Erdőrezervátum Program 2022). The reserve consists of a core area and a buffer zone. This study examined the inner part (*Figure 1b*).

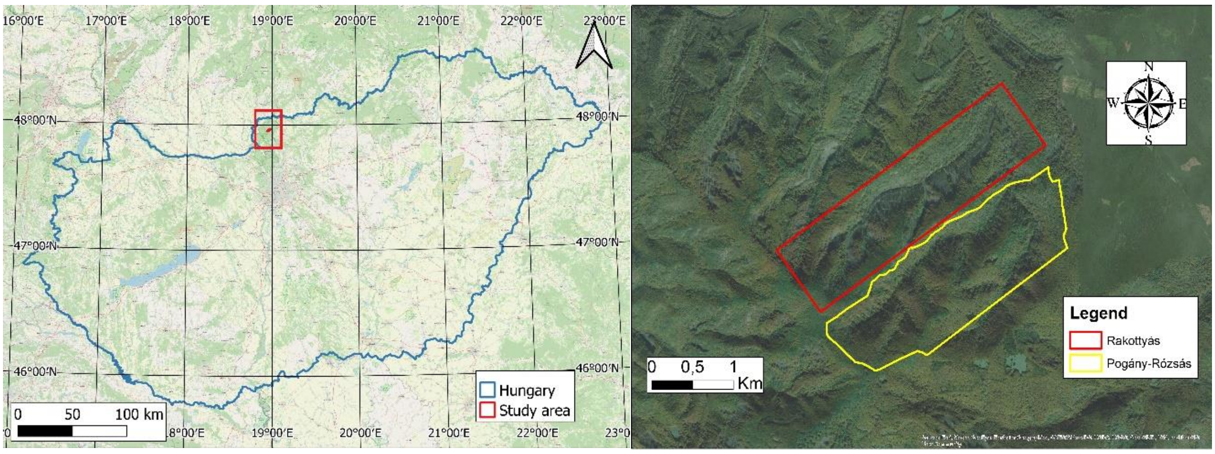

Figure 1 a, b. Börzsöny Mountains in Northern Hungary (a), which contains the two study sites, the Rakottyás (north) and the Pogány-Rózsás (south) valleys on Google Maps aerial image in 2021 (b)

The main tree species of the study area are European beech (*Fagus sylvatica*), mixed with European ash *(Fraxinus excelsior)*, sessile oak *(Quercus petraea)*, European hornbeam (*Carpinus betulus*), sycamore maple (*Acer pseudoplatanus)*, chequers (*Sorbus torminalis)*, wild cherry (*Prunus avium*), Turkey oak (*Quercus cerris*) and European larch (*Larix decidua*). In increasingly larger areas, forest management has shifted from a rotation system with clearcutting to a permanent forest cover system (Ipolyerdő 2017). The forest site conditions (according to the Hungarian forest laws) are similar in the two study sites, i.e., they belong to the beech climate zone. The soil origin type is mainly ranker (Leptosols of World Reference Base for Soil Resources), while brown forest soil (Luvisoils) occurs to a smaller extent. The soil texture is silty, and the rooting depth is deep and semi-deep. Hydrologically, the rooting depths are independent of water surplus, meaning that the forest obtains water only from precipitation.

2.2 ALS survey

The study areas were covered by an ALS survey of about 1600 hectares, from which the Rakottyás and the Pogány-Rózsás valleys cover around 630 ha. (*Figure 1*). The flight took place on 29 August 2015 (~9 months after the damage) and a point cloud was created with a Leica ALS 70-CM scanner with 30 points/m^2 density. From the digital point cloud, a Digital Terrain Model (DTM), a Digital Surface Modell (DSM), and a normalised Digital Surface Modell (nDSM) were derived. Further, the DTM was the base of slope and aspect maps.

The 3D point cloud was processed in Lastools 191111 (Isenburg 2012). The 2D rasters with 1x1 m spatial resolution were derived from the point cloud and were analysed with ArcGIS 10.7 (ESRI 2019), and QGIS 3.20 software.

2.3 Data processing

Raw ALS data processing started with the tiling of the point cloud into 100 ha large tiles in the Lastools program using the *lastile algorithm* (Figure 2) and was followed by the classification of points (echoes) into two classes: vegetation (class 1) and terrain (class 2) by *lasground*. In the next step, second class points were classified into low (0–2 m), medium (2–5 m), and high (>5m) vegetation classes (classes 3,4,5) according to their height by *lasheight*. Error points were filtered out, identified as being isolated, and having unrealistic values in class 7 by *lasnoise* based on 4 m distance and 5 points. Those points could be due to bird hits, random hardware, or software errors.

DTM was constructed from the last field echo using the *lasground* algorithm, while DSM was constructed from the first, uppermost vegetation echo according to *lashheight*. The nDSM was made of DSM using the replace z option to obtain vegetation height instead of elevation. From the 3D laz point clouds, 2D rasters were generated with *las2dem,* resulting *in* 1x1 m resolution tif files.

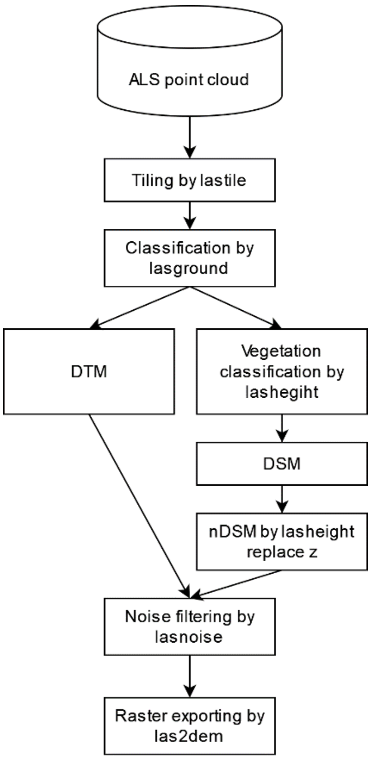

Figure 2. Flowchart of ALS data processing in Lastools.

We used ArcGIS and QGIS for raster processing and analysis. First, we merged the separate DTM, DSM, and nDSM tiles into single DTM, DSM, and nDSM rasters, respectively. Secondly, we filtered out extreme and unrealistic values in the rasters with a Gaussian filter in focal statistics (3x3 pixel rectangle) in triple-time iteration. This second filtering was needed to cease holes that remained in rasters. Thirdly, we generated slope (given in % (0-100)) and aspect (measured in degrees clockwise from 0 (north), 90° (east), 180° (south), 270° (west) to 360° (north again)) rasters based on the DTM. Comparative analyses were performed on two spatial levels, i.e., at the forest compartment level and a pixel-level based on these maps.

A database of forest compartment polygons was generated where all datasets were aggregated to the polygon level. First, we did an intersection of the Area of Interest (AOI) and a dataset of forest compartments. The ground-based data to filter the AOI provide data about site conditions and the ground-based validation was retrieved from the Hungarian National Forestry database of the Hungarian National Land Centre. The forest compartment layer was clipped by the AOI mask of Rakottyás and Pogány-Rózsás valleys based on centroids inside the polygons. The ground-surveyed forest damage from the National Forest Damage Registration System was added to the clipped polygons by joining the same forest compartments with a unique ID field. Polygons were filled with data from elevation, slope, aspect, and vegetation height rasters by zonal statistics using mean values; thus, these values were added to the attributes besides the ground-based damage and site condition information.

The ground-based dataset is from the Hungarian National Forestry database and the forest protection damage reports of the National Forest Damage Registration System (OENyR). The OENyR has data on damage frequency and intensity given for each forest compartment of Hungary, which is systematically collected and reported at least four times per year at the end of each quarter, except for quarantine pests, which must be reported immediately (Hirka 2018). The damage frequency is the number of damaged given trees compared to all trees in the same species in the compartment expressed in the percentage (0–100%), i.e. if 30 oak are damaged in a compartment containing 100 trees, then the frequency is 30%. The damage intensity shows the severity of damage and health deterioration compared to the healthy state, given in percentage (0–100%). For example, if half of the canopy is missing due to defoliation in the compartment, then the intensity is 50 %. This study used damage frequency and collected the reports from 2–19 December 2014. Based on these reports, 3,630 ha of forest in 75 compartments was damaged in the whole of the Börzsöny Mountains. From this, 1,144 ha were moderately damaged (26-60% damage intensity), 7 ha were severely damaged (61-99% damage), and 663 ha were thoroughly damaged (100% damage) (Hirka 2015). The two study sites suffered damage on 193 of 797 hectares.

Comparative spatial analysis of the two studied valleys was created at the pixel and forest compartment levels. The Zonal Statistics as Table (Spatial Analyst) function was used to calculate mean values from nDSM pixels within a forest compartment. The mean values of forest compartments were compared to the field-based damage frequency data. Regarding the pixel level datasets, the damage frequency polygons were rasterized into a 1x1 m resolution raster and with the nDSM raster, and a confusion matrix was created. The elevation, slope, aspect, and tree height rasters were also compared at the pixel level in the two valleys.

Regarding the ALS data, the damaged forest threshold was set below 5 m on the nDSM raster showing vegetation height to eliminate pixels with pioneer vegetation and to show unforested areas or fallen trees caused by ice. The ground-based report damage threshold was set to at least 90% regarding frequency. According to these rules, every pixel was reclassified. Vegetation height pixels below 5 m received the value of 0 while values above 1 were marked as damaged and non-damaged. When damage frequency reached at least 90%, the ground-based dataset received a 0; when it did not, it was labelled as 1. In the next step, the two reclassified rasters were compared with the SCP plugin of QGIS (Congedo 2021), resulting in a confusion matrix map.

In the matrix, 1 signifies damage by both methods (True Positive, TP), 2 signifies damage shown by ALS but not ground-based reports (False Positive, FP), 3 is damaged by ground-based reports but not ALS (True Negative, TN), and 4 stands for undamaged by both methods (False Negative, FN). In the confusion matrix, the true positive pixels show when the model correctly predicted the positive class (TP), while the true negatives show where the model correctly predicted the negative class (TN). False positive (FP) indicates the cases when the model incorrectly predicts the positive class. The pixel is a false negative (FN) when the model incorrectly predicted the negative class. The elements of the matrix are calculated as: P = TP+ FN; N = FP + TN; Pc = TP+ FP; Nc = FN +TN; SUM = P + N = Pc +Nc, and the matrix elements are derived as:

- Sensitivity = Probability of true positive P(TP) = TP/P
- Specificity = Probability of true negative P(TN) = TN/N
- Precision = Positive predictive value P(TP) = TP/Pc
- Negative predictive value P(TN) = TN/Nc
- Total Accuracy = Probability of accurate classification P(Acc) = (TP + TN)/SUM.

3 RESULTS AND DISCUSSION

We examined the site attributes and the extent of forest damage in both study sites. The topographic properties were partly similar in the two compared study areas. Both sites were similar in area (Pogány-Rózsás is 328 and Rakottyás 289 ha) but elevation (*Figure 3*), aspect (*Figure 4*), and slope (*Figure 5*) differed. Pogány-Rózsás was situated on higher and steeper slopes, while Rakottyás was more north-facing. Three heights (on the nDSM map) also differed due to the damage (*Figure 6*). To visualize the differences between Pogány-Rózsás and Rakottyás, elevation, slope, and aspect were compared on a radar diagram (*Figure 7*).

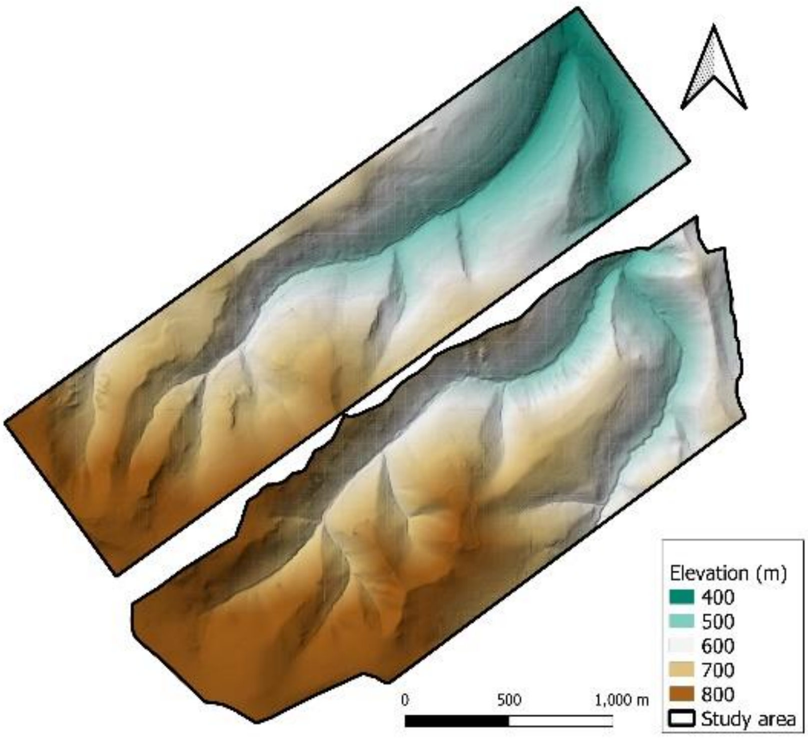

Figure 3. Elevation of Rakottyás and Pogány-Rózsás valleys based on DTM. Pogány-Rózsás is situated at higher mean elevation (696 m) then Rakottyás (632 m)

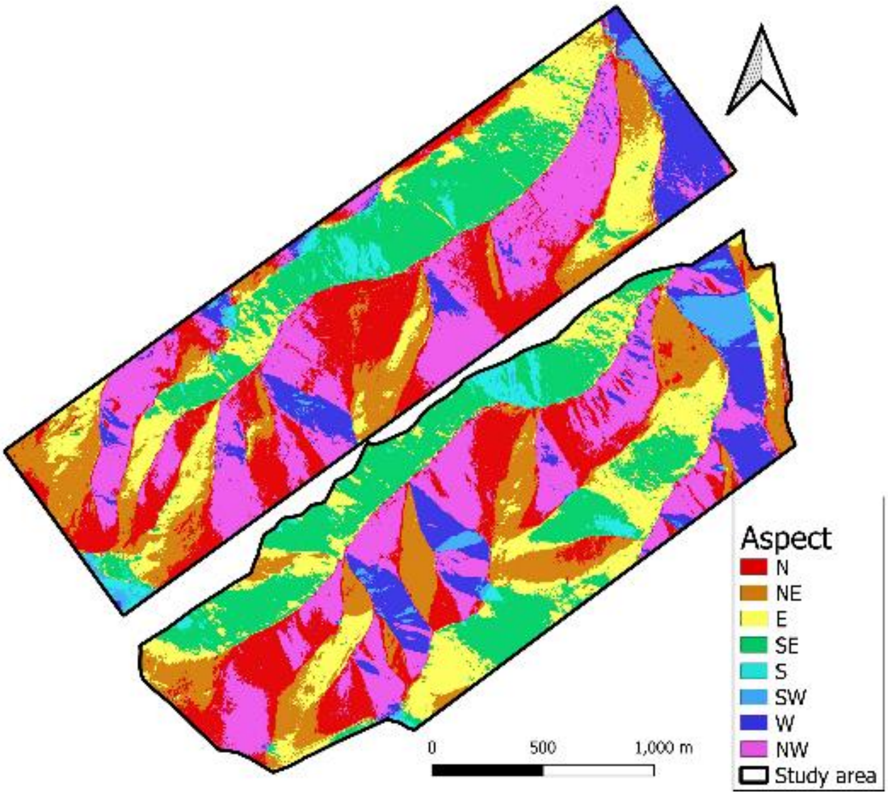

Figure 4. Aspect of Rakottyás and Pogány-Rózsás valleys based on DTM. The most typical slopes are the northerly in Rakottyás and east-facing ones in Pogány-Rózsás

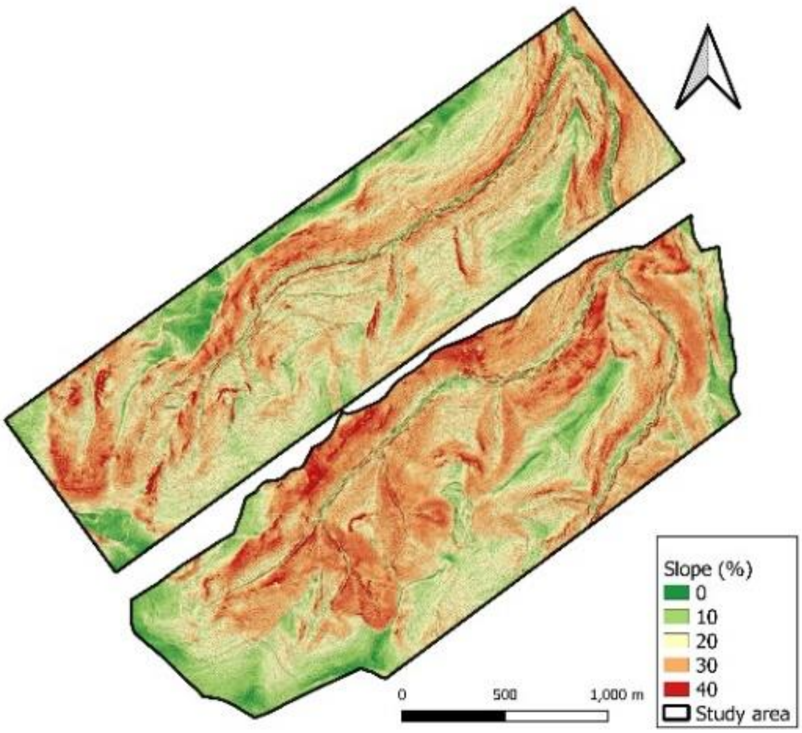

Figure 5. Slope of Rakottyás and Pogány-Rózsás valleys based on DTM. Pogány-Rózsás is slightly steeper (46% in mean) then Rakottyás (42%), but less damaged

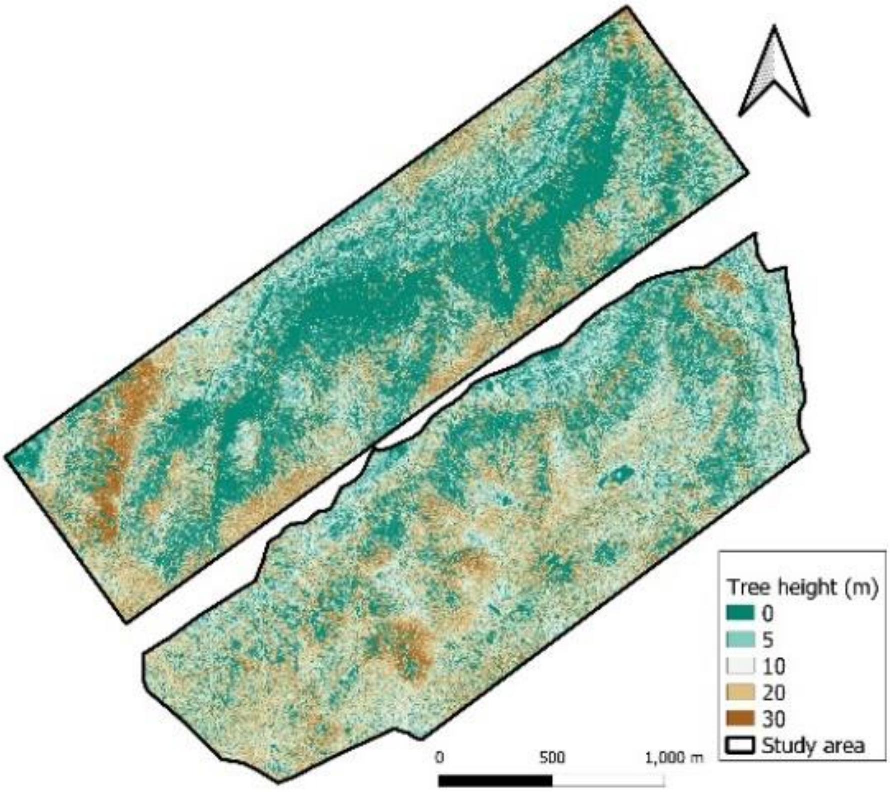

Figure 6. Vegetation height of Rakottyás and Pogány-Rózsás valleys based on nDSM. Pogány-Rózsás had more heterogenic forest heights, i.e., more small-scale differences, while the forest height in the managed Rakottyás was more homogeneous; however, this is due to the larger flat area caused by the damage

Table 1. The comparative pixel-level analysis of geographical conditions (elevation, slope, aspect) of Rakottyás and Pogány-Rózsás valleys expressed in %.

Elevation [m]			Slope [%]			Aspect		
	Pogány-Rózsás	*Rakottyás*		*Pogány-Rózsás*	*Rakottyás*		*Pogány-Rózsás*	*Rakottyás*
500	1.10	13.63	5	1.16	2.03	N	20.42	29.23
600	22.11	29.25	10	5.23	6.34	NE	22.45	21.38
700	30.63	29.73	20	23.78	27.55	E	24.03	22.28
800	24.83	18.75	30	43.95	48.97	SE	29.92	23.63
800 <	21.33	8.64	30 <	25.89	15.11	S	3.18	3.49
						SW	3.83	2.46
						W	11.88	11.70
						NW	26.37	36.47
Total	100	100		100	100		100	100

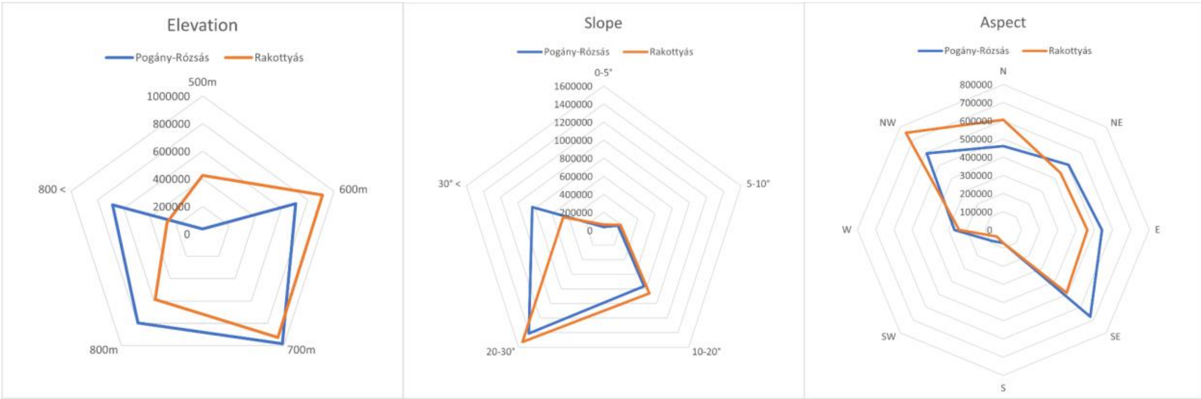

Figure 7. Elevation (a), slope (b), and aspect (c) conditions of Rakottyás and Pogány-Rózsás valleys based on DTM. The most frequently damaged slopes are the NW-facing in Rakottyás and the SE ones in Pogány-Rózsás. Steep slopes between 20–30° are the most frequent, and 700 m is the most typical height above sea level.

The comparative analysis of ground-based datasets provided information about the sixty forest compartments. The analysis was based on the damage ratio calculated from the damaged area compared to the total forest compartment area (*Table 2*) (*Figure 8*) according to the Hungarian Forest Damage Database. The comparison revealed that the Rakottyás Valley suffered moderate damage in eight forest compartments where the damage ratio was between 40–60%, while Pogány-Rózsás suffered severe damage (60–100%) in 12 forest compartments. In Pogány-Rózsás forest reserve, more damage was registered on the ground; however, according to the remote sensing method (RS), it was less damaged than Rakottyás. Nonetheless, the number of compartments is not directly or practically comparable because Pogány-Rózsás contains almost twice as many polygons as Rakottyás. Despite this, the compartment sizes are significantly larger in Rakottyás. In addition, several compartments are only slightly damaged (0-20% damage ratio) here, but their number is significant.

Table 2. Comparative analysis of Rakottyás and Pogány-Rózsás valleys based on ground-based damaged data.

Damage ratio (%)	*Rakottyás* Forest compartments (pcs)	*Pogány-Rózsás* Forest compartments (pcs)
0–20	11	24
20–40	2	2
40–60	8	1
60–80	0	5
80–100	0	7
Total	21	39
Total area (ha)	289.41	327.65
Damaged area (ha)	82.2	111.08
Damage ratio (%)	28.4	33.9

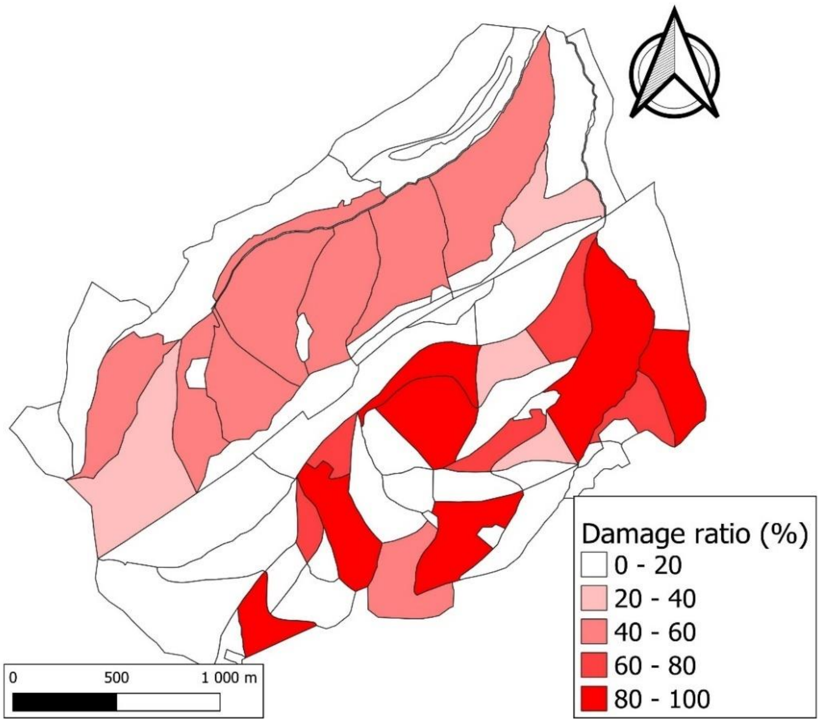

Figure 8. Ground-based damage ratio in Rakottyás and Pogány-Rózsás valleys. The difference between the damage severity and the size and number of compartments is visible in the two valleys.

The pixel-level damage analysis of ALS data was completed to compare the reclassified nDSM raster and the ground-based reports. The confusion matrix showed the precision, negative predicted values, sensitivity, specificity, and total accuracy (*Table 3*). The ground-based and RS-based methods partly agreed on the damage, which can be seen in *Figure 9* and explained by several factors.

Table 3. Confusion matrix of remotely sensed (ALS) and field-based datasets

		Predicted class			
		Positive (pixels / %)	Negative (pixels / %)		
Actual class	Positive (pixels / %)	1,514,889 / 26	1,138,339 / 19.6	0.57	Sensitivity (%)
	Negative (pixels / %)	1,518,346 / 26.1	1,650,833 / 28.4	0.52	Specificity (%)
		0.50	0.59	0.54	Total accuracy (%)
		Precision (%)	Negative predicted value (%)		

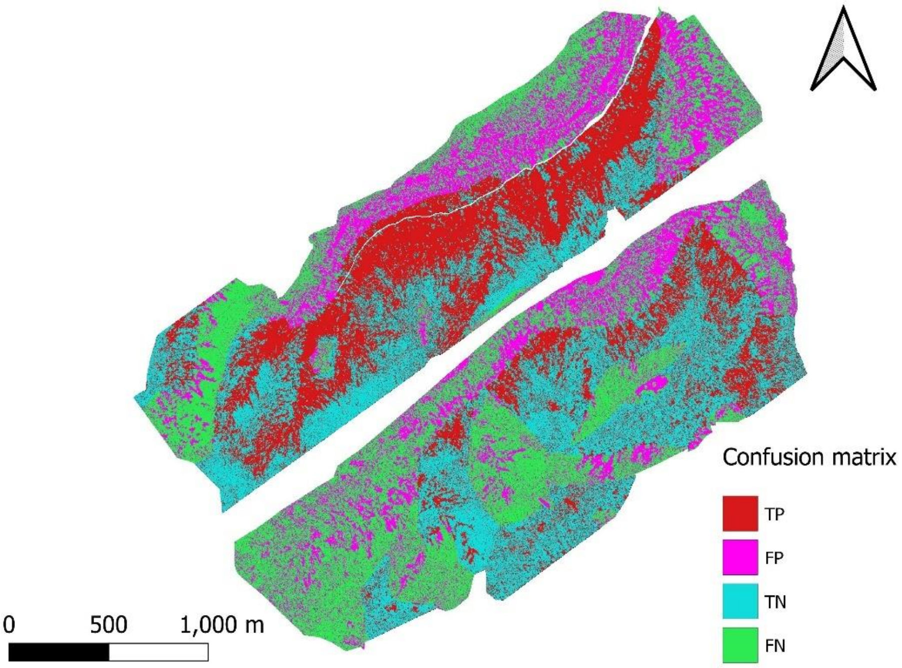

Figure 9. Confusion matrix of ALS and ground observed damage in Rakottyás and Pogány-Rózsás valleys. The colours indicate damage detected by both methods (red), by ALS (purple), by ground-based survey (cyan), and by none of the methods (green).

Based on this classification, at least one method showed damage 71.7% of the area, while both methods showed damage 26%. However, the category of no-damage covers a quarter of the AOI with 28.4%. The large average size of forest compartments, the threshold of ALS damage, and the method of ground-based data collection could all be reasons for this. The average size of the forest compartments in both valleys is large, in Pogány-Rózsás, it is 7.7 ha and 13.5 ha in Rakottyás. The average for the two study sites is 10.6 ha, but some compartments reach up to 27 ha. Since the ground-based data covers all forest compartments and do not specify the exact location of the damage, the datasets result in coarse resolution data compared to high-resolution 1x1 m rasters from ALS, which causes problems with pixel matching. The full compartment level surveying is a weakness of the ground-based dataset. The moderate precision (0.5), specificity (0.52), sensitivity (0.57), and total accuracy (0.54) could be explained by that.

When compartments were compared to each other on a pixel scale of ALS data in the two valleys that both field and ALS data covered, Rakottyás exhibited 54.3% damage, while Pogány-Rózsás exhibited only 36.7% (*Figure 10*). Thus, the 5 m ALS damage threshold successfully uncovered the difference between the valleys (*Table 4*). The difference could be attributed to stand differences. Rakottyás had even-aged stands, similar mean height, and a rotation system, while Pogány-Rózsás contained uneven-aged and more natural stands, which suffered less damage; however, this was not surveyed separately.

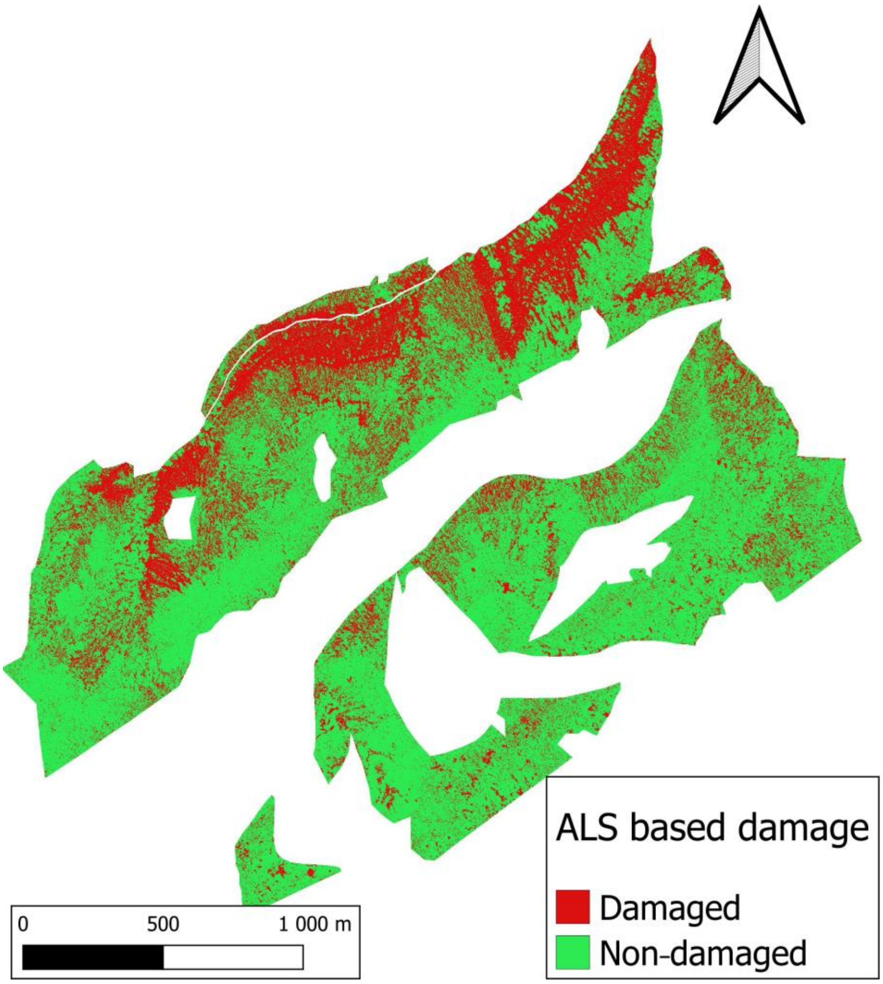

Figure 10. Comparison of two valleys on pixel scale of ALS damage data, where Rakottyás showed significantly more damage (54.35%) than Pogány-Rózsás (36.74%)

Table 4. Comparative damage survey of the two valleys on a pixel level based on ALS and field-based datasets.

Rakottyás			*Pogány-Rózsás*	
Value	Pixel count	%	Pixel count	%
0	1,439,331	54.35	1,115,011	36.74
1	1,208,880	45.65	1,920,283	63.26
Total	2,648,211	100	3,035,294	100

The different scale of the two datasets remains a problem, but the comparison accuracy could be increased with the aggregation of ALS data at the forest compartment level with which the field survey was created. For this, the ALS-based damage values (0 and 1) were aggregated with a majority filter for compartments to be directly comparable to field reports constructed at that level. In Pogány-Rózsás, 15 of the 21 compartments were damaged by both methods, while in Rakottyás this ratio was 26 of 39, resulting in 71.43% and 66.67 % accuracy, respectively.

Regarding the terms of comparative analysis, it would have been desirable to have two ALS datasets, one taken before the damage (pre-event) and one after (post-event) and compare them to show changes. Since pre-storm ALS data was unavailable, we could not compare the pre-state and post-state in the same manner Honkavaara et al. (2013) did in their study. However, we managed to show the applicability of ALS data on forest damage sites using only the post-event dataset. Chirici et al. (2018) utilised similar methods to assess forest windthrow damage in Italy using single-date, post-event ALS data, and found a 63% relative standard error when ALS was compared to a field survey in total volume estimation. They recommend the method because it is more efficient than fieldwork and provides satisfactory estimates with a given uncertainty. Notwithstanding, ALS-based snow damage detection in Finland with a bi-temporal dataset proved more accurate (78.6%) with 5x5 m pixels (Vastaranta et al. 2011). In addition to abiotic damage such as snow break or windfall, the bi-temporal method can detect biotic damage as Solberg et al. (2006) proved with LAI-based defoliation caused by insect gradation in Norway where the field-measured and ALS-based Leaf-Area Index (LAI) showed a strong correlation (R^2 = 0.87–0.93).

Although ALS in operation forestry is still rare, it has been employed several times in Norway. Noordermeer et al. (2020) used site index mapping (based on tree height at a given age) and forest disturbance classification, and Næsset (2007) evaluated methods for stand-based forest inventory where point clouds were used to predict six biophysical stand variables based on regression equations in forest planning. Both studies presented promising results. They report a total accuracy of 87–94 % for forest disturbances and 3–13 % standard deviation for tree height, basal area, and timber volume estimation compared to field-based measurements.

In addition to ALS, other RS methods like Synthetic Aperture Radar (SAR) can be also utilised to monitor ice break. Zoltán et al. (2021) applied Sentinel-1 for the same damage event in Börzsöny and revealed a 65.7 % overall accuracy albeit with a significant crown loss overestimation (55–58%).

Certain aspects of field surveys like determining soil properties could also be interesting since it could be connected to the ice damage. A shallow ranker soil is more likely prone to this type of damage compared to brown forest soil with deeper rooting depth; however, as these site conditions showed, elevation, aspect and slope have greater significance. The most severe damage occurred at particular elevations (600–700 m), slopes (2–30°) and aspects (N, NW).

4 CONCLUSIONS

The combined ALS and ground-based method successfully showed the ice break damage in Börzsöny Mountains. However, the significant differences experienced in the surveyed damage based on different methods tend to originate in the various methodologies. One reason is that the ground-based survey registered whole compartments as damaged ones regardless of the extent of the damage. On the other hand, ALS remote sensing utilises large-scale digital maps showing the exact location of the damage. Another reason for differences resides in the presence of obstacles in a ground survey. These obstacles include difficult accessibility on steep terrains, compartments containing many fallen trees, dangerous road conditions, unfavourable weather, or a lack of human resources. These difficulties often make it impossible to complete a survey, leading to damaged compartments with no field data. Although RS methods provide a solution to these issues, the cost of RS is significantly higher on smaller scales. Consequently, the combination of both methods provides the most suitable way.

Regarding larger scales, RS could offer much faster, even semi-automatized, advanced technology for forest damage surveying. Moreover, novel algorithms can increase accuracy. An ALS survey can be completed in a single day or a few days after the forest damage has occurred. The software used offers increasingly automatized methods, ensuring that data acquisition, processing, and evaluation can be performed in days, rather than over the course of months as is often the case with fieldwork. Furthermore, fieldwork requires far more organisation and human labour. RS and artificial intelligence offer effective ways to ameliorate this labour intensity.

The damage threshold offers another probable reason for differences. We chose a threshold below 5 m for damaged forests in connection with vegetation height because of the nine-month time difference separating the damage event and the survey. This period is nearly equivalent to an entire vegetation season, during which pioneer vegetation tends to grow quickly. The subjective threshold is intended to mean the difference between the constant height within a stand, which is supposed to be a healthy forest and the damaged part of the stand. The artificial intelligence-based algorithms could also help to improve thresholds by making them more objective and reveal real differences. They could also help to more accurately extrapolate datasets like tree height measurements of all trees on the field, which are not available evenly for whole study areas. It would also be desirable to study the event on two datasets (pre-and post-event) supported by artificial intelligence to detect forest structure and changes in it due to the damage. This approach could help to detect top- or branch breakage, which the current study did not investigate. Further research into such breakages is required to include them in damage surveys.

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