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DAMAGE CAUSED BY HARVESTER HEAD FEED ROLLERS TO ALDER, PINE AND SPRUCE

The harvester head causes damage to the bark and wood on the lateral surface of the processed assortment. The severity of the damage may be influenced by the construction of the harvester head and tree species characteristics, such as bark thickness and wood hardness. The study aimed to recognise and compare damage caused to hardwood and softwood. Wood from alder, pine and spruce was harvested using a Valmet 911.4 harvester equipped with a 360.2 head. Logs measuring 2.40 and 2.50 m in length were used in this study. The depth of the damage caused by the feed roller spikes was measured using a digital caliper. Comparison of these defects across the three species revealed that as bark thickness increased so the depth of damage to the timber decreased. Damage to the alder logs in the form of dents and gouged timber fibres was shallow: from 1.7 to 3.7 mm, and significantly less than that to the softwood logs: in the pine from 5.9 to 7.8 mm, and in the spruce from 3.9 to 5.6 mm. Damage to the middle and top logs for each species was similar and depth varied little along the entire length of the processed assortment. Such damage only slightly lowered the quality of the alder wood, which had the thickest bark. Application of the Valmet 911.4 harvester caused less damage to the alder wood than to the softwood (pine and spruce).

Introduction

The bark and wood of processed logs are damaged by the harvester head. Certain sections of the harvester head, to a varying degree and extent, can lower the quality of the roundwood. The harvester head is equipped with a set of

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2-4 feed rollers which determine the feed speed of the wood and can significantly affect the quality of the delimbing process [Sowa et al. 2013]. The rolls should control the transfer of logs at a speed of several metres per second, without slipping or causing excessive mechanical damage [Węgrzyn and Leszczyński 2014]. As an alternative to the steel spikes on feed rollers, rubber spikes were proposed, but although rubber spikes caused less damage to the wood, their traction properties were much poorer [Mäkelä 1993, as cited by Nuutinen et al. 2010].

Researchers have also raised the issue of blue-stain – a secondary defect, which affects wood damaged along the lateral plane. This is related to the loss of bark during transfer through the harvester head [Lee and Gibbs 1996]. A further problem which frequently arises in harvester-processed roundwood is assortments that have not been properly delimbed [Gerasimov et al. 2012]. Hatton et al. [2015] set out to determine the significance of branch cutting speed during processing, and indicated, amongst other things, the need to investigate differences in this parameter according to tree species. Likewise, bucking accuracy can vary depending on the species of the tree being processed, as well as the diameter of the logs cut [Bembenek et al. 2015].

Damage to roundwood caused by feed rollers, the subject of this study, is not well recognised. The work of Spinelli et al. [2011] concerning poplars focused on surface damage to logs, while Mederski [2013] studied the use of a harvester in a mixed pine and birch stand. Connell [2003] investigated eucalyptus wood damage, highlighting the frequency of splitting during the felling and bucking of the logs by harvester.

In this study, the extent of the damage to three species of wood was investigated: one broadleaved – black alder (*Alnus glutinosa* Geartn.) and two conifer – Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* (L.) H. Karst). Pine and spruce are species commonly cut and processed by harvester. Alder, due to morphological features of the trunk which are similar to coniferous species, is also successfully cut by harvester. The analysed species exhibit different physical and mechanical properties. The density of dry wood varies from 450-600, 300-860 and 300-640 kg m^{-3}, for alder, pine and spruce, respectively [Wagenführ 2006]. Additionally, these species are characterised by different bark thickness. Taking the above-mentioned characteristics into account, it was hypothesised that the penetration of the feed roller spikes would be shallower when the bark was thicker. Therefore, the objective of the research was mainly to recognise and compare the depth of damage of the broadleaved species – alder, and the two softwood species: pine and spruce. Special attention was paid to the mean and maximum depth of damage and its distribution along the stem.

Materials and methods

Logs from the three species of tree were harvested using a Valmet 911.4 harvester equipped with a 360.2 head. The harvester was produced in 2008 and the feed rollers – which determine the extent of the damage – had been replaced approximately six months prior to the study. There were no signs of wear on the rollers. Roller width was 25 cm and height 45 cm, and it was equipped with 6 steel spikes of 15 mm in height. The roller pressure was 75-120 bars.

Logs measuring 2.50 m (hardwood) and 2.40 m (softwood) in length were cut from the middle and top sections of the stem. Timber from the butt section was not included in this study, as it was processed into long logs and examined according to different methodological assumptions [Karaszewski et al. 2016].

The extent of the damage to the timber was assessed 3 weeks after harvesting in all cases. After this time the cuts had opened slightly allowing more accurate measurements to be taken. The average monthly temperature during the study was 17.2°C. The logs were cut from the following trees: alder from location I (alder I) – 84 years old, and from location II (alder II) – 91 years old, pine – 80 years old, and spruce – 75 years old.

The depth of the damage on the logs was measured using the depth gauge on a Mitutoyo digital caliper (30 cm jaw length) connected to a portable computer. In order to achieve the most accurate results possible, the chip of wood damaged by the feed roller spikes was removed with a chisel. As the trunk moved through the harvester head, one spike cut three 'walls' of a wood chip. The fourth 'wall' of the chip was cut manually with a chisel and the wood chip was removed using a small screwdriver. Measurements were taken at the deepest point of damage next to the semi-circular wall cut by the steel spikes (fig. 1). The depth of the damage was measured in three sections of each log: at the bottom (the biggest diameter), in the central section and at the top (the smallest diameter). In order to get a full picture of the damage, six measurements were taken within a given section of the roundwood, in four rows created by the spikes along the log (fig. 1). The measurements were taken on both sides of the log, thereby assessing both sides of the feed rollers. The thickness of the bark (together with the phloem), detached from near the point of the depth measurement, was also measured using the Mitutoyo digital caliper. Three measurements of bark thickness were made at each point where depth of damage was measured.

The results of the depth of damage study were analysed according to two criteria: 1) mean depth for a log, where all the measurements in a given set (e.g. the results from a top log) were used to calculate the mean, and 2) maximum depth, where the mean of the maximum depth was taken from three measurement points along the log – top, middle and bottom. Three variables were taken into account: 1) tree species, 2) trunk section – logs cut from the middle or top section of the stem: middle logs and top logs, and 3) in the case of the alder, trees from two stands/locations were analysed - alder I and alder II.

Two alder stands were selected for research in order to have a better representation of hardwood samples. However, in the initial analysis, both the alder group samples were considered separately in case there were any differences.
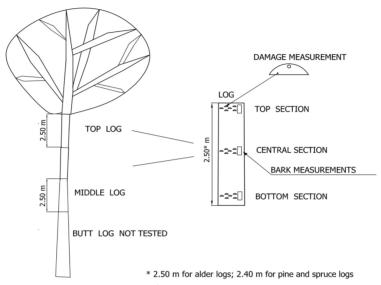

Fig. 1. Log damage measurement points

Prior to the one-way ANOVA analysis, the Bartlett's test for equality of variance and the Cramér–von Mises criterion to verify the null-hypothesis that the population is normally distributed were performed. The significance level for the analysis was $\alpha=0.05$.

A detailed comparative analysis based on orthogonal contrasts was performed (tab. 1).

Table 1. Basic contrast coefficients

Tree groups	Contrast 1 alder logs in comparison to the pine and spruce logs	Contrast 2 comparison between the alder logs from both stands	Contrast 3 pine logs in comparison to the spruce logs
Alder I	-1	-1	0
Alder II	-1	1	0
Pine	1	0	1
Spruce	1	0	-1

The following basic contrasts were investigated: Contrast 1 – mean depth of damage recorded in the alder logs (from both stands) in comparison to the pine

and spruce logs; Contrast 2 – comparison of mean depth of damage between the alder logs from both stands; Contrast 3 – mean depth of damage to the pine in comparison to the spruce logs. In addition, the above-mentioned contrasts were investigated for bark thickness. Statistical data was processed using R software.

Results and Discussion

In total, 32 trees (16 alder, 8 pine and 8 spruce) and 64 logs were measured (32 alder, 16 pine and 16 spruce), and 2304 depth of damage measurements were taken. Due to the lack of variation between the mean and maximum depth of damage on the middle and top logs for each species, this division was not considered in the models and in further analysis (figs. 2a, 2b).
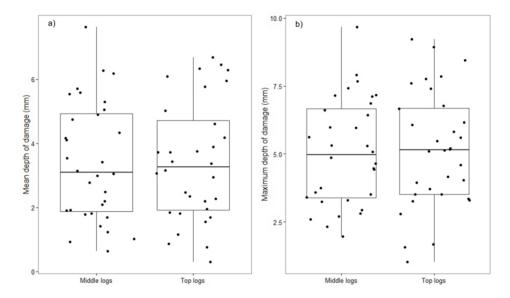

Fig. 2. Mean (a) and maximum (b) depth of damage to middle and top logs

Elements in box-plots: ● – single observations; lower whisker is the smallest observation greater than or equal to lower hinge – 1.5 * IQR (the inter-quartile range); lower edge of notch is a median – 1.58 * IQR / sqrt(n); middle is a median; upper edge of notch is a median + 1.58 * IQR / sqrt(n); upper whisker is the largest observation less than or equal to upper hinge + 1.5 * IQR

Likewise, there was no significant difference in the mean ($Pr (> F) = 0.064$) and maximum ($Pr (> F) = 0.053$) bark thickness between the middle and top logs (figs. 3a, 3b). There was a statistically significant difference between the bark thickness of the analysed species ($Pr (> F) < 2e^{-16}$***). The analysis of contrasts revealed that the alder bark was the thickest of all the species ($Pr (> |t|) < 2e^{-16}$***) and that the pine bark was thinner than the spruce bark ($Pr (> |t|) = 2.07e^{-09}$***).
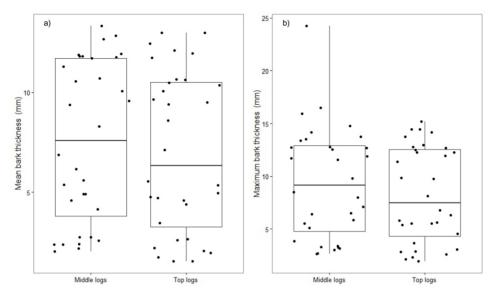
Fig. 3. Mean (a) and maximum (b) bark thickness of middle and top logs

Elements in box-plots: • – single observations; lower whisker is the smallest observation greater than or equal to lower hinge – 1.5 * IQR (the inter-quartile range); lower edge of notch is a median – 1.58 * IQR / sqrt(n); middle is a median; upper edge of notch is a median + 1.58 * IQR / sqrt(n); upper whisker is the largest observation less than or equal to upper hinge + 1.5 * IQR

The results of the variance analysis regarding the differences in damage to the wood of the studied species revealed highly significant differences between the mean size of damage as well as the maximum size of damage (tab. 2).

Table 2. Results of variance analysis: mean and maximum depth of damage between species

Feature	Intercept	Degrees of freedom	Sum of squares	Mean square	Value F	Pr (> F)
Mean depth of log damage	species	3	174.26	58.087	87.501	< 2.2 e⁻¹⁶***
	error	60	39.83	0.664	–	–
	total	63	214.09	–	–	–
Maximum depth of log damage	species	3	197.85	65.950	60.951	< 2.2 e⁻¹⁶***
	error	60	64.92	1.082	–	–
	total	63	262.77	–	–	–

Standard significance code: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

The analysis of damage caused to particular species revealed less damage in the alder than the pine and spruce. This was confirmed by both the mean and maximum values (tab. 3).

Table 3. Mean and maximum depth of damage in the tested species; 95% confidence interval

Tree groups	Mean depth of log damage	Maximum depth of log damage	Mean bark thickness	Mean bark thickness + mean depth of damage
	mm			
	±0.4	±0.5	±0.6	±0.6
Alder I	2.2	3.7	10.6	12.8
Alder II	1.7	3.3	11.3	13.0
Pine	5.9	7.8	2.2	8.1
Spruce	3.9	5.6	5.0	8.9

The mean depth of damage ranged between 1.7 mm for alder II and up to 5.9 for the pine, while the maximum depth of damage ranged from 3.3 mm for alder II to 7.8 mm for the pine (tab. 3). Regarding bark thickness, the relation was precisely the opposite: the lowest mean thickness was recorded for the pine bark (2.2 mm), while the spruce bark was thicker (5.0 mm). The alder bark from both stands was the thickest (10.6 and 11.3 mm for alder I and II, respectively; tab. 3).

Highly significant differences in the mean depth of damage to the alder compared to the coniferous species were confirmed, $Pr (> |t|) < 2e^{-16}$*** (tab. 4).

Table 4. Basic contrast values

Contrasts	Estimator	Standard error	Value t	Pr (> |t|)
Contrast 1 alder logs in comparison to the pine and spruce logs	1.582	0.130	12.166	$< 2e^{-16}$***
Contrast 2 comparison between the alder logs from both stands	-0.210	0.184	-1.143	0.258
Contrast 3 pine logs in comparison to the spruce logs	-1.065	0.184	-5.791	$2.74e^{-07}$***

Standard significance code: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1.

No difference was recorded in the mean depth of damage to the alder wood regarding location, $Pr (> |t|) = 0.258$ (tab. 4). Statistical analysis revealed highly

significant differences in the mean depth of damage to the pine logs in comparison to the spruce, $Pr (> |t|) = 2.74e^{-07}$*** (tab. 4).

The deepest total penetration (understood as penetration through the bark and wood tissue) caused by the feed roller spikes was measured in the alder stems. The total depth of spike penetration for this species was 12.8-13.0 mm, while the results for the two coniferous species were significantly lower (tab. 3).

The comparison of all the species measured revealed a clear linear relation between the depth of damage and bark thickness, in both mean and maximum damage results (fig. 4).
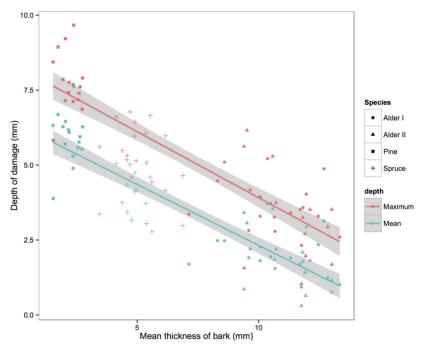

Fig. 4. Relation between mean and maximum depth of damage and mean thickness of bark for all the analysed species

Regression analysis of the dependent variables reflected the linear models for depth of damage:

$$\text{Mean depth of damage} = 6.386 - 0.406 \times \text{ToB}_{mean} \qquad (1)$$

$$\text{Maximum depth of damage} = 8.315 - 0.440 \times \text{ToB}_{mean} \qquad (2)$$

where: ToB – thickness of bark.

For the depth of damage models, the coefficients of determination R^2 were 0.776 and 0.742 for the mean and maximum, respectively. The significance of

the coefficient estimators was statistically confirmed for both the models with Pr (> |t|) < 2e^{-16}***.

The bark of the black alder, especially in older trees, is quite thick and split into scales [Surmiński 1980]. In the research presented, an age difference of 7 years between both the alder stands (locations) did not reveal any variation in the depth of damage. Apart from the effects of the harvester head on stem transfer, it might be expected that thicker bark would provide better protection for the wood beneath. The 15 mm-long spikes of the feed rollers punctured the bark, additionally compressing it and then damaging the wood. As the bark of pine and spruce is thinner, the spikes penetrated the outer wood layers more deeply. However, wood tissue cannot be ignored, and possibly the harder wood of the alder could have limited the spike penetration in comparison with the softwood of the pine and spruce. The fact that the alder wood suffered the least feed roller damage is as hypothesised, although this has not been confirmed in any literature to date. The correlation of the degree of damage – both mean and maximum values – on the mean thickness of bark provides a starting point for further discussion on log harvesting in broadleaved and mixed tree stands. An important methodological element of this paper was the investigation into the three timber species harvested using the same machine and harvester head. A different machine equipped with a head with a different configuration of spike shape and size would result in damage on a different scale. A comparison of five types of feed rollers performed by Nuutinen et al. [2010] revealed different damage depths in birch, pine and spruce. The depth of damage in the tested species exhibited broad dispersion: birch 1.8-6.0, pine 4.2-8.7 and spruce 4.3-8.7 mm, with mean values of 3.7, 5.5 and 5.8 mm, respectively. The results presented in this paper revealed that the alder suffered the least damage, with a mean value of 1.7-2.2 mm. The mean damage to the pine and spruce was 5.9 and 3.9 mm, respectively.

The processing of unbarked wood was mentioned for a reason. During harvesting in spring at the start of the growing season, logs stripped of their bark after harvesting are a common sight, especially in broadleaved species. The delimbing knives can easily strip the logs which means the harvester head may, to some extent, be in contact with the stripped wood and affect the timber directly, thereby increasing the depth of the damage.

Generally speaking, damage caused by the Valmet 360.2 harvester head did not exceed a depth of 1 cm. This information is beneficial to practitioners from both the forestry and timber industries. Worth noting is that the resulting depth of damage should in fact be doubled, considering that it occurs on both sides of the outer surface of the stem. For this reason, such damage to the wood should perhaps be recognised as a significant factor in wood processing. The applied regulations, standardisation or technical framework conditions should take these defects into consideration.

In assessing damage to the outer layer, one aspect should be emphasized. When timber is left in the forest, such defects, which are comparable to shallow wounds, allow access to pathogens which affect the quality of the wood to a greater extent than the original damage. Thus far, there has been no data in the literature on disease progression in hardwood timber after machine harvesting. In conifers, Lee and Gibbs [1996] noted a maximum development of blue-stain on up to 10% of the surface at 10 weeks after harvesting. Due to how the head functions, harvesters can spread fungi that cause discolouration in softwood. The feed roller spikes carry fungal spores which are transferred as the spikes penetrate the wood [Uzunovic et al. 2014]. Fungal disease may not only affect industrial wood, but may also be a reason for the lowering of the quality of wood chips for energy purposes [Kropacz and Fojutowski 2014]. It should also be remembered that damage to the outer surface of the stem increases the risk of accidents during processing, especially where lines are not fully automated [Connell 2003].

The mean and maximum values presented show the problem of wood quality deterioration from a slightly different perspective. The mean values provide a better picture of all the resulting damage, and also include information about the absence of damage in accordance with the methodology used. During the study, there were points where 3 to 4 measurements out of 6 equalled 0 mm. On the one hand, these values reduced the value of the mean, making it possible to marginalize the problem of timber damage. On the other hand, they illustrated the depth of damage over a larger area of wood. Zero values and values less than the maximum were present in the outer rows measured (the damage created in four rows on the timber by the feed rollers was measured). Additionally, the size of the trees felled by the harvester should be taken into consideration. For thinner assortments, the feed roller spikes were only able to cut into the bark or wood of a processed log to a limited extent (fewer rows). Thick assortments, where the feed rollers are in contact with more of the surface, were affected differently.

A maximum depth of timber damage is to be expected from the spikes which create the middle row of damage. This is the point where the feed rollers first make contact with the wood. The maximum values indicate how deeply the timber is damaged, where the incision or indentation of wood fibres end. In the case of timber production for garden components, wood processing cuts to the maximum depth of damage. During processing, shallower damage is removed after surface cutting, while the deepest damage requires a greater depth of log to be removed and causes a major loss of wood. It therefore seems important to make data on both aspects available to interested parties, who will then be able to exploit this information in relation to the timber processing methods they apply.

Conclusions

The quality of the alder wood processed using the Valmet 911.4 harvester equipped with the 360.2 head was rated as good as regards the damage caused by the feed rollers. This assessment was based on a comparison of the quality of the black alder wood with the Scots pine and Norway spruce. This machine can be used for the harvesting of alder timber with the expectation that little damage will appear on the logs.

Damage to the alder timber in the form of indentations and incisions in the wood fibres was shallow, up to 0.5 mm, and was significantly less deep than damage on the softwood logs. The main reason was a difference in bark thickness. The comparison of the three species confirmed that as the thickness of the bark increased, the depth of damage decreased. However, the harder wood could have also caused the shallower spike damage to the alder. The hardwood defects did not lower its quality significantly. The depth of the damage was similar along the whole length of the processed log.

Damage to the softwood did not exceed 1 cm. The pine timber was affected to a greater extent than the spruce.

There was no difference in the damage level between the top and middle logs.

There is a risk of secondary defects such as discolouration, which can cause a lower efficiency in plywood production from valuable assortments.

The findings within this paper suggest that further research into this field is recommended, taking into account the following variables: other broadleaved forest species of different wood hardness, high quality assortments (mainly veneer and plywood timber), the harvesting season, and varying harvester heads.

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