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ORIGINAL PAPER

Harvester productivity and tree damage in thinning operations in pine stands in relation to the width of skid trails

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ABSTRACT

Fully mechanised timber harvesting in cut-to-length method (CTL) has a number of advantages compared to tree-length (TL) and whole tree method (WT), including lowering unit costs, increasing productivity and reducing or even eliminating heavy manual labour. The demographic changes we are seeing, and thus the expectations of the workforce and competition in the labour market, mean that fully mechanised work or automation will be essential in the future.

The aim of this article is to analyse the damage to remaining trees in the stand and the efficiency of the work in relation to the width of the skid trails (narrow 2.7 m and wide 3.5 m). Analyses were carried out during the first thinning cuts in a 25-year-old pine stand with so-called industrial wood. A small tracked excavator equipped with a harvester head was used in the experimental plots. The efficiency of the work is influenced by the volume of a single tree, the thinning intensity and the stand density. The same variables also determine the effect on the amount of damage in the stand remaining.

The parameters characterising the damage to the trees remaining in the stand indicate the occurrence of significantly longer wounds in the sample plots with wide access trails and a higher total area of wounds (+40%) compared to the damage observed in the sample plots with narrow access trails. From the results obtained, it can also be assumed that the very serious damage, deep injures in the wood of trunk and root amputation are random and do not depend on the width of the trails.

The results show the importance of choosing the right machine to facilitate work in dense stands. The observed wounds according to Meyer's tree damage classification do not allow statistically significant differences between damage occurring with both narrow and wide skid trails. However, any bark damage and other damage to tree trunks increases the risk of head rot and thus significantly reduces the future potential for top quality timber. Narrow skid trails reduce non-productive areas and simultaneously increase the difficulty of mechanical thinning. However, when using wide skid trails (3.5 m), a higher operating efficiency of approximately 12% was observed.

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Introduction

Timber harvesting respects the principles of continuity and sustainability of forest resources. Restrictions on clear cutting and silvicultural regulations indicate a strong need for thinning of younger stands, which points to the challenges of forest harvesting (Mederski *et al.*, 2016, 2021). In most European countries, two methods of timber harvesting are used (Moskalik *et al.*, 2017). The tree-length method is preferred by less mechanised or wood energy harvesting operations. The cut-to-length method is used for highly mechanised harvesting and wood for industrial purposes. The high capital investment in machinery requires high productivity and high annual use. Productivity is influenced by, among other things, machine size and characteristics, forest stand, and site conditions. In general, the productivity of cut-to-length harvesting varies from 3 m^3/h to 42 m^3/h, depending on the silvicultural treatment (Mederski *et al.*, 2016; Moskalik *et al.*, 2017; Szewczyk *et al.*, 2023).

Thinning as a forest management strategy is the selective removal of trees, primarily undertaken to improve the growth rate or health of the remaining trees. It can also contribute to climate change mitigation, depending on its net effect on forest carbon (C) stocks. Ruiz-Peinado *et al.* (2016), based on the long-term experiment in a Scots pine *Pinus sylvestris* L. stand, found that the effect intensity of thinning reduced the volume of C stocks in the standing biomass, but did not change this accumulation in the soil, forest floor or mineral soil.

Del Río Gaztelurrutia *et al.* (2017) noticed that heavy thinning leads to reduced volume yield, which varies according to region, site and stand age. The stability of the stand in relation to snow and wind is lower after the first thinning and increases in the long term. The impact of extreme droughts on the growth of trees is less pronounced in thinned stands, which is related to a better ability to recover from the drought. In general, thinning reduces wood quality, litter mass and structural diversity of the stand, while having a neutral or positive effect on other ecosystem services, although these effects may vary depending on the thinning regime and intensity. However, for most ecosystem services, information is scarce.

The biological processes of stand growth can be adversely affected by damage to the residual stand caused by forestry operations. Damage depends on many factors such as logging intensity, size of trees felled, harvest planning, cutting technique or harvesting method (Dykstra and Heinrich, 1996), and often lead to the increment the trees on the edge of skid trails (Stempski *et al.*, 2021). Picchio *et al.* (2019) found that wound intensity in beech and pine forest stands depended on slope gradient, with larger wounds and a higher number of wounds detected in thicker trees. The position of the wound on a tree is related to the stand density and the size of the winched wood. Any kind of damage to a standing tree can lead to an infection by pathogenic micro-organisms (Markovic *et al.*, 2013). The size of the damage and its position on the tree correlate with the occurrence of infection and decay. As a result of analyses, Lotfalian *et al.* (2010) have presented a method for estimating damage from felling and skidding with effect on economy and forest regeneration.

Picchio *et al.* (2020) found that the least impactful mechanical forest operations have harvester-forwarder technologies, while greater damage was expected from ground-based extraction systems (skidders) and cable yarders. Animal power, if used, tended to be very forest neutral. Damage can be reduced through the optimal planning of skid trails and strip roads, the careful execution of forest operations, and the training of operators.

Short wood harvesting (cut-to-length method, CTL) has a number of advantages, including reducing unit costs, increasing productivity and reducing or even eliminating heavy manual labour. Observed demographic changes, and thus the demands of the workforce and the impact of the market, mean that fully mechanised work or automation will be essential (Pierzchała *et al.*, 2018; Holzinger *et al.*, 2022). The often abundant natural regeneration or artificial renewal of the forest is a challenge for further management and silvicultural work (Szewczyk *et al.*, 2023), with the aim of both producing the maximum amount of timber in line with ecological requirements and obtaining some of the highest quality wood, so-called special wood.

Therefore, the spread of mechanisation of work has led to an increased interest in damage caused by the use of machinery. One of the initial aspects was the problem of making stands accessible, and with it the limitation of the so-called productive area, the emergence of clear-cut growth and thus branched trees, whose knots indicate an inferior quality class of harvested timber. While the working conditions have forced the acceptance of skid trials on tree stands, the question of the width of this trails is still open. It is assumed estimated at a minimum of 2.5 m, and at one time even 6-7 m width (widened on curves) was recommended. It has been found that skid (access) trials can increase biodiversity, but higher traffic intensity leads to soil compaction and therefore decrease the number of species (Latterini *et al.*, 2023).

Therefore, this article aims to analyse the damage to trees left behind and the operational efficiency depending on the accessibility of the forest. A small tracked harvesting machine was used on the plots during the harvesting of the first industrial timber, the so-called merchantable wood. In this context, it is important to consider how limiting clear-cut width on skid trails and thinning intensity affect harvest efficiency and damage on the residuals trees.

Materials and method

The harvester used in this study was built on a 34 kW Kubota KX057-4 mini-excavator with added an Arbro 400S stroke harvester head. The trees to be cut were processed into 2.5 m logs (cut-to-length technology, CTL) with a minimum diameter of 5 cm inside the bark, and then placed along the trails. The foresters marked tree clearly to be identified by the operator. Due to the relatively short crane range (6.5 m), the harvester had to move off the trail to perform thinning on the entire area of the designated sample plots. The detailed information about machine characteristics was previously presented in a publication about first commercial thinning of Scots pine stand (Leszczyński *et al.*, 2021).

The stand was located at an altitude of about 300 m above sea level, in flat terrain, on the Tarnogród Plateau (eastern part of the Sandomierz Basin). The plateau has a continental climate. The sample plots were located in a 25-year-old Scots pine (50°13043" N; 23°12039" E) stand growing on a 1.4×1.8 m grid containing two 3.5 m wide skid trails (WT35) established at regular intervals of about 40 m during planting. Three additional 2.7 m narrow skid trails (NT27) were created by removing a row of planted trees to facilitate mechanised thinning.

Due to the large number of trees to be removed and for the sake of observer safety, small 25×20 m sample plots were established (10 m on either side of the skid trails). This study involved a total of 20 sample plots (1 ha, Fig. 1) located along wide skid trail (WT35). Using a random generator applied in Statistica 13 (TIBCO Software Inc., 2017) software package the same number (20) sample plots located along narrow skid trail (NT27) was chosen from primary 30 plots. The time structure analysis was used for all data gathered for 440 trees harvested on WT35. The same number of working cycles for 440 trees was randomly chosen from data base gathered for trees harvesting on narrow skid trail (NT27). The random selection of data was essential and necessary step to balance the experiment and avoid the associated complications

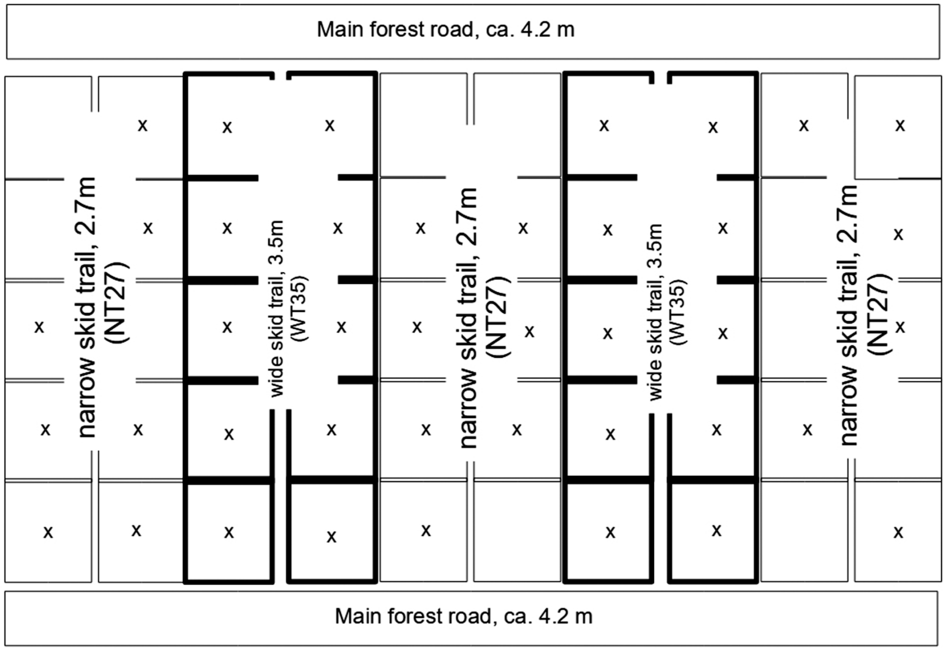

Fig. 1.
Scheme of sample plot locations

of statistical analyses. For data analysis only the harvester processes have been included, which means that data collection has been done after felling and processing but before extracting the trees.

The presented paper focused on the relationship between product output and productive work time input called operational efficiency or productivity in operational time. The productive work time covered felling and processing of trees, and driving (manoeuvring, machine positioning). The non-work time consists of unplanned interruption, rest and failure time. The working time study was carried out used IUFRO classification modified by Magagnotti and Spinelli (2012). The duration of the various work elements was measured in harvesting work cycles (felling and processing of trees, drive to the tree, operational delays, rest, failure). Measurements were calculated to an accuracy of 1 s using a PSION WorkAbout data recorder with dedicated software TIMING 1.0.

Product output was determined indirectly (Bruchwald, 2004) for pine stem volume inside bark. The over bark diameter at 1.3 m diameter at breast height (DBH) was measured directly for selected to felling trees with a digital calliper. Tree heights were calculated indirectly from a curve plotted on basis of 5% measurement trees.

The analysis of tree damage consisted of an inventory and description of individual trees. In order to capture differences, the focus was on measuring the distance from the ground to the base of the wound placement, its length and width. Based on the latter two parameters, the wound area was calculated from the ellipse area formula. On the basis of the description collected, the wounds were also classified into one of the nine injury classes (Table 1) according to Meyer classification (Giefing *et al.*, 2012).

The tree damage index (*W*) and volume-weighted tree damage index (*WDI*) were then calculated (Grzywiński *et al.*, 2020):

Table 1.
Meyer's tree damage classes (Giefing *et al.*, 2012)

Damage class	Place of damage	Damage type
1	bark – bole (trunk) or root neck	bark scratch
2	bark – roots	bark scratch
3	cambium – bole (trunk) or root neck	scratched bark, opened or damaged cambium
4	cambium – roots	wood fibres wounded
5	wood – bole (trunk) or root neck	wood fibres wounded
6	wood – roots	wood fibres wounded
7	tree – bent	slightly tree bent with opportunity for further development
8	tree – bent significantly	significantly tree bent with small chance for further development
9	tree – damaged	broken or pulled-off tree

$$W = \frac{\sum_{R=1}^{9} I \cdot R}{N} \tag{1}$$

$$WDI = \frac{\sum_{R=1}^{9} I \cdot R}{N \cdot C} \cdot 1000 \tag{2}$$

where:

I – number of trees damaged in the sample plot in a given damage class,
R – number of tree damage class (Table 1),
N – total number of trees remaining on the sample plot recalculated to 0.25 ha after treatment,
C – amount of wood removed from the sample plot recalculated to 0.25 ha [m^3].

Homogeneity of sample plots was evaluated including by calculating tree density, tree volume, thinning intensity as the volume of harvested merchantable timber relative to total merchantable timber, as well as the relative spacing index (*RSI*) for the dominant tree height (Meredieu *et al.*, 2003):

$$RSI = 100 \cdot \frac{AS}{H_{dom}} \tag{3}$$

where:

AS – is mean spacing between trees in meters (trees are assumed to be positioned on a triangular grid),
H_{dom} – is the mean height of the highest 10% of trees.

A multivariate analysis of variance (ANOVA/MANOVA) using a generalized linear model (GLM) was conducted to determine the effect of explanatory variables on operational productivity. The MANOVA analysis was conducted to determine intergroup differences while controlling for other variables. Contrast analysis (scheduled comparisons) was used to determine a difference by reducing the intergroup effect and Levene's test for detecting differences in variance of analysed characteristics. Initial analysis of the raw data indicated that the assumptions of the model were not met. Therefore, the main part of the analysis was conducted for the data after logarithmic transformation using the following formula:

$$\ln(y) = b_0 + b_1 \cdot \ln(x_1) + b_2 \cdot \ln(x_2) + b_3 \cdot \ln(x_3) + b_4 \cdot x_4 \ [m^3 \cdot PMH^{-1}] \quad (4)$$

where:

y – productivity in operational time [$m^3 \cdot PMH^{-1}$],
x_1 – intensity of cuts (share of volume),
x_2 – volume of a single tree inside bark [m^3_{inbark}],
x_3 – relative spacing index (RSI) [m],
x_4: {NT27=1; WT35=0} – work on small skid trail.

Where the assumptions of parametric methods were violated, differences in data parameters were determined using Kruskal-Wallis analysis of variance and non-parametric *post-hoc* tests. In order to determine differences in proportions (frequencies), a test of differences in structure ratios was used. The data analysis was carried out using Statistica 13 pocket software (TIBCO Software Inc., 2017) and function (tests) built in.

Results

In order to check the homogeneity of the sample plots (Table 2), a one-way analysis of variance (ANOVA) was carried out along with a check of the basic assumptions of the method. The results generally indicated that there were no statistically significant differences for the two groups of sample plots located at wide (3.5 m, WT35) and narrow skid trials (2.7 m, NT27). The only deviation noted was a greater relative spacing index (RSI) variance for plots located along narrow operational routes (NT27). Due to the robustness of the ANOVA/MANOVA analysis to the model assumptions (TIBCO Software Inc., 2017), it was assumed that this case, however, did not significantly affect the homogeneity thesis of the study plots.

In order to eliminate the influence of the independent variables and to capture possible differences in the mean values of operational efficiency, a contrast analysis (planned comparisons) available in ANOVA/MANOVA module was carried out. The result (Fig. 2a) indicates a higher average operational efficiency and lower variability (variance) when working on wide skid trails (WT35). Analysis of the operational times of the harvester cycle shows that there was no statistically significant difference in both the number of passes and the processing time for

Table 2.
Characteristics of test sample plot

Variable	Unit	WT35					NT27				
		Aver.	Me	Min	Max	SD	Aver.	Me	Min	Max	SD
Diameter at breast height (DBH) over bark	cm	11.7	11.0	6.0	23.5	3.7	11.8	11.0	6.0	27.0	3.9
Initial tree density	$N \cdot ha^{-1}$	2353	2520	1480	3340	457.5	2206	2180	1160	3660	632
Relative spacing index (RSI)	m	12.2L	11.6	10.1	15.1	1.3	13.1L	12.6	9.6	17.1	2.2
Volume of a single tree inside bark,	m^3_{inb}	0.074	0.074	0.022	0.157	0.028	0.081	0.082	0.032	0.149	0.028
Intensity of thinning, share of volume	%	21	21	6	59	13	24	23	7	55	12
Number of trees harvested	pcs.	22	20	5	40	10	25	27	11	39	8

L – statistical significant Levene's test (F=8.9385, p=0.005) a single tree (Fig. 2b, d). What was statistically significant was the increase in travel time between trees, which was 39% greater when operating on narrow skid trails (NT27, Fig. 2c).

Figure 3 shows the share of individual process operations in the work cycle. Tests carried out for the structure indicators showed a statistically significant difference, a higher (0.29) share of driving time ($z=2.387$, $p=0.017$) on narrow skid trails (NT27) and no effect of the width of the routes on the share of felling and processing time (around 0.6: $z=0.307$, $p=0.544$).

The analysis of the operating efficiency cross-sections shown in Figure 4 indicates both a non-linear pattern and a change in the strength of the effect of the explanatory variables (dispersion). A greater effect of treatment intensity with a concomitant increase in the random nature of the volume of trees harvested was observed in the sample plots located along narrow skid trails (NT27). Therefore, in order to linearize the relationship and the influence of outlier variables reduction, further detailed performance analyses were carried out for transformed variables (ln).

A MANOVA analysis was carried out to confirm intergroup differences while controlling for other variables. The results in Table 3 confirmed the statistically significant effect of the width of the skid trail, the volume of the tree harvested and the intensity of the treatment on the operating efficiency of the machine. It is also worth noting that the width of the skid trail explains $\eta^2 \approx 13\%$ and the intensity $\eta^2 \approx 32\%$ of the variance. Operating on a narrow skid trail (NT27) is characterised by approximately ($b4=-0.1227$) lower operational efficiency (11.6% less, assuming average parameters of experiments).

In the study plots located along the wide skid trails, the fewest (n=15) injured trees were noticed (Table 4). In contrast, there were twice as many (n=37) in the plots located along the

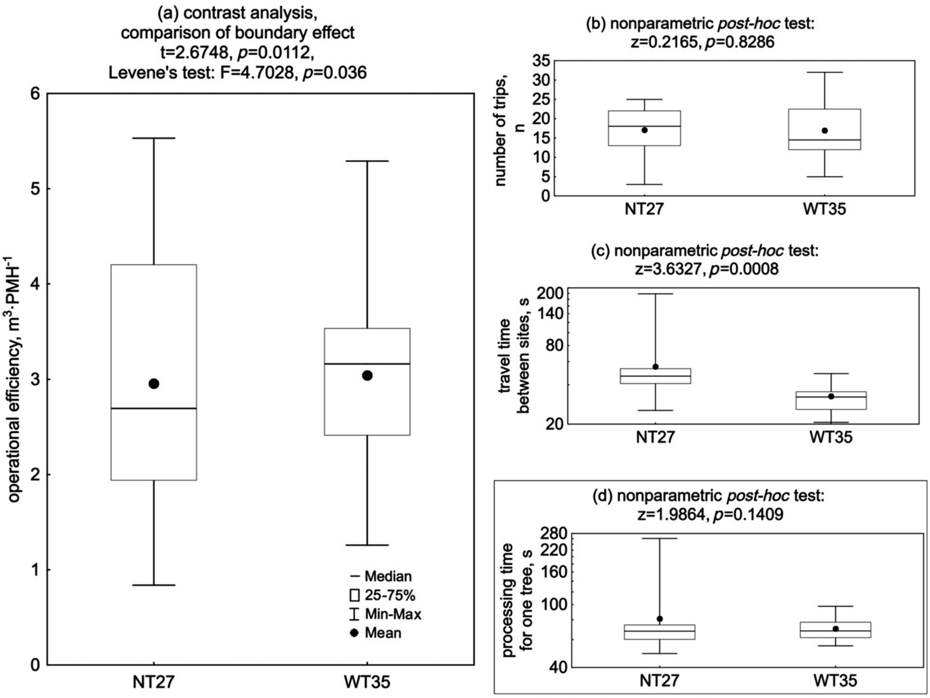

Fig. 2.
Characteristics of harvester work cycles

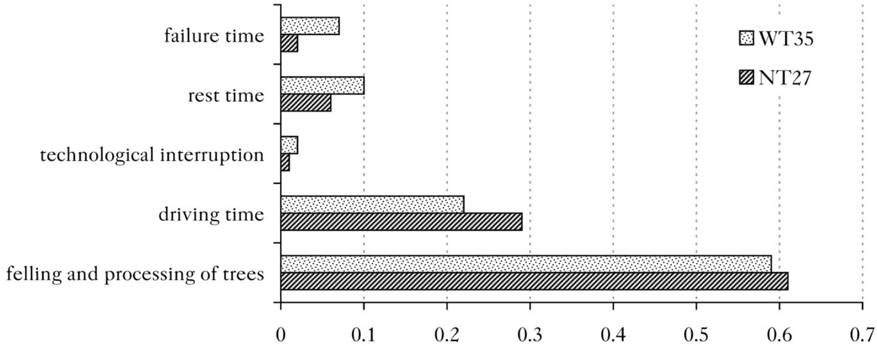

Fig. 3.
Share in group of work time

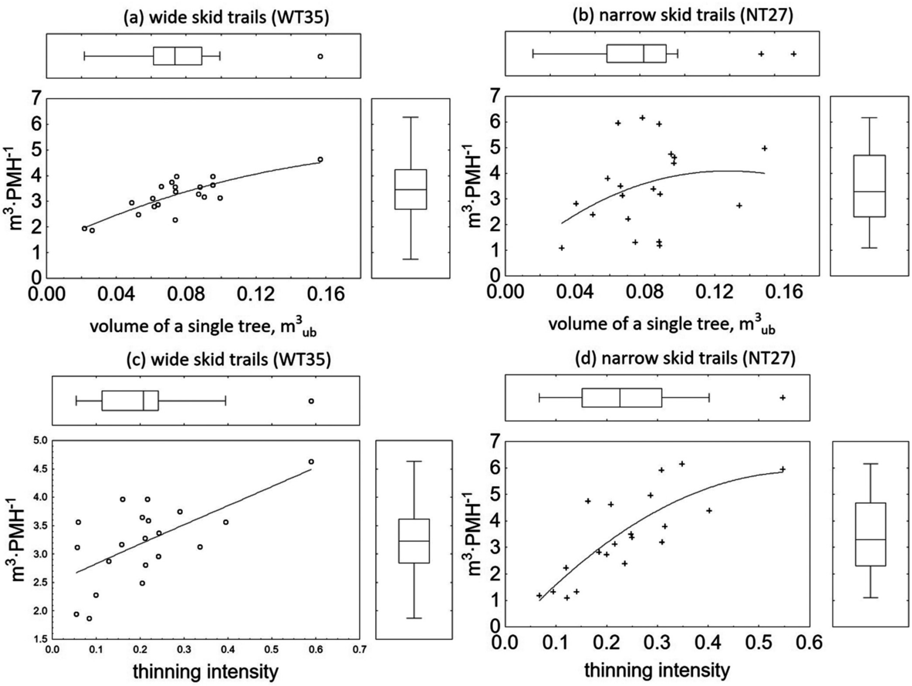

Fig. 4.
Impact of edge variables on operational efficiency

Table 3.
Model regression parameters, MANOVA (R^2=0.7949, $R^2_{Adj.}$=0.5898, df=4, F=5.0165, *p*-value<0.001)

Variable	Value	Std. error	t-Stat	*p*-value	η^2
b_0, intercept	3.8543	1.4108	2.7320	0.0098*	0.1758
b_1, intensity	0.4250	0.1056	4.0261	0.0003*	0.3165
b_2, volume	0.5322	0.1704	3.1223	0.0036*	0.2179
b_3, RSI	–0.2978	0.4671	–0.6376	0.5279	0.0115
b_4: {NT27=1; WT35=0}	–0.1227	0.0523	–2.3454	0.0248*	0.1359

* statistically significant p-value<0.05

narrow skid trails. The calculated share of injured trees in relation to the total number of trees remaining in the stands was 0.784% and 2.17%, respectively. A formal test of the significance of differences in structure indices (z=4.347, *p*=0.0003) confirmed the effect of the width of the skid trail on the amount of damage noticed.

Statistical analyses of the values of parameters characterising wounds and damage to residual trees (Table 4) indicate the occurrence of significantly longer wounds on trees located by wide skid trail (WT35) and an associated greater wound area (+40%) in relation to damage found by narrow trails (NT27). Within the analysed groups of variables, an equal proportion of deep stem wood damage (more than 3 mm) was also noted, which did not exceed 0.06%. In both analysed study plots, 3 (1.6 ‰) cases each of amputations of the roots were also visually noted, which occurred as a result of manoeuvring (rotations of the crawler harvester) on the trials. The height of damage placement did not exceed 160 cm, and the difference in both groups was statistically insignificant (Kruskal-Wallis ANOVA: F=0.3058, *p*=0.583). Therefore, based on the results presented, it is possible to accept the thesis that very severe damage, *i.e.* deep stem wood damage and roots amputation, is random and independent of the width of the trail.

Mean values of tree damage indices (W) as well as weighted logging damage indices (WDI) according to Meyer classifications ranged from 0.1-0.19 and 7.57-2.99 (Table 5) for plots located at wide (WT35) and narrow skid trails (NT27), respectively. The observed skewness of the distributions was an indication to use non-parametric tests to test the hypotheses of equality of damage class indices according to Meyer. The obtained values of the ANOVA Kruskal-Wallis test [W: H(1, N=40)=1.397, *p*=0.2372; WDI: H(1, N=40)=2.419, *p*=0.1198] do not allow the conclusion of statistically significant differences. In a simplified manner, it can therefore be assumed

Table 4.
The characteristics of the observed wounds and damage on the remaining trees

Variable	Me	Min	Max	q_{25}	q_{75}
WT35, n=15					
Base height [cm]	50.0	0.0	122.0	26.0	95.0
Length [cm]	10.0a	4.0	25.0	6.0	13.0
Width [cm]	5.0	3.0	16.0	3.0	7.0
Share of perimeter	10.15	6.52	29.63	8.11	16.13
Wound area [cm^2]	31.42b	14.14	148.44	18.85	51.05
NT27, n=37					
Base height [cm]	64.0	4.0	160.0	34.0	84.0
Length [cm]	6.0a	2.0	20.0	5.0	9.0
Width [cm]	4.0	1.0	8.0	3.0	6.0
Share of perimeter	10.3	2.3	19.6	7.3	11.5
Wound area [cm^2]	22.0b	3.1	84.8	13.7	31.4

a – statistical significant (nonparamteric *post-hoc* test, z=2.4338, *p*-value=0.0149
b – statistical significant (nonparamteric *post-hoc* test, z=2.0602, *p*-value=0.0394

Table 5.
Meyer's tree damage indicators (W) and weighted with the amount of harvested wood (WDI)

Variable		Aver.	Me	q_{25}	q_{75}	SD
W	WT35	0.17	0.07	0.00	0.201	0.24
	NT27	0.19	0.00	0.00	0.11	0.45
WDI	WT35	7.57	1.82	0.00	5.62	15.27
	NT27	2.99	0.00	0.00	0.95	7.46

that the width of the skid trails has no influence on the damage classes of the trees remaining according to Meyer's classification.

Discussion

Cut-to-length harvesting has been identified as a cost-effective method in the timber supply chain (Palander *et al.*, 2019; Szewczyk *et al.*, 2023). The small size of the trees in thinning operations has the greatest impact on the lower productivity and increases the cost of the silvicultural treatment. It is also expected that small and low-cost machines will be used in young stands (Mederski *et al.*, 2018).

The Arbro head analysed was also used to harvest hardwoods for energy purposes in the coppiced forests, demonstrating similar productivity (Suchomel *et al.*, 2012). The productivity of a harvester with a stroke head is lower than that of rollers and depends on factors such as the type of assortment and the shape of the branch. Suchomel *et al.* (2012) expected that the potential productivity of the Arbro harvester would be 51 m^3/day.

The study discovered that working on narrow skid trials (NT27) resulted in a reduction of passes. This led to smaller and less severe wounds that were expected to heal more quickly. A similar opinion is expressed by Tavankar *et al.* (2022), who found wounds from extracting to be more severe to trees than wounds from felling tree, and the process of wound healing can take more than 10 years. These findings are consistent with the conclusions of Palander *et al.* (2019), who highlighted the potential for improved quality of harvested materials. Several studies have shown a high percentage of frontal rot after logging, which is twice as high in trees with bark damage (Kohnle and Kändler, 2007; Putz *et al.*, 2008). Working on narrow trails resulted in a significant increase in the percentage of damaged trees, from 0.8% (NT27) to 2.2% (WT35). Thinning is a crucial technique for forest management that necessitates the use of machinery. However, the extent of damage caused is largely influenced by human factors and technical solutions. Bembenek *et al.* (2020) pointed out that the time of day and light conditions play an important role in limiting the level of tree damage in machine logging, as they affect operator fatigue and concentration levels during work. When the concentration of the machine operator decreases, the likelihood of tree damage increases simultaneously in the immediate vicinity of skid trails and in the manoeuvring zones of the hydraulic crane and felling head. In their study, Cudzik *et al.* (2017) compared two commonly used systems, tree length (TLS) together, and evaluated the damage caused to trees and soil. The results indicate that although the skid trail in CTL technology covers almost twice the area needed in TLS, CTL technology resulted in much less change in soil compaction density and only around 3-4% of trees were damaged, which is half the amount in TLS. This low percentage of damaged trees is attributed to the correct adaptation of the machines to local conditions and treatment requirements, as found in this study.

Vasiliauskas (2001) analysed the literature on damage caused by post-harvest and skidding operations. It was noted that a significant proportion of the remaining trees in older stands can be damaged during mechanised selective felling in forests, particularly when operations are carried out in summer. Damage most often occurs during timber transport, with the majority of resulting wounds being near the base of the tree and up to 200 cm^2 in size. In this study, the wounds did not exceed 150 cm¸, which suggests a correlation with the early spring harvest period. According to a study by Campu and Borz (2017), the season in which the timber is harvested, is one of the factors influencing the area of injuries. Similar conclusions were reached in their study by Grzywiński *et al.* (2020), who showed that the level of damage and the area of injury from logging in the full growing season can exceed by several times the analogous values occurring during the period of tree dormancy (late autumn – early spring).

Ursić *et al.* (2022) analysed the causes, intensity, location and extent of damage to standing trees. They found that at moderate intensity (about 12-13%), there was the highest incidence of bark damage (about 35%). On average, 83% of the damage (peeled bark) was located up to 1.3 m above the ground, and the wound area most often (67%) did not exceed 100 cm^2. The most significant cause of this damage was harvester operation (59%). Shabani *et al.* (2021) investigated the susceptibility of remaining trees to damage from selective logging and found that the range and extent of damage to remaining trees was strongly influenced by slope and stand density. Selective chainsaw harvesting in mixed-age stands (Tavankar *et al.*, 2013) resulted in the destruction of 1.4% of trees and damage to 3.4% of trees remaining in the plot, while skidder caused three times more damage.

Camp (2002) and Cântar *et al.* (2022) found that damage mostly occurs during thinning operations due to the small spaces between trees. However, applying silvicultural principles to prepare the stand for natural regeneration resulted in a significant decrease in damage. Picchio *et al.* (2011) and Kizha *et al.* (2021) note that forestry equipment requires various adaptations and improvements to facilitate manipulation in dense forest stands. As an example, Sampo's small machines (Szewczyk *et al.*, 2023) allow for tilting the hydraulic crane not only in the parallel direction but also perpendicular to the axis of the harvester.

In their analysis of damage in Douglas-fir *Pseudotsuga menziesii* (Mirb.) Franco stands, Han and Kellogg (2000) found that the harvester caused wounds of approximately 3.5 cm in width on average, which is slightly less than what was observed in our case study. They also noted that forwarding was responsible for root damage. Han and Kellogg suggest that optimal trail spacing of 18.5 m or less can help to avoid much of the damage, and that limiting trail width to 4 m can also be effective. However, the tests for significance of differences conducted in the present study did not show an effect of trail width on some wound parameters (such as width or base height). In contrast, a significant difference was found for wound area.

Picard *et al.* (2012) reported an increased proportion of trees dying due to tree damage, based on literature data. The damage rate varied with the size of the damaged trees and divided equally between damaged and destroyed trees, with damaged trees experiencing three times the mortality rate in 5-10 years. An equation relating the proportion of trees damaged to logging intensity was fitted. A significant effect was found, with lower damage for the level of logging intensity, in agreement with the size of felled trees. In the opinion of these authors, considering at least the relationship between damage and harvesting intensity would improve the accuracy of forest management forecasts. In this study thinning intensity constituted the second most important factor influencing damage levels. The volume of felled trees played the most important role. Skid trails cause numerous collateral problems that affect ecosystem conservation. Yilmaz (2010) documented that long-term timber extracting reduces the annual diameter at breast height (DBH) growth and increment of nearby trees, but this value depends on edaphic and climatic conditions.

Tree growth and increment on the undisturbed area was found to be about 60% greater than the skid road. The effect of skid trails on tree growth was also demonstrated by Stempski *et al.* (2021). However, the results of their study were different. They found that trees bordering skid trails presented significantly higher volume increment values than trees growing deeper in the stand. Such a trend was observed for narrower (2.5 m) and wider (3.5 m) trails equally, and the increase in tree volume near the trails was greater than the increase in tree volume deep in the stand by 30% and 35%, respectively. It can be surmised that a similar trend would be observed in the stand from the present study, but confirmation of this conjecture requires time and more extensive analysis after about 10 years.

This paper presents an analysis of the first thinning on plots intended for hand-machine operations in the context of artificial restoration. To accommodate transport machines, wide working roads (WT35) were assumed at a distance of approximately 40 m. The density of the current and future skid trails met the foresters' expectations of limiting the excluded areas. The selection of the narrowest operational routes has eliminated concerns regarding the 'edge effect' and, with the appropriate machinery, has significantly reduced damage to the remaining trees. These elements highlight the importance of choosing harvesting methods that meet various criteria, including economic, social, and product quality. Meeting the new standards is crucial due to the significant rise in demand for machine-based methods of stand management (Marchi *et al.*, 2018).

Conclusions

In the timber supply chain, fully mechanised cut-to-length harvesting systems have been identified as a cost effective method. According the literature, skid trails using the CTL method cover an area of almost less than twice the area required for the tree to length. Both thinning intensity, number of trees felled and productivity affect the number of wounds on remaining trees.

The parameters characterising the injuries on the remaining trees indicate the occurrence of significantly longer wounds on the trees found by the wide skid trail and a correspondingly larger wound area (+40%) in relation to the damage found by the narrow skid trail. Based on the results, it can be assumed that very severe damage in deep stem wood and root amputation, is random and independent of the width of the skid trails.

Compared to the large number of standing trees, the number of damage caused by the lightweight crawler harvester was very small. This shows the importance of choosing the right machine to facilitate work in dense stands. Meyer's tree damage classifications do not allow to conclude statistically significant differences between injures caused by narrow and wide skid trails. Therefore, it should be remembered that damage to the bark and other injuries to the tree increase the risk of frontal rot that reduced the potential of highest wood quality in the future.

Although the narrow skid trail reduces the area of the forest excluded from silviculture, the thinning process is difficult. A higher average operating efficiency and a lower variability of about 12% were observed on the wider skid trails.

Authors' contribution

Conceptualization – K.L.; methodology – K.L., A.S.; validation – K.L.; resources – K.L; data curation – K.L.; writing – original draft preparation – M.K, K.L., A.S.; writing – review and editing – M.K, K.L., A.S.; visualization – K.L.; funding acquisition – K.L.

All authors have read and agreed to the published version of the manuscript.

Conflict of interest

Authors declare there is no conflict of interest.

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STRESZCZENIE

Efektywność pozyskania drewna harwesterem i uszkodzenia drzew w zależności od szerokości szlaków zrywkowych

Pozyskiwanie drewna krótkiego (metoda CTL) ma szereg zalet, w tym obniżenie kosztów jednostkowych, zwiększenie wydajności i ograniczenie lub nawet wyeliminowanie ciężkiej pracy fizycznej. Obserwowane zmiany demograficzne, a tym samym oczekiwania pracowników i konkurencja na rynku pracy oznaczają, że w pełni zmechanizowana praca lub automatyzacja będą w przyszłości nieuniknione. Odnowienia sztuczne oraz naturalne stanowią wyzwanie dla dalszych prac pielęgnacyjnych i hodowlanych, których celem jest wyprodukowanie zarówno jak największej ilości drewna z uwzględnieniem wymogów ekologicznych, jak i uzyskanie drewna najwyższej jakości, m.in. drewna specjalnego.

Dlatego też upowszechnienie mechanizacji prac doprowadziło do wzrostu zainteresowania szkodami powodowanymi przez zastosowanie maszyn w cięciach pielęgnacyjnych. Jednym z pierwszych aspektów był problem udostępnienia drzewostanów, a wraz z nim ograniczenie tzw. powierzchni produkcyjnej, powstawanie drzew skrajnych, odsłoniętych, rozgałęzionych, słabo oczyszczonych, o gorszej klasie jakości pozyskiwanego drewna. O ile warunki rynku pracy wymusiły akceptację mechanicznej pielęgnacji drzewostanów, to kwestia ich udostępnienia oraz szerokości szlaków zrywkowych pozostawała nadal otwarta. Przyjęto, że minimalna szerokość szlaku powinna wynosić 2,5 m, jednak w pewnym okresie istniały też zalecenia, aby projektować szlaki o szerokości nawet 6-7 m, które uwzględniają poszerzenia ze względu na tzw. zachodzenie maszyn na ewentualnych zakrętach.

Niniejszy artykuł ma na celu analizę uszkodzeń drzew pozostających w drzewostanie i efektywności prac w zależności od szerokości szlaków operacyjnych (wąskich 2,7 m i szerokich 3,5 m). Analizy przeprowadzono podczas pierwszych cięć trzebieżowych w 25-letnim drzewostanie sosnowym z tzw. pozyskaniem grubizny na cele przemysłowe. Na powierzchniach doświadczalnych (ryc. 1) wykorzystano małą koparkę gąsienicową wyposażoną w głowicę harwestera. Głównym celem badań były rozważania, w jaki sposób ograniczenie szerokości szlaków zrywkowych i intensywność trzebieży wpływają na wydajność pozyskania oraz uszkodzenia drzew pozostających, przy założeniu takich samych warunków drzewostanowych (tab. 1 i 2).

W łańcuchu dostaw drewna pozyskanie metodą sortymentową (*cut-to-length*, CTL) zostało uznane za metodę efektywną kosztowo. Według danych literaturowych udostępnienie drzewostanu dla metody CTL obejmuje jednak obszar prawie dwukrotnie większy niż oczekiwany w metodzie drewna długiego (*tree length*, TL). Na efektywność prac (tab. 3) wpływają miąższość pojedynczego drzewa, intensywność trzebieży oraz udostępnienie drzewostanu (ryc. 2-4). Te same zmienne określają również wpływ na wielkość uszkodzeń w drzewostanie pozostającym.

Parametry charakteryzujące uszkodzenia drzew pozostałych na powierzchni (tab. 4) wskazują na występowanie znacznie dłuższych ran w próbie z szerokimi szlakami operacyjnymi oraz ich większą sumaryczną powierzchnię (+40%) w stosunku do uszkodzeń zaobserwowanych w próbie z wąskimi szlakami operacyjnymi. Na podstawie uzyskanych wyników można również przypuszczać, że bardzo poważne uszkodzenia (głęboko w drewnie pnia lub amputacja korzeni) mają charakter losowy i nie zależą od szerokości szlaku operacyjnego.

W porównaniu z dużą liczbą drzew stojących liczba uszkodzeń spowodowanych przez lekki harwester gąsienicowy była bardzo mała. Pokazuje to, jak ważny jest wybór odpowiedniej maszyny

ułatwiającej pracę w gęstych drzewostanach. Zaobserwowane rany według klasyfikacji uszkodzeń drzew Meyera (tab. 1 i 5) nie pozwalają na stwierdzenie statystycznie istotnych różnic pomiędzy uszkodzeniami występującymi zarówno przy wąskich, jak i szerokich szlakach operacyjnych. Jednakże wszelkie uszkodzenia kory oraz inne uszkodzenia pni drzew zwiększają ryzyko wystąpienia zgnilizny czołowej (wewnętrznej), a tym samym wpływają na znaczne ograniczenie w przyszłości potencjału na drewno najwyższej jakości.

Wąskie szlaki operacyjne zmniejszają powierzchnię tzw. wyłączoną z hodowli, ale jednocześnie zwiększają utrudnienia w procesie trzebieży maszynowej. Jednak przy zastosowaniu szerokich szlaków zrywkowych (3,5 m) zaobserwowano wyższą, o około 12%, wydajność operacyjną.