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ASSESSMENT OF SMARTPHONE-BASED 3D SCANNING AS AN ALTERNATIVE TO XYLOMETRY FOR MEASURING SMALL, IRREGULAR WOOD PIECES GENERATED DURING HARVESTING

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ABSTRACT

This study evaluates the applicability of smartphone-based 3D scanning for measuring small, irregular wood pieces generated by felling notches in windthrown Norway spruce (*Picea abies* L.) stands. A total of 114 notch pieces were measured using both a conventional xylometric method and a smartphone-based 3D scanning method. The volumes obtained by the two methods showed an exceptionally strong correlation ($r = 0.9993$) and excellent absolute agreement (ICC = 0.9992). The Bland–Altman analysis indicated 95% relative limits of agreement of −15.36% to +25.20%, together with a significant proportional bias. The total notch loss index was 0.186% using xylometry and 0.184% using 3D scanning. The regression analysis showed that notch height was the only significant predictor of the loss index. The results indicate that smartphone-based 3D scanning is a promising method for estimating the volume of small and irregular wood pieces, although its interchangeability with xylometry requires predefined acceptable measurement limits.

KEYWORDS: Timber losses, notch, 3D scanning, xylometry, windthrow.

INTRODUCTION

The phenomenon of windthrow has been extensively studied, particularly with regard to its ecological, social and economic impacts (Ulanova 2000; Brüchert & Gardiner 2006), including its effects on the carbon balance (Thürig et al. 2013; Seidl et al. 2014; Samariks et al. 2020). Research has addressed windthrow from the perspective of its causes, effects, and the measures required for its appropriate management (Bogdan & Coşconea 2010; Martínez-Alvarado et al. 2012; Schindler et al. 2012; Birot & Gardiner 2013; Găbrian & Budeanu 2013; Ciocirlan & Câmpu 2024,2025). One aspect that has received less attention is the quantification of timber losses occurring during the harvesting of timber from stands affected by windthrow.

Research on reducing timber losses has been conducted in Romania for more than five

decades (Rusu et al. 1955; Andreescu & Amzica 1959; Pavelescu 1970; Ciubotaru 1998; Ciubotaru et al. 2012; Borz et al. 2014; Borz & Proto 2025;), as well as internationally (Koopmans & Koppejan 1997; Boltz et al. 2003; Asner et al. 2009; Malik & Hopewell 2011; Sofuoglu & Kurtoglu 2012; Behjou et al. 2016; Kärhä et al. 2018; Aryal et al. 2022; Gülci et al. 2023; Dvořák et al. 2025). The recovery of the economic value of timber originating from stands affected by biotic and abiotic factors is a topic of growing interest in the context of the current climate change, under which an increase in the frequency of such disturbances is anticipated (Kärhä et al. 2018). At the same time, in several countries, timber demand is increasingly shifting towards renewable resources, with wood being considered a lower-carbon emission alternative to fossil fuels (Gülci et al. 2023). Timber losses are inherent to forest harvesting operations and are documented both in the case of planned harvesting operations, where reported values range between 1 and 3% (Ciubotaru 1998), and in the case of unplanned operations, such as those caused by windthrow, where losses may be significantly higher (Behjou 2016), reaching up to 8% of gross volume (Pavelescu 1970; Ciubotaru 1998) or 7.747% (Ciocirlan & Câmpu 2025).

The use of modern volumetric assessment methods for quantifying losses generated during harvesting operations may contribute to increasing the efficiency of certain operations traditionally performed using conventional, labour-intensive methods (Borz & Proto 2025). A method for estimating notch losses, although they represent a relatively small proportion of total tree volume, is reported by Đuka et al. (2020) who proposed estimating volume by approximating the notch as a cylindrical shape. Câmpu (2015) uses the xylometric method to determine the volume of firewood pieces with lengths of less than 1 m and irregular shapes. The use of the 3D scanning method represents a novelty for application to very small and highly irregular pieces generated by felling notches, direct comparison with the xylometric method, validation under a specific timber loss context and quantification of measurement agreement. The objectives of the present study are to determine the volume of timber losses associated with the notch using the xylometric and the 3D scanning method; to detect under what conditions the 3D scanning method can be an alternative to the xylometric method; to calculate the loss index, and to analyze the influence of the dimensional and technological parameters of the notch on loss index in spruce stands affected by windthrow.

MATERIALS AND METHODS

Study location

The study area is located in the Curvature Carpathians, at the contact zone between the Brețcu Mountains, Vrancea Mountains and Buzău Mountains, in the upper third of the basin formed by the Bâsca Mare and Bâsca Mică rivers. The forest area is managed by the Forest District of Comandău (Fig. 1). The main characteristics of the stand are presented in Tab. 1.

Experimental design of 3D scanning

To achieve the objectives of the study, four experimental plots were established, each with an area of 2000 m² (50×40 m). The plots were located in areas considered most representative

for the stand, using a GPS device (Garmin GPSMAP 64sx), and were positioned along the slope (Fig. 2). All trees within the sample plots were inventoried, both uprooted (windthrown) and standing trees (Tab. 2).

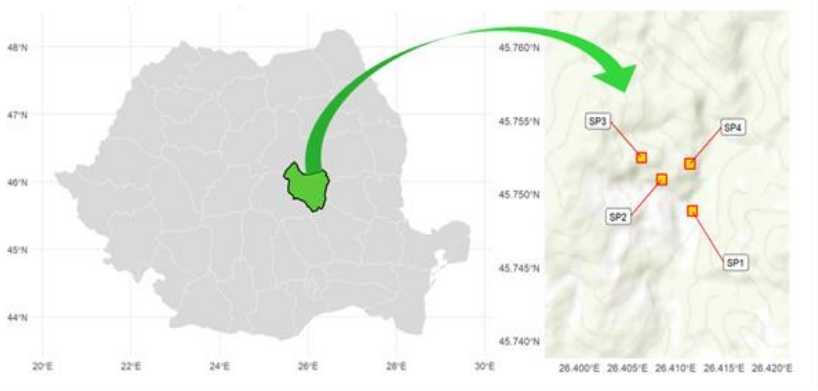


Fig. 1: Study location.

Tab. 1: Tree stand characteristics.

Forest compartment	Area (ha)	Altitude (m)	Aspect	Species	Age (years)	Composition (%)	Site class	Crown density	Average diameter (cm)	Average height (m)
				Spruce	85	50	II		34	28
110 C	7.13	1340	SE	Spruce	60	30	III	0.8	26	21
				Spruce	105	20	II		40	30



Fig. 2: The setting up of sample plots.

Tab. 2: General data from sample plots.

Sample plots	Coordinates		Number and volume of trees					
	Latitude	Longitude	Uprooted trees		Standing trees		Total	
			No.	(m^3)	No.	(m^3)	No.	(m^3)
SP1	45.748840	26.411710	43	40.099	80	42.892	123	82.991
SP2	45.750980	26.408540	86	68.658	12	6.998	98	75.656
SP3	45.752480	26.406440	52	129.598	8	11.320	60	131.918
SP4	45.752060	26.411450	105	114.049	14	9.321	119	125.370
Total	-	-	286	345.404	114	70.531	400	415.935

Simultaneously with the collection of the notches, data on the dimensional characteristics of the sampled trees were recorded. Each notch was assigned a unique identification code corresponding to the experimental plot of origin and the tree order number within the plot. The harvesting system used was the long log and pole system. The working team consisted of

three operators: a chainsaw operator (using a Husqvarna 372 chainsaw), an assistant, and the operator of a TAF 690 Perkins skidder. The team members had more than five years of shared professional experience and were familiar with safe working procedures for both chainsaw operations and timber extraction machinery, as well as with the specific conditions of windthrow harvesting operations. Three-dimensional characteristics were measured using a diameter caliper and measuring tape, while notch dimensions were measured using a caliper and a goniometer. The latter was used to measure the notch angle (Fig. 3). To determine timber losses in the notch, two distinct methods were applied: a scanning-based method and a xylometric (water displacement) method.

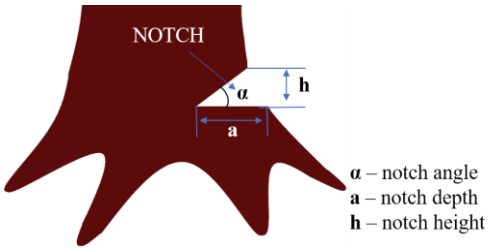
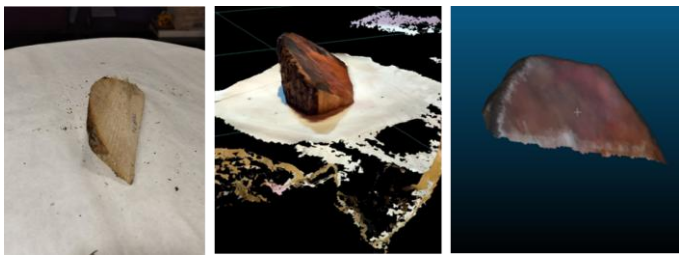


Fig. 3: Dimensional parameters of the notch.

The scanning method involved the use of a digital application developed by Forest Design company, installed on a Huawei P40 Pro mobile device. Both the camera and the time-of-flight (ToF) sensor are standard features of the smartphone. The Forest Design Scanner (FDS) application uses images captured by the camera and distance measurements between the device and the scanned log, provided by the ToF sensor, to construct the 3D model of the logs. Therefore, the procedure used does not constitute standard image-based photogrammetry, which relies exclusively on images, nor LiDAR scanning, but rather a smartphone-based 3D scanning method. Each notch was scanned individually on a work table by capturing successive images from multiple angles, in order to obtain a highly accurate three-dimensional representation of its shape. Prior to data acquisition, preliminary tests were conducted to optimize scanning conditions. The best results in terms of contour detection and shape recognition were obtained on a white background under uniform ambient lighting, predominantly from above. To increase accuracy, each notch was scanned three times, and the resulting 3D models were processed using CloudCompare v.2.12.2 software in order to determine the volume (Fig. 4).



a) *b)* *c)*

Fig. 4: 3D scanning of the notch: a) preparation of the notch; b) scanning result – virtual image (point cloud) using the Forest Design Scanner app, c) final 3D model and volume determination using CloudCompare software.

This method has been previously employed for the measurement of timber assortments resulting from forest harvesting operations (Borz & Proto 2022; Niță & Borz 2023). FDS was used to acquire three-dimensional data and generate virtual representations of the timber pieces (Fig. 4). The models generated during the scanning process were initially stored on a smartphone and subsequently exported as three-dimensional point cloud models.

Data processing was performed using CloudCompare v.2.12.2 (2022), a software platform designed for the visualization, editing, and processing of three-dimensional point clouds and surface models. The software was used to reconstruct the three-dimensional geometry of the timber pieces and determine their individual volumes. The three-dimensional geometry of each timber piece was reconstructed using the "Poisson Surface Reconstruction" algorithm available in CloudCompare. The resulting three-dimensional models were subsequently inspected and segmented to remove points that did not correspond to the timber piece under analysis. Following this filtering and segmentation procedure, a three-dimensional model representing the actual geometry of each timber piece was obtained, allowing its volume to be accurately determined. Volume calculations were performed using the "Mesh Volume" tool implemented in CloudCompare. The scanning of the timber blocks was done within a few days after the field collection, in order to preserve, as much as possible, natural moisture conditions and to avoid shrinkage effects that could have influenced the results.

Xylometric method

The xylometric method, a classical and widely used technique for determining the volume of small-sized and irregularly shaped wood pieces. This method is based on the physical principle that a submerged object displaces a volume of liquid equal to its own volume (Vintilă 1942; Câmpu 2015). Depending on notch dimensions, two xylometric cylinders equipped with valves were used, with the diameters of 40 cm, respectively 20 cm and 100 cm height. The displaced water volume was measured using graduated cylinders (Fig. 5).



Fig. 5: Xylometric method used for notch volume determination.

$$I_{notch} = \frac{V_{notch}}{V} \times 100, \quad (1)$$

The volume (V) of each tree was calculated using the following regression equation:

$$\log V = a_0 + a_1 \log d_{1.30} + a_2 \log^2 d_{1.30} + a_3 \log h + a_4 \log^2 h, \quad (2)$$

where: V – tree volume; d – DBH (breast height diameter measured at the height of 1.30 m);

h – tree height. a_0, a_1, a_2, a_3, a_4 – regression coefficients established for spruce (a_0 = -4.18161, a_1 = 2.08131, a_2 = -0.11819, a_3 = 0.70119, a_4 = 0.14818) (Giurgiu et al. 2004).

Data analysis

The statistical analysis of data involved the determination of the main statistical indicators of the variations of the loss volume (mean, standard deviation, variation coefficient, minimum and maximum). The loss values obtained by the two methods were compared using the t-test: Paired two sample for means. Also, the agreement between methods was assessed using Bland–Altman analysis, with the mean difference representing systematic bias and the 95% limits of agreement (LoA) calculated as bias ± 1.96 SD (standard deviation) of the differences. Relative differences were additionally evaluated because the measured volumes covered a wide range. Pearson's correlation coefficient was calculated to describe linear association, while absolute agreement was quantified using a two-way random-effects, single-measure intraclass correlation coefficient (ICC[2,1]). Proportional bias was assessed by linear regression of the paired differences on the mean of the two methods. All tests were two-sided, and $p < 0.05$ was considered statistically significant. The correlations between loss index and notch parameters have been studied by using multiple and simple linear regressions.

RESULTS AND DISCUSSION

Volume of timber losses associated with the notch

The analysis was conducted on 114 trees, of which 80 were located in sample plot 1, while the remaining trees were distributed across sample plots 2, 3 and 4 (12, 8 and 14 trees, respectively). This uneven distribution of trees may be reflected in the total volumes of notch losses estimated for each sample plot. The volumes of timber losses, determined using the xylometric and 3D scanning methods, are similar both at the level of the entire dataset and at the level of each individual sample plot. The total volume of losses estimated by the xylometric method was 0.131 m³, compared to 0.129 m³ obtained using the scanning method. At the sample plot level, the highest total volumes of notch losses were recorded in sample plot 1, regardless of the method used (0.076 m³ using xylometry and 0.074 m³ using scanning), while the lowest values were observed in sample plot 4. These differences may be attributed to the different number of standing trees in each sample plot. At the same time, the mean values of loss volume per tree indicate variations between plots, suggesting that, beyond the effect of the number of standing trees, there may also be differences related to tree size or to the execution of the notch (dimensional parameters of the notch). To assess whether there is a statistically significant difference between the means of the two variables, a paired-samples t-test was performed using 114 pairs of observations (Tab. 3). The xylometric method yielded a mean volume of 1153.19 ± 1437.17 cm³ (range, 25–9940 cm³), whereas the 3D scanning yielded a mean volume of 1138.81 ± 1455.21 cm³ (range, 25–9921 cm³). The paired differences were approximately normally distributed (Shapiro–Wilk W = 0.981, p = 0.113). The mean difference (+14.38 cm³) and the paired-samples t-test (t = 2.752; p-value of 0.007) indicates that the difference between the two means is statistically significant at the 5% level. In particular, the volumes obtained by the xylometric method has a significantly higher

mean value than those obtained by the 3D scanning method. Furthermore, the Pearson correlation coefficient (r = 0.99) indicates an exceptionally strong positive linear association between the volumes obtained by the two methods. This suggests that the two series of volume values follow a very similar pattern of variation. Nevertheless, despite their strong correlation, their mean values differ significantly, indicating that the observed difference is unlikely to be attributable to random variation alone.

The Bland–Altman analysis showed 95% LoA (limits of agreement) from −94.97 to +123.73 cm³, indicating that the difference between the two methods for an individual measurement could range from approximately 95 cm³ lower to 124 cm³ higher than the xylometric value (Tab. 4) (Fig. 6).

Tab. 3: Testing the differences between notch volume measured using the xylometric and the 3D scanning methods.

t-Test: Paired two sample for means	Xylometric method (cm^3)	3D scanning method (cm^3)
Mean	1153.193	1138.814
Variance	2065457.325	2117630.100
Observations	114.000	114.000
Pearson correlation	0.999	
Hypothesized mean difference	0.000	
df	113.000	
t Stat	2.752	
P(T<=t) one-tail	0.003	
t Critical one-tail	1.658	
P(T<=t) two-tail	0.007	
t Critical two-tail	1.981	

Tab. 4: Summary of statistical agreement between xylometric and 3D scanning measurements (Bland-Altman test).

Parameter	Result	Parameter	Result
Paired observations	114	Mean relative bias	+4.92%
Xylometric volume, mean ± SD	1153.19 ± 1437.17 cm³	Relative 95% LoA	−15.36% to +25.20%
3D scanning volume, mean ± SD	1138.81 ± 1455.21 cm³	Paired t-test	t(113) = 2.752; p = 0.0069
Mean difference (xylometry − 3D)	+14.38 cm³	Pearson correlation	r = 0.9993; p < 0.001
95% CI of mean difference	+4.03 to +24.73 cm³	ICC(2,1), absolute agreement	0.9992
SD of differences	55.79 cm³	Proportional bias	slope = −0.01248; p = 0.00045
95% LoA	−94.97 to +123.73 cm³	Observations outside LoA	10/114 (8.8%)

Note: LoA - limits of agreement; CI - confidence interval; SD - standard deviation; ICC(2,1) - two-way random-effects, single-measure intraclass correlation coefficient for absolute agreement.

Ten of the 114 paired observations (8.8%) were outside the 95% LoA. These observations were retained in the primary analysis because departure from the Bland–Altman limits alone does not constitute a sufficient basis for excluding measurements. Because the measurement range was wide, from 25 to 9940 cm³, relative agreement was also examined. The mean relative bias was +4.92%, with relative 95% LoA of −15.36% to +25.20%. Thus, although the average difference was approximately 5%, individual measurements could show considerably larger relative discrepancies. The proportional-bias analysis demonstrated a significant association between the paired difference and the mean volume (slope = −0.01248, p = 0.00045), indicating that the magnitude and direction of disagreement varied according to the size of the measured

volume. The two methods showed an extremely strong linear association (Pearson r = 0.9993, p < 0.001) and an excellent absolute agreement according to ICC(2,1) (ICC = 0.9992). These findings indicate that the 3D scanning closely tracked the xylometric measurements across the studied volume range. However, the high correlation and ICC should not be interpreted as evidence of complete interchangeability, given the statistically significant systematic and proportional biases identified by the Bland–Altman analysis. The two techniques should not be considered fully interchangeable without defining an a priori acceptable error threshold. An accepted limit of error of 25% would mean that the two methods can be considered fully interchangeable. The appropriate acceptance limit should therefore be defined according to the intended application and independently of the observed results.

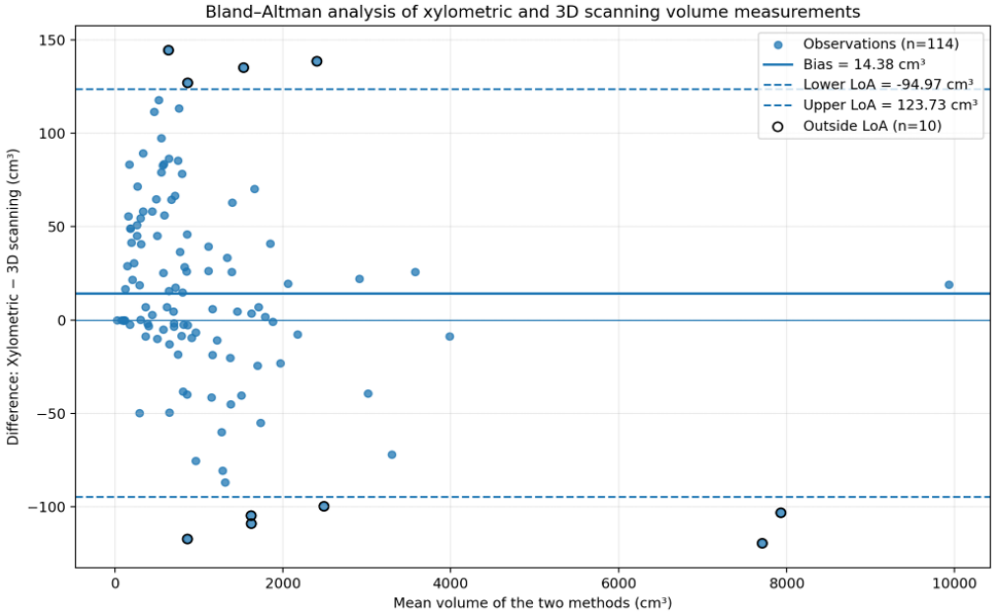


Fig. 6: Bland–Altman analysis of xylometric and 3D scanning volume measurements. The solid horizontal line represents the mean difference (bias, +14.38 cm³), and the dashed lines represent the lower and upper 95% limits of agreement (−94.97 and +123.73 cm³, respectively). Open circles indicate observations outside the 95% limits of agreement.

Particular attention must be paid to measurements performed using the xylometric method. The results may be affected by errors caused by: water adhering to the wood surface, air trapped in irregularities or cavities, incomplete immersion, reading errors of the graduated cylinders, water leakage, water absorption by the wood; changes in moisture content, etc. Because the pieces are relatively small, these effects could be more important.

Regarding the accuracy of the 3D scanning method, Niță and Borz (2023), using the same FDS application and the same Huawei P40 Pro smartphone model to scan logs, demonstrated that accuracy depends on the method and settings used for shape reconstruction, the size of the objects, and the amount and distribution of the captured three-dimensional information. In their study, Poisson reconstruction resulted, on average, in an overestimation rather than an underestimation compared with the reference method, indicating that the direction of the difference cannot be attributed exclusively to this reconstruction stage. Therefore,

the slightly lower mean volume obtained through 3D scanning cannot be explained solely by the potential smoothing of surface irregularities during Poisson reconstruction, or exclusively by the specific characteristics of the water displacement method. The observed difference may result from the combined effects of 3D data acquisition, the reconstruction of the geometry of small, irregularly shaped pieces, and the sources of error specific to the xylometric method.

The loss index

The loss index shows similar values between the two methods, both at the level of each sample plot and across the entire dataset. The total values of the loss index were 0.186% for the xylometric method and 0.184% for the scanning method. At the sample plot level, the highest values of the loss index were recorded in sample plots 2 and 3, regardless of the method used, while the lowest values were observed in sample plot 4. The mean loss index has the values of 0.169% by the xylometric method and 0.163% by the 3D scanning method (Tab. 5).

Tab. 5: Timber loss index variation.

Sample plot	*Ix (xylometric method)* (%)	*Is (scanning method)* (%)
1	0.158 ± 0.081 (0.026–0.397)	0.150 ± 0.083 (0.026–0.403)
2	0.210 ± 0.070 (0.094–0.332)	0.213 ± 0.073 (0.092–0.325)
3	0.211 ± 0.082 (0.111–0.315)	0.212 ± 0.078 (0.119–0.315)
4	0.171 ± 0.086 (0.057–0.405)	0.171 ± 0.086 (0.057–0.407)
Total	0.169 ± 0.082 (0.026–0.405)	0.163 ± 0.084 (0.026–0.407)

*± *SD (min–max).*

Correlations between the loss index and dimensional parameters of the notch

The mean values of the parameters analyzed differ between sample plots (Tab. 6), reflecting structural variability among standing trees in windthrown and differences in notch execution. For conventional felling operations, the recommended notch depth is approximately one-third of the stump diameter, while the notch angle should be approximately 45°. However, under windthrow conditions, these dimensional parameters may vary considerably depending on the condition of the trees. In the case of trees with broken stems, the notch depth may reach up to one-half of the stump diameter, while the notch angle varies according to the tension state of the tree (Câmpu & Robb 2022).

Tab. 6: Mean values of the notch parameters for standing trees.

Sample plot	Notch depth (a) (cm)	Notch angle (α) (°)	Notch height (h) (cm)
1	9.3	44.8	8.9
2	11.3	41.1	10.7
3	16.5	39.5	13.4
4	9.8	45.2	9.7
Total	10.1	44.1	9.5

The values of the loss index and its variation across sample plots suggest the presence of operational and technological factors influencing the level of losses. In this context, a regression analysis was conducted in order to assess the relationships between the loss index

and the dimensional parameters of the notch (depth, height and angle) (Tab. 7). The overall regression model was statistically significant, ($F_x = 39.049$, $p < 0.001$; $F_s = 45.071$, $p < 0.001$) indicating that the three notch geometry parameters, considered jointly, provide a significant explanation of the variability observed in the loss index. The model accounted for 51.8% of the variance of I_x% ($R^2 = 0.518$) and 55.7% of the variance of I_s% ($R^2 = 0.557$). The individual regression coefficients showed that notch angle and notch depth ware not statistically significant predictors of the loss index (I_x% and I_s%), in both cases $p > 0.05$. In contrast, notch height was found to be a statistically significant positive predictor of the loss index ($p < 0.05$).

Tab. 7: Multiple linear regression analysis of loss index.

ANOVA				The significance of the variable's coefficient				
R^2	Standard Error	Degrees of freedom	F	Variable	Coefficient	Standard Error	t Statistic	p - value
Multiple linear regression analysis of Ix% in relation to α, a and h								
0.518	0.057	Regression 3 Residual 109	39.049***	Constant	0.040	0.072	0.578	0.577
				α	-0.001	0.001	-0.591	0.555
				a	0.004	0.004	1.133	0.258
				h	0.013	0.004	2.997	0.003**
Multiple linear regression analysis of Is% in relation to α, a and h								
0.557	0.057	Regression 3 Residual 109	45.741***	Constant	0.058	0.071	0.821	0.413
				α	-0.002	0.001	-1.099	0.273
				a	0.004	0.004	0.900	0.369
				h	0.015	0.004	3.536	0.0005***

Note: Asterisks denote F significance and significant correlations: 0.01 < p-value* < 0.05; 0.001 < p-value** < 0.01; p-value*** < 0.001; *Ix%* - loss index (xylometric method); *Is%* - loss index (3D scanning method); α – notch angle; a – notch depth; h – notch height.

This result indicates that an increase in notch height is associated with an increase in the loss index. Overall, the regression results suggest that notch geometry accounts for a substantial proportion of the observed variability in the loss index. Among the notch geometric parameters considered, notch height is the only variable that demonstrates a statistically significant unique contribution to the loss index. Analysis of the direct correlation between the loss index and the notch height shows a Pearson correlation coefficient of $r = 0.69$ for the xylometric method and $r = 0.71$ for the 3D scanning method ($p < 0.001$ in both cases).

The present study aimed to quantify the timber losses represented by the extracted notches in standing trees within windthrown stands during the felling operation. Two distinct methods were used to determine these losses, namely the xylometric method and 3D scanning method. The correlation between the results obtained using the two methods indicates that the 3D scanning method may represent a viable alternative for assessing small and irregularly shaped wood pieces, particularly when conventional measurement procedures are time-consuming.

The level of timber losses is closely linked to the organization of the forest harvesting process in terms of work planning, availability of appropriate machinery, workforce qualification, continuous technological improvement, and adequate technical supervision (Andreescu & Amzica 1959). These factors become even more important in the case of windthrown stands, where working conditions are significantly more challenging.

In the case of standing trees, this kind of timber losses occur even when the compensation between stumps exceeding and those not exceeding the regulated stump height is considered.

These losses are mainly caused by the inability to perform felling cuts that comply with the maximum stump height required by current regulations, due to the presence of boulders, logging residues, stems or broken tops near the tree base (Ciocirlan & Câmpu 2025). In windthrown stands, the magnitude of notch losses is further influenced by slope inclination, the direction of tree felling or uprooting relative to terrain gradient, as well as tree dimensions.

Timber losses resulting from felling operations are often referred to in scientific literature as technological wood consumption and represent the amount of wood lost during the harvesting process as a consequence of specific processing operations (Ciubotaru, 1998). According to Borz et al. (2014), notch losses relative to tree volume vary by species, being estimated at 0.89% for oak, hornbeam and beech, 1.11% for Norway spruce, and 1.20% for silver fir. In the current research, the loss index values ranging between 0.184% and 0.186% are comparable with those reported by Ciubotaru (1998) for coniferous species (0.18%), indicating a relatively low level of losses under the conditions analyzed.

Existing studies indicate that the volume of timber remaining at the harvesting site may differ from the officially reported production values, with such differences depending on harvesting methods and measurement techniques (Dvořák et al. 2025). From this perspective, it should be noted that the lack of knowledge or underestimation of on-site residual losses may affect the accuracy of the final harvested timber balance.

CONCLUSIONS

The results obtained in this study highlight that timber losses generated by the execution of the notch can be quantified by using both xylometric and scanning methods, with very similar values of the loss index obtained with the two approaches. The 3D scanning demonstrated excellent overall agreement with the xylometric method for volume measurement. However, the Bland–Altman analysis identified a small, but statistically significant systematic bias and a significant proportional bias. The relatively wide limits of agreement at the individual-measurement level indicate that a high correlation between the two techniques does not, by itself, establish their interchangeability. Therefore, the 3D scanning may be considered a highly promising alternative method for volume assessment, but its use as a substitute for xylometry should be based on a predefined acceptable measurement error and further evaluation of the observed proportional bias.

Statistical analysis showed that the variation in the loss index is more strongly influenced by the notch height, confirming that notch height was the only statistically significant predictor among the notch geometry variables considered.

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