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How much timber from Norway spruce (*Picea abies* L.) is left on the harvesting site as treetops? A study on scaling and grading yields of harvesters

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Abstract

Key message Timber losses during Norway spruce (*Picea abies* L.) harvesting with the cut-to-length method were analyzed using data from 41,948 stems. The volume of timber left on the site after CTL harvesting reached 0.111% overall and 0.454% for stems larger than 34 cm DBH, compared to official production records. On the other hand, for small stems, a surplus of 2.50% of timber was extracted compared to official records. Optimizing measurement accuracy and harvester technology is essential to improve economic efficiency.

Context Volume estimation during forest harvesting frequently involves losses due to production technologies and errors of measurement methods. Treetop losses, timber left unrecorded at the harvesting site, represent a significant source of inaccuracies without systematic study.

Aims This article aims to assess the volume of treetop timber left on the harvesting site and to evaluate the size of these losses in operational records for Norway spruce (*Picea abies* L.) processed using the cut-to-length (CTL) method.

Methods We compared standard inventory methods with operational records on a raw sample of 41,948 Norway spruce stems with diameters at breast height (DBH) ranging from 10 to 34 cm, processed by harvesters. We quantified the unrecorded timber in terms of treetop losses and analysed their impact on forestry production records.

Results The assessment revealed that for stems with a DBH up to 17 cm, there was between 0.153 and 2.50% of operational surplus timber compared to inventory. This surplus decreases with increasing DBH, turning into losses, which at the diameter class of 33.1 to 35 cm reached 0.454% of the volume of harvested timber.

Conclusion The findings highlight that treetops timber losses were significant, suggesting that increased accuracy in recording treetop dimensions could improve yield calculations and economic outcomes for forest operations. Additionally, the results indicate that potential adjustments are needed for automated machine scaling methods to reduce these discrepancies.

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Keywords Forest harvesting, Volume estimation errors, Timber losses, Timber scaling, Bucking, CTL-method, Harvester technology

1 Introduction

Volume estimation losses are an inseparable part of forest operations. They reflect (i) production losses caused by stem damage during harvesting, (ii) inadvertent mistakes during timber production, (iii) errors based on the methodical approaches to measuring timber in the various forestry disciplines, (iv) the inability of the harvesting technologies to extract all desired timber from the forest stands, and (v) inefficient supply chain management, which prohibits utilising the full potential of the resource base due to the lack of potential customers for all assortments produced (Simanov 2003). The last two items relate largely also to treetop errors.

Post-harvest scaling can introduce several losses or errors into the volume records, potentially causing economic losses. Timber volume estimation errors during scaling caused by bucking at a diameter other than 7 cm over bark (treetop losses) are one of several timber production losses in forest operations in the Czech Republic. Even if the threshold topping diameter is different in other countries (Vidal et al. 2016), the fact that in actual timber production, the machine systems (or machine operators) will buck at a diameter different from the threshold is universal, resulting in this kind of loss occurring wherever fully mechanised cut-to-length (CTL) harvesting is performed. Timber losses caused by bucking the final log at a diameter larger than the threshold between timber and smallwood (treetop losses) are one of several timber production losses recognised in forest operations. In Czechia (Vidal et al. 2016), timber production with a diameter of less than 7 cm over bark is considered logging residue. The volume of timber left at the harvesting site practically presents a loss for forest owners compared to the timber volume estimated during inventory.

Discrepancies between timber scaling and forest inventory outputs are either errors caused by methodical differences or actual timber losses during harvesting. Indeed, it is necessary to stress that timber volume is estimated differently in forest inventory and timber scaling. In forest inventories, data are obtained based on repeated field measurements of inventory areas and their mathematical and statistical evaluation is based on the"Estimation of a difference of two ratios under the infinite population approach to NFI sampling"(Adolt 2017; Vidal et al. 2016). In timber scaling, the volume of each harvested stem or log is estimated by applying a volume estimation formula, such as Huber's, with the midspan diameter under bark and required length serving as inputs. In mechanised logging, harvesters equipped with forest machine systems compliant with the Standard for forest machine data and communication (StanForD) do this automatically while processing the tree and apply a specified price type, which, for example, calculate the volume based on midspan diameter and grade according to the top-end diameter (m3 toDE) or midspan diameter (m3 miDE) (Natov et al. 2018).

Actual losses in forest harvesting include allowances, cutting windows, bucking losses, stem breakage, stump volume, theft, and treetop losses. These losses are typically left outside of the operational records when they occur before scaling takes place (Simanov 2003). Allowances cause underreporting of the volume of produced timber by 1.7 to 2.3% of the total scaled volume, and the loss differs based on the quality grade—reaching 0.2 to 1.3% for pulpwood or 2.1 to 3.9% of the total scaled volume for industrial roundwood (Dvořák et al. 2020; Löwe et al. 2019a, b). Bucking cuts account for about 0.2% of the scaled volume (Kopřivík 2022). According to Aryal et al. (2022), the production losses reach as much as 7.4% directly after harvesting and, in extreme cases, up to 29.0% when bucking to upgrade the timber (e.g., cutting degraded timber at the ends of a log), compared to the volume of standing trees. Another potential source of loss can be the surface-level damage caused by feeding cylinders or delimbing knives of harvester heads, which can reach up to 4% of stem volume (Karaszewski et al. 2016). Furthermore, Gellerstedt and Dahlin (1999) report that considerable losses, between 1.7 and 6.9%, can be attributed to stump volume due to the inability of the fellers to cut at ground level. The results of Uri et al. (2015) support this claim, stating that the mass of the stumps (without roots) ranges between 12.7 and 23.9 t ha^{-1}. With a mean volumetric mass between 380 and 400 kg m^{-3}, i.e., 31 to 60 m^3 ha^{-1} of timber is frequently unused because their use by downstream industries is discouraged due to economic and environmental reasons.

Errors in volume estimation also arise due to the differences in timber measurement methods. Li et al. (2015) compared six volume estimation models, which yielded volumes between −16.2% and +48.1% different to Kozak's taper model (Kozak 1988). Regarding errors caused by measurement methods, Huber's formula is used in Central Europe to estimate volume. The rounding down of midspan diameter to the nearest centimetre results in 5.7 to 6.2% volume underestimation compared to the sectional scaling for Norway spruce (Dvořák et al. 2016a, b; Löwe et al. 2019a, b; Natov et al. 2019; Sedmíková et al. 2020), while Huber's formula itself yields a 7.5% underestimation of volume compared to the water immersion method (Hohmann et al. 2017).

Losses also arise from leaving timber and smallwood on the harvesting site after harvesting. These losses include treetop losses, supplemented by slash from limbs. Detailed analysis of logging residue volume was conducted by, e.g., Stankic et al. (2014), Berg et al. (2016), Bouriaud (2013) or Dvořák et al. (2023), who transformed the results into models or conversion factors intended for scaling the logging residues based on the stem volume of harvested trees, while Hardy (1996) scaled the residues based on pile shapes. Scaling the logging residues is challenging because numerous factors, such as stand density, age, crown shape, species, logging method, and others, can result in estimation errors (Gryazkin et al. 2017; Tahvanainen and Forss 2008).

The partially mechanized harvesting systems use that use the tree-length and whole-tree logging methods enable the chainsaw workers to buck the top end precisely at the threshold between timber and smallwood—7 cm in Czechia. Assortment production is then conducted at log yards, meaning all timber scaling for recordkeeping purposes already took place, and the errors stem from other processing operations. On the other hand, harvesters enable felling and assortment production at the stump, using built-in forest machine systems and price matrices to maximise the value of the timber they harvest (Natov et al. 2018). Depending on the conditions agreed upon by the contract parties, this means that, in some instances, the operator can perform the last bucking cut at a diameter larger or smaller than the threshold. Thus, the aggregated treetop losses increase with the increasing use of harvesters, e.g., in Northern Europe, where the machines account for 95% of all harvesting (Spinelli et al. 2021). Similarly, harvesters are also popular in other regions, such as Central Europe (e.g., in Czechia 51%, Poland 30%) (Kormanek et al. 2023), or North America, where they account for about 30% (Gellerstedt and Dahlin et al. 1999) of the harvesting.

The treetop loss is interesting because it can result in a loss or a surplus of timber for the forest owner compared to the volume obtained from NFI data, which use the idealized 7 cm top end bucking threshold for stem volume calculations. If the operator bucks at a diameter larger than 7 cm, the forest owner"lost"timber in harvesting, compared to inventory. On the other hand, several timber grades allow for top-end diameters smaller than seven centimetres, such as poles, mining wood, pulpwood, or firewood (Räisänen and Nurmi 2011), e.g., 4 to 5 cm in Finland or Czechia (Dvořák et al. 2020; Malinen et al. 2006).

Estimating the volume of the treetops is difficult because they do not have a standard geometric shape. The lateral view of the logging residue relates to the part of the taper that converges asymptotically, while from the crown portion to the top, it decreases linearly. Räisänen and Nurmi (2011) analysed the mass of the treetops related to their large end diameters. They found that the mean dry mass content of the treetops doubled with a diameter increase of 2 cm. Similarly, Kiljunen (2013) constructed models for estimating the dry mass of logging residues from data obtained from harvester forest machine systems. The model is based on the diameter one meter away from the large end, the top-end diameter of the last log, the diameter of the last log one meter away from its top end, and the length of the last log.

Forest inventory considers tree volume differently from forest harvesting. According to Gschwantner et al. (2019), Austria, Denmark, Estonia, Finland, Latvia, Norway, Romania, and Sweden account for the whole tree height, including treetops, in inventory volume estimation, whereas in harvesting, only timber is scaled and recorded. These methodological differences can cause discrepancies between the two methods and the different figures, which can then cause disagreements between stakeholders. To remediate this issue, we intend to assess the volume of timber left at the harvesting site as treetops and assess the potential for securing additional timber usable for the downstream industries. For a single tree species, this issue has two sides: the qualiative and the quantitative side. From the qualitative perspective, we presume that harvester technology enables the increased yield for lower timber quality grades, such as pulpwood or energy wood, compared to the presumed amount of timber based on forest inventory. This is because quality grades are defined by characteristics that occur regardless of the quantitative parameters of the produced timber. Furthermore, quantitative parameters also play a role, when typically sawmills and saw log processing plants limit the top end diameter, they accept in shipments to approximately 20 cm. On the other hand, the pulpmills and energy plants usually permit a minimum top-end diameter of 4 cm. To connect these idiosyncracies to factual recordskeeping, this study aims to systematically quantify and analyse the timber volume losses known as treetop losses and assess their impact on timber production records related to stem diameter classes.

2 Material and methods

A sample, containing data from 41,948 Norway spruce stems processed by harvesters was the data set used in this study (Dvořák et al. 2025). The primary data were gathered from three harvesters controlled and calibrated according to Natov et al. (2018) and operated by the state enterprise Military Forests and Estates, Horovice Division. This division managed 27,787 hectares of forest in the Central Bohemian Region of the Czech Republic (49.785169 N, 13.976932E). The proportion of Norway spruce (*Picea abies* L.) in this division was 80%, laid out evenly across age classes. The average annual timber production in the years 2019–2023 amounted to 283,000 m^3. The percentage of timber harvested by CTL machinery in the same period was 61%.

Gathering and primary processing of data into a usable format was conducted according to Jankovský et al. (2019). During timber production, individual stem data (*.stm; STM) were saved into the forest machine systems of the harvesters. Each STM file contained data on lengths and diameters, measured in 10 cm consecutive sections from the felling cut until the last bucking cut at the top end of the last log produced from a particular stem. We filtered out trees with stem lengths smaller than 7 m from the original database, as those were likely operator errors, broken or forked trees. Likewise, we filtered out stems longer than 40 m, as those were also likely operator errors (e.g., the improper ending of the production of one stem, thus recording two processed stems in one STM file). We filtered 11,009 stems from the original database (Dvořák et al. 2025).

During primary data processing, we assigned each stem a diameter at 1.3 m ($d_{1.3}$) distance from the felling cut. This variable served as a proxy for the diameter at breast height (DBH), which was used to estimate the volume of standing timber during inventory. The diameter at breast height as a variable was not available from the forest machine records; even if it is available in the machine records, it is only estimated by the forest machine systems and not measured. Understandably, the two diameters were not identical. However, $d_{1.3}$ is used as a proxy for DBH in scaling, and the diameters were not substantially different upon inspection. Assigning the $d_{1.3}$ was necessary to enable further analyses—predicting total stem length (including treetop) and assigning the stems into diameter classes, as used during forest inventory. Particular stems were then assigned into diameter classes according to the DBH proxy. The diameter class value represents the median of the diameter intervals (e.g., diameter class 10 contained stems with diameters between 9.1 and 11.0 cm). Based on the diameter of the last bucking cut, the stems were divided into three groups—(i) group A: trees with the diameter at the last cut larger than 7 cm, (ii) group B: trees with the diameter of the last cut smaller than 7 cm, and (iii) group C: trees with the diameters at the last cut equal to 7 cm.

Based on the consecutive measurements of the stem diameters, we proceeded to fit the diameter data using the exponential function, which is typically used for growth models in dendrometry in Czechia (Korf et al. 1972; Křepela 2002) (1).

$$d(h) = axe^{bh} + c \tag{1}$$

where:

*d*stem diameter at the measurement location (mm).

*h*stem length from the foot up to the measurement location (dm – decimetres, tens of centimetres).

*a, b, c*coefficients.

We assessed the goodness of the fit by the normalised *Root Mean Square Error/RMSE* by Eq. (2):

$$RMSE = \frac{\sqrt{\sum_{i=1}^{N} \frac{(y_i - \widehat{y}_i)^2}{N}}}{\max(\widehat{y}_i) - \min(\widehat{y}_i)} \tag{2}$$

where:

*N*number of values recorded for stem diameter (number of measured sections) (ks).

$y_i$actual stem diameter values (cm),

$\widehat{y}_i$ modelled stem diameter values (cm).

The prediction of the total stem length (including treetop) was based on the consecutive sectional diameter measurements, starting at $d_{1.3}$. The reason behind this was that the diameters measured up to this point are usually less precise than those following this threshold because they are estimated by the forest machine systems (the distance between the felling cut and measuring device located at the opposite end of the harvester head) and made inaccurate further by potential buttress formation on specific trees. Further, once the fitting procedure for a particular tree was finished, we only accepted the results with the corresponding goodness of fit value (see Eq. 2) smaller than or equal to 0.5 (Sharma et al. 2019). Finally, we neglected trees with a total volume exceeding 1 m^3, generally considered the volumetric threshold for harvesting by harvesters (Dvořák and Natov 2016).

We approached the tree volume calculation using the trapezoid discretisation method (Atkinson 1989) (3).

$$\int_a^b f(x)dx \approx \sum_{i=1}^{N} \frac{f(x_i) + f(x_{i-1})}{2} \Delta x_i \tag{3}$$

where

$$\Delta x_i = x_i - x_{i-1}$$

$f(x_i)$ function discretised over the area $b - a$ with the infinitesimal step Δx. Assuming the tree was shaped as a truncated cone and its parameters were given by Eq. (1), Eq. (3) took the following form (4).

$$V = \int_{h_{\frac{1}{3}}}^{h_{lastcut}} \pi \left(\frac{d(h)}{2}\right)^2 dh \approx \sum_{i=1}^{N} \pi \frac{d^2(h_{i-1}) + d^2(h_i)}{8} \Delta h_i \quad (4)$$

where

$$\Delta h_i = h_i - h_{i-1}$$

In this approach, we calculated the volume of the tree as the superposition of infinitesimal rings of different diameters *d(h)* spanning across all the measured heights, with the tree profile approximated by the obtained fit.

The total volume of a tree was calculated from the felling cut to the last bucking cut and denoted as V_{total}. The reference stem volume was calculated for conditions, as if the last bucking cut of the particular tree was made at exactly 7 cm diameters. We then defined as a loss (group A, V_{loss}) or surplus (group B, $V_{additional}$) the volume of the section between the actual bucking cut (for group A at diameters larger than 7 cm, for group B at diameters smaller than 7 cm) and the threshold of 7 cm. We also observed the trees with the last cut located precisely at 7 cm (group C). Assuming N_A, N_B, and N_C were the number of trees successfully fitted and accepted in groups A, B, and C, we defined the total volume estimation loss as $v_{total\ loss}$ (5).

$$v_{totalloss} = \frac{\sum_{i=1}^{N_A} V_{loss_t} + \sum_{i=1}^{N_B} V_{additional_i}}{\sum_{i=1}^{N_A+N_B+N_C} V_{total_i}} \quad (5)$$

The mathematical methods chosen for this analysis are suited for detailed technical assessments of timber volume losses, as they allow for precise quantification of losses across tree diameter classes. To enable comparability of the results of this study to forest inventory methods, we chose an analytical approach compatible with how measurements are treated in the case of forest inventory in the Czech Republic.

We analysed the effects of the specific diameter classes defined by forest inventory, and the machines used to carry out the harvesting operations on the loss or surplus of timber through a linear mixed model (LMM). The stem diameter classes were used as fixed effect, and the machine model was used as a random effect. We used the pseudo-R and the Akaike information criterion (AIC) to assess the model. To analyse the losses for specific diameter classes defined by forest inventory, we used a One-way analysis of variance (ANOVA). To test the homogeneity of the variances between the particular diameter classes, we used the Bartlett test and the Newman-Keuls test to compare the diameter classes. We also used the Tukey HSD post-hoc test for informational purposes because, although the Bartlett test results pointed towards using the Newman-Keuls, Tukey HSD provided additional information on the differences between the groups. The parametric tests were chosen based on the sample size and the qualitative assessment of the normality of data distribution.

3 Results

Table 1 shows the distribution of the spruce stems into diameter classes according to stem volume, frequency, and ratio of the group to the whole sample. There were 457 logs (106.8 m^3) in the data set, where the last bucking cut was performed exactly at 7 cm diameter. The low number of these stems was due to the high accuracy of the diameter measurement in millimetres. The number of stems where bucking resulted in a volumetric loss was 6161 (1360 m^3). On the other hand, on 4391 stems (1356 m^3), the last bucking cut was performed at diameters smaller than 7 cm, thus resulting in a volumetric surplus.

The total within-class volume of the losses representing loss (−) and surplus (+) ranged between −18.0 and +14.9 m^3. For diameter classes 10 to 16, the scaling balance showed a surplus rather than loss, i.e., production was larger than the forest inventory mandates by +0.153 to +2.50% (Table 2). Based on the taper curves of the stems, the machine price matrices enabled a high proportion of producing poles and pulpwood, where the accepted top end diameter threshold was 2 cm or 4 cm respectively. From diameter class 18 onwards (Fig. 1), the losses started to increase, from −0.0730 to −0.454% of the scaling volume, based on the respective diameter class. The largest loss was reached in diameter class 34 (Table 2). From the total stem volume of the samples (2823.67 m^3), a consolidated loss of 0.111% (3.13 m^3) was produced. The loss of timber in treetops was 0.233% when calculated based on the weighted mean in particular volume classes.

The number of outliers in the data set was 144 (Fig. 2), no extremes were observed. The share of outliers on the overall number of observations was 1.32%. The values were not excluded from the analyses, as they were essential in the context of the study. The production was affected by numerous factors, which cannot be eliminated and are operator-specific in the case of the human factor.

The LMM (Table 3) showed that the machine used was significant as a random effect factor ($p < 0.001$), along with the stem diameter class used as a fixed effect ($p < 0.001$). Even so, the marginal pseudo-R2 reached the same value as the conditional pseudo-R2–0.054. That

Table 1 Structure of the analysed data set of timber production processed by the CTL method – distribution of stems into diameter classes according to stem volume, frequency and ratio of the group to the whole sample. Distinguishes trees where the last cut was made above and below the threshold diameter of 7 cm, which affects the reported timber volume

Diameter class	Stem volume with the top end diameter		Number of stems with the top end diameter		Share of diameter class according to volume		Share of diameter class according to number	
	≥ 7 cm	< 7 cm	≥ 7 cm	< 7 cm	≥ 7 cm	< 7 cm	≥ 7 cm	< 7 cm
	[m³]		[pcs]		[%]			
1	2	3	4	5	6	7	8	9
10	4.27	9.97	74	192	0.15	0.35	0.67	1.74
12	22.46	49.59	282	698	0.80	1.76	2.56	6.34
14	60.93	99.42	563	995	2.16	3.52	5.11	9.04
16	92.81	141.63	647	1031	3.29	5.02	5.88	9.37
18	120.77	169.33	624	912	4.28	6.00	5.67	8.28
20	158.31	181.87	634	725	5.61	6.44	5.76	6.59
22	176.20	181.99	547	562	6.24	6.45	4.97	5.10
24	187.67	155.12	454	396	6.65	5.49	4.12	3.60
26	194.91	155.14	385	306	6.90	5.49	3.50	2.78
28	192.46	108.09	295	184	6.82	3.83	2.68	1.67
30	152.23	67.71	212	100	5.39	2.40	1.93	0.91
32	68.48	32.16	91	47	2.43	1.14	0.83	0.43
34	31.81	8.31	40	13	1.13	0.29	0.36	0.12
Total	**1463.32**	**1360.35**	**4848**	**6161**	**51.82**	**48.18**	**44.04**	**55.96**

Table 2 Losses and surpluses in timber production records compared to forest inventory resulting from treetop bucking position for individual stem diameter classes

			Total loss (−) Total surplus (+)				
Diameter class	Loss	Surplus	Share in the total volume produced	Mean	Median	Variance	Standard deviation
	[m³]	[m³]	[%]	[m³/stem]		[-]	[m³/stem]
1	2	3	4	5	6	8	9
10	0.178	0.533	2.50	0.00134	0.00243	0.0000081	0.00285
12	0.864	1.90	1.44	0.00106	0.00231	0.0000096	0.00311
14	1.95	2.51	0.354	0.000364	0.00167	0.000012	0.00342
16	2.19	2.55	0.153	0.000213	0.00138	0.000012	0.00344
18	2.35	2.14	− 0.0730	− 0.000138	0.00114	0.000013	0.00363
20	2.50	1.69	− 0.239	− 0.000597	0.00053	0.000014	0.00381
22	2.04	1.28	− 0.210	− 0.000679	0.0000539	0.000014	0.00369
24	1.66	0.869	− 0.231	− 0.000933	0	0.000013	0.00365
26	1.61	0.667	− 0.267	− 0.00138	− 0.000380	0.000015	0.00388
28	1.22	0.392	− 0.276	− 0.00173	− 0.00109	0.000015	0.00388
30	0.866	0.239	− 0.289	− 0.00204	− 0.00191	0.000014	0.00381
32	0.392	0.0941	− 0.296	− 0.00216	− 0.00174	0.000015	0.00388
34	0.208	0.0260	− 0.454	− 0.003	− 0.00393	0.000017	0.00418
Total	**18.0**	**14.9**	**− 0.111**				

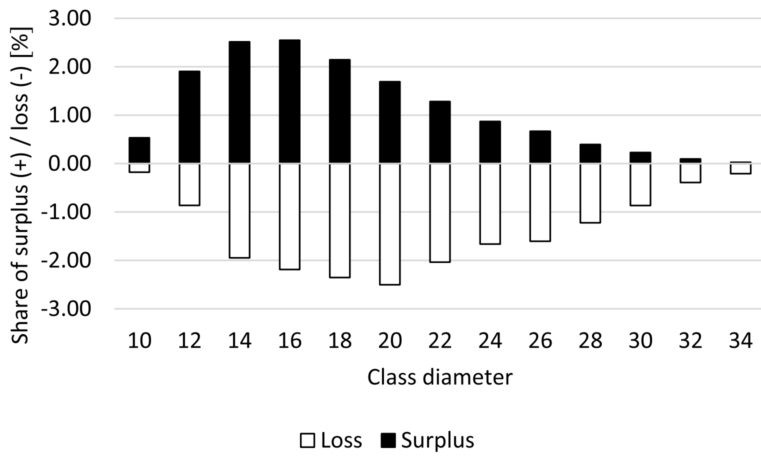

Fig. 1 Loss and surplus ratios for particular stem volumes in diameter classes. The stem diameter class is the central value of a stem diameter interval at breast height (e.g., stem diameter class 10 relates to diameters at breast height of 9.1 to 11.0 cm

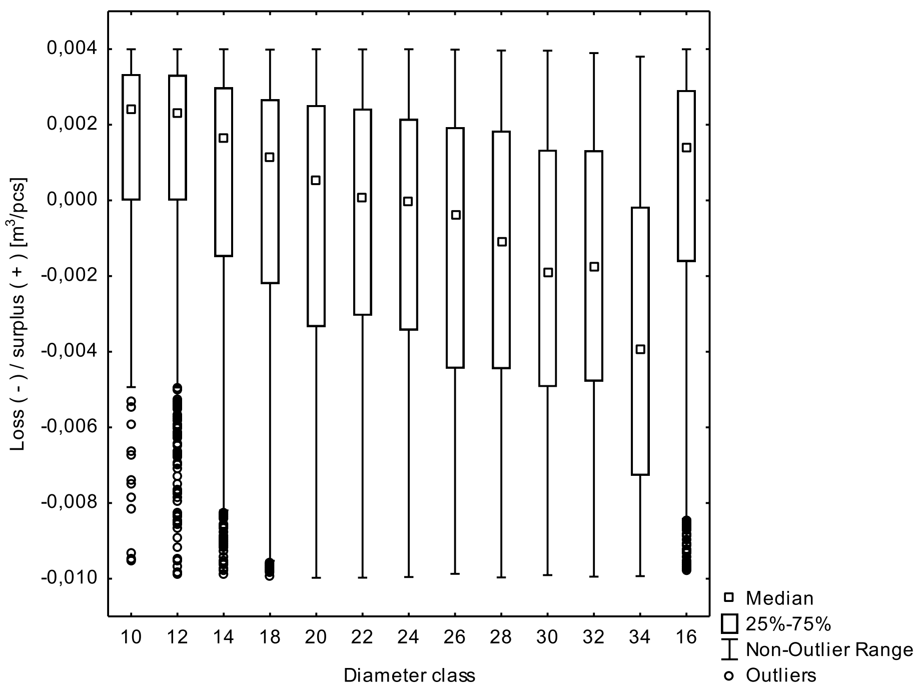

Fig. 2 Box-and-whisker plot visualising outliers of losses and surpluses of timber related to the volume of particular stems in individual stem diameter classes. The stem diameter class is the central value of a stem diameter interval at breast height (e.g., stem diameter class 10 relates to diameters at breast height of 9.1 to 11.0 cm)

points toward no or a very limited effect of the machine on the loss or surplus of timber compared to the planned volume. To provide a model that is not overparametrized, we therefore opted for using a one-way ANOVA. The ANOVA confirmed that the differences among the diameter classes were significant (Table 4). The subsequent Bartlett test showed that variances between diameter classes were heterogeneous ($p < 0.001$). Thus, the Newman-Keuls test was chosen as the primary post hoc testing method (Table 5). The results of the Newman-Keuls test showed no statistically significant difference among the losses of the following diameter classes: 10/12, 14/16/18, 18/20/22, 20/22/24, 24/26, 26/28, 28/30/32. Despite this, keeping diameter classes 10 to 18 separate is desirable because it is a more suitable practical implementation, compatible with forest inventory methods.

Table 3 The description of the linear mixed model, which shows the effects of the stem diameter class and harvester used on the share of losses or surpluses of volume of timber compared to the full stem volume

Model dimension dependent on variables losses and surpluses				
		Number of levels	**Covariance structure**	**Number of parameters**
Fixed effects	Intercept	1		1
	Diameter class*	13		12
Random effects	Harvester type	3	Variance Components	1
Residual				1
Total		17		15
Information criterion dependent on variables losses and surpluses				
Akaike's Bayesian Criterion (BIC)$^{\Delta}$			-92,567.8	
Coefficients of determination				
Pseudo-R Square measures	Marginal^{0}		0.054	
	Conditional^{00}		0.054	
Type III tests of fixed effects dependent on variables losses and surpluses				
Source	Numerator df	Denominator df	*F*-value	*p*-value
Intercept	1	10,996	187.7	< 0.001
Diameter class	12		52.0	< 0.001

*The stem diameter class is the central value of a stem diameter interval at breast height, $^{\Delta}$ statistical measure of the quality of the model, ^{0} the share of variance explained by the fixed effect, ^{00} the share of variance explained by all effects

Table 4 The outcomes of one-way analysis of variance showing the effects of the stem diameter class on the share of losses or surpluses of volume of timber compared to the full stem volume

Effect	**Degr. of freedom**	**Sums of squares**	**Mean square**	***F-value***	***p-value***
Intercept	1	0.0024	0.0024	190	< 0.001
Factor – Diameter class*	12	0.0080	0.00067	52	< 0.001
Error	10,996	0.14	0.000013		

* The stem diameter class is the central value of a stem diameter interval at breast height (e.g., stem diameter class 10 relates to diameters at breast height of 9.1 to 11.0 cm

Table 5 Newman-Keuls significance test of differences of losses (−) or surpluses (+) for the individual tree diameter classes, (MS = 0.00001, df = 10,996)

Diameter class	**Mean error [m^3]**								
10	**0.0013**	*********							
12	0.0011	***							
14	0.00036		***						
16	0.00021		***						
18	– 0.00010		***	***					
20	– 0.00060			***	***				
22	– 0.00070			***	***				
24	– 0.00090				***	***			
26	– 0.0014					***	***		
28	– 0.0017						***	***	
30	– 0.0020							***	
32	– 0.0022							***	
34	– 0.0034								***

Moreover, Fig. 3 shows that the differences between these diameter classes were on the statistical significance threshold. The Tukey HSD test also supported the findings, which confirmed that the differences were statistically significant.

4 Discussion

The annual production of spruce timber using the CTL method is approximately 11.3 million m^3 in the Czech Republic (MZe 2023). The harvesting volume and the context provided in the study mean that the amount of timber left on sites after harvesting in Czechia was approximately 108,000 m^3 per annum. According to Sahoo et al. (2018), the share of treetops in the total volume of logging residues is substantial, ranging from 16 to 40%. Furthermore, Keays (1971) estimates the mean share of the volume in treetops on merchantable timber to be 11%. Hakkila (1989) reports that the total volume of treetops left on the harvesting site after clear-cut logging ranges between 4 and 6 m^3 ha^{-1} for Norway spruce, whereas 6–7 m^3 ha^{-1} are left on the harvesting sites after clear-cut and 4–5 m^3 ha^{-1} after thinnings of Scots pine Gryazkin (2017). These figures are larger than the amount we presumed, likely due to the fact that the authors include all branches and other slash in them, while we specifically calculated the volume of timber on the portion of the stem between the 7 cm threshold and the place where the machines made the final bucking cut. The scope of our study prohibits us from structuring the loss of timber according to assortment groups accurately but considering the variability of production conditions from a temporal and spatial perspective, along with the changing demands from customers, that is a secondary problem.

Even so, treetop losses are commonly not documented; they are viewed as insubstantial or combined with other materials as logging residues, making identifying their volume impossible (Šťícha et al. 2019). However, they are an inseparable part of the mosaic of volume losses or estimation errors in timber scaling. International comparisons are difficult because treetops and timber definitions differ from one country to another. Considering this, Gschwantner et al. (2019) expect that the reported potential loss of volume of merchantable timber in treetops ranges from 0.6% (Romania) to 8.6% (Finland) compared to national forest inventories.

Naturally, smallwood, in the form of logging residues can be beneficial to forest soil health and stand stability—improving the rate of soil restoration after harvesting operations (Perron et al. 2022), nutrient cycling (Smolander et al. 2019), decreasing harvesting-induced compaction (Cambi et al. 2015) and preventing growth decrease after harvesting operations (Mäkinen and Smolander 2025). Leaving deadwood in forest stands also benefits biodiversity and improves stand health (Graf et al. 2022; Stokland et al. 2012),

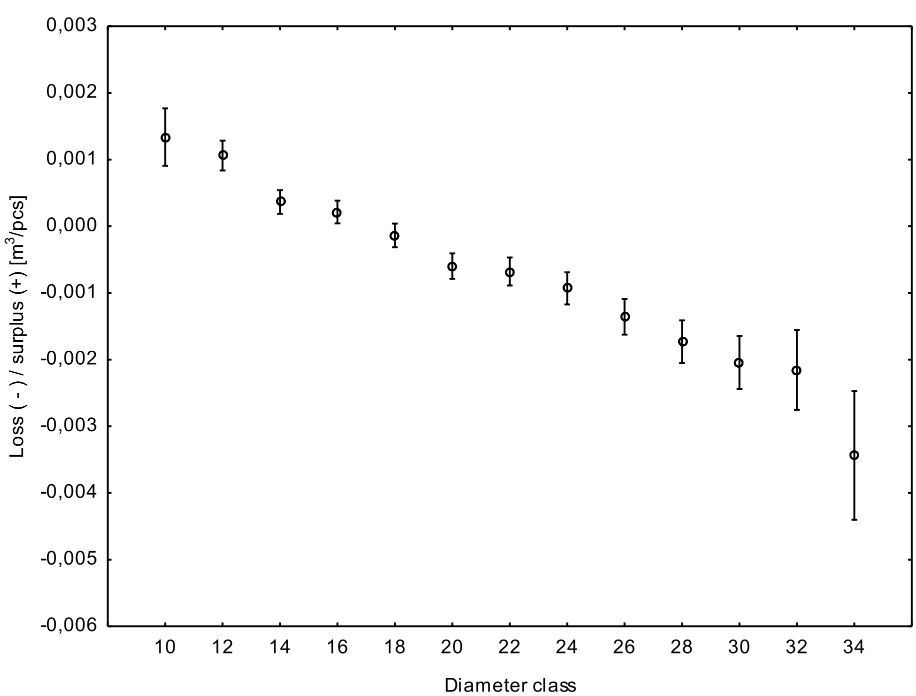

Fig. 3 Visualisation of the post-hoc analysis for losses (–) or surpluses (+) of the volume of timber compared to the full stem volume in particular tree diameter classes. The stem diameter class is the central value of a stem diameter interval at breast height (e.g., stem diameter class 10 relates to diameters at breast height of 9.1 to 11.0 cm)

which is desirable, considering the effects of climate change on the state of European forests. Knowing how much residue was produced during harvesting operations can, therefore, support the forest owners in making data-driven and informed decisions on optimising biomass usage to reach the environmental and economic goals of the owners.

The assumption that harvester technology can produce more timber than anticipated in the inventory in the lower quality grades was confirmed. The increased yield is enabled by using the StanForD standard (Skogforsk 2023; Strubergs et al. 2021) to record the timber production with a top-end diameter smaller than 7 cm. The StanForD enables value-optimised production of assortments of specific grades and dimensions directly at the harvesting site according to the customer's demands. This is done by using (site-specific if needed) price matrices that are put into the forest machine systems as **.apt* (StanForD Classic) or **.pin* (StanForD 2010) file types (Natov et al. 2020). According to Holzleitner et al. (2019), the machine systems enable the minimum top-end diameter of 40 mm. The only limitation to increasing yield is whether the customer accepts a top-end diameter smaller than 7 cm. This scenario was supported by the decreasing loss trend related to $d_{1.3}$—smaller trees are more likely to produce more low-grade logs. The threshold, where consolidated surplus turned to a loss, was recorded at the diameter class 18. A potential inflexion of the trend came again at diameter class 34, though we could not thoroughly verify whether the lower loss compared to previous diameter classes was a data anomaly or said inflexion point of the trend. There can be two potential reasons for this behaviour: (i) the lower frequency in the diameter class, because it was at the limit of cutting diameter of the technology used, and (ii) even though the production prescription was the same as for similar diameter classes, the stem dimensions enabled the production of more pulpwood logs, with smaller threshold top end diameters.

Besides methodical differences between inventory and operational recordkeeping, timber can be lost from records in treetops during salvage logging. According to NTT (2024), stem breakages caused by windthrow, snow, or biotic pests are the most frequent loss of timber. For example, in the case of aspen, the volume of sawlogs was reduced by 37.7%, pallet blocks by 11%, and technological wood by 8.9% compared to standard logging. Furthermore, Čakša et al. (2021) report that the volume of logging residues unsuitable for processing increased to 34.0% after salvage logging. Kerbes and McIntosh (1969) focus on the breakage of treetops, where they report the amount for 2.2% of the total stem volume. Indeed, in certain production conditions, treetop biomass can amount to a substantial part of the total stem volume usable in the downstream industries.

The CTL harvesting method is based on producing logs at the stump, which can lead to performing the topping cut of the last log at diameters other than the threshold between timber and smallwood. Therefore, a specific treetop loss or surplus can occur compared to the tree-length or whole-tree methods. The actual loss (or surplus) of timber occurs regardless of the scaling procedure. However, the representation of this error in operational records is based on the accuracy and precision of the measurements performed. The automated scaling of timber by harvesters enables detailed volume monitoring tied to individual stems and provides an accurate representation of production comparable to conventional methods of timber scaling. If properly calibrated, the machines should not add substantial variability to the scaling results. This was the case in our study, as the machine model, though showing as having significant effects, did not contribute to the explanatory power of the constructed LMM. Of course, the disadvantage is that operators can introduce systemic errors to the measurements (e.g., by improperly performing control measurements and calibrations of the measurement systems and incorrectly setting the price type or price matrix). Considering treetop losses specifically, the variability of stem taper from one individual tree to another poses an added uncertainty.

From a practical point of view, the results of this study could lead to improved settings of price matrices in harvesters, which are closely linked to the timber trade. Considering the practicability of the study results, a market analysis for such timber should be conducted as a follow-up to this study to estimate the economic efficiency of limiting this kind of loss. Similarly, other economically important tree species should be studied to holistically assess the aggregated size of the loss. Nevertheless, the results provide valuable insights into automated timber scaling and the caveats of interpreting the differences between the operational records and forest inventory outcomes.

5 Conclusion

The treetop losses are mainly tied to mechanised CTL harvesting in coniferous forest stands. Therefore, this study was focused on spruce, which is frequently harvested by harvesters in Europe. We found that the variability of the volume of timber in treetops varies depending on the total volume of the stem, i.e., the stem diameter class significantly affected the volume of timber left on the harvesting site in the form of treetops. Data also showed that harvesters indeed provide a good opportunity to increase timber yield compared to motor-manual harvesting, especially for lower quality grades, where the customers allow for top end diameters smaller than the usual 7 cm threshold. This was evident in smaller diameter classes, where the machines were able to produce high shares of poles or pulpwoood. On the other hand, for stems, where the diameter class were larger, the machines performed the last bucking cuts at diameters larger than 7 cm, thus producing less timber than planned. Overall, however, the difference in volume produced and planned reached a relatively low value, though when aggregated, even minimal loss can account for a substantial volume of timber that does go unrecorded.

This study provided a detailed examination of volume losses when using harvesters, explicitly tackling the quantification of treetop losses, thus filling a gap in forest research that was not systematically addressed in previous studies. If it is economically and environmentally suitable, the subsequent optimisation of the supply chain and technologies can decrease these losses. Nevertheless, it is important to uncover the sources of deviation and strive for compatibility of industrial data. Our priority was to focus on the losses in smaller log diameter classes because many spruce-dominated forest stands were decimated by bark beetle outbreaks in Czechia, and thinning operations in young stands will likely be a priority soon. We focused on a single species, and a single source of losses could be considered a limit of this study. We also want to broaden the scope to include different tree species in the future.

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Authors' contributions
Jiří Dvořák and Martin Jankovský are the initiators of the idea, and led the preparation of the study, and the comprehensive processing of data into the results. Material preparation and data collection were performed by Pavel Natov and Jiří Dvořák. Mathematical and statistical analysis were performed by Marcel Štolc, Andrej Liška and Arkadiusz Stańczykiewicz. Michal Allman prepared the research for the study. All authors contributed to the study conception and design. All authors read, commented and approved the final manuscript.

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Data availability
The datasets used and analysed during the current study are available in the Zenodo data repository (Dvořák J, Natov P, Štolc M (2025) How much timber from Norway spruce (*Picea abies* L.) is left on the harvesting site in the form of treetops? A study on scaling and grading yields of harvesters. V1. Zenodo. [Data set]. https://doi.org/10.5281/zenodo.14690727.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

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