Impact of Season and Harvester Engine RPM on Pine Wood Damage from Feed Roller Spikes

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Abstract

*Harvesters have become a common solution for wood harvesting in coniferous and broadleaved stands. Unfortunately, not every customer will accept logs with damage on the lateral surface of the roundwood caused by feed roller spikes. The extent of the wood damage caused by the spikes of harvester heads depends mainly on the type of feed rollers and tree species. The objective of the study was to investigate the external damage to pine (*Pinus sylvestris L.*) roundwood from harvester head spikes depending on the season of the year and harvester engine RPM, as well as the significance and potential consequences of such damage. The scope of the study also included an analysis of wood damage depth in three stem sections. The experimental plots selected were all in an 85-year-old pure pine stand. Logging was performed using a Ponsse Beaver harvester with an H60e harvester head manufactured in 2006. The mean depth of wood damage at all the points of measurement was 4.1 mm, while the maximum depth of wood damage totalled 5.3 mm. The depth of wood damage depended on the season of the year in which the logging work was performed, the harvester engine RPM and the stem section from which the log was processed. The damage was the deepest during summer operations and the shallowest during winter and springtime. The differences were statistically significant, however, the difference in the depth of damage was only 1 mm in average. Deeper wood damage was found at a lower engine RPM. Wood damage depth differed axially, and the least damage was found in the bottom logs.*

Keywords: bark loss, harvesting head, mechanised logging, pilodyn, Pinus sylvestris L.

1. Introduction

Nowadays, harvesters can be used for wood harvesting in coniferous and broadleaved stands (Mederski et al. 2016). Currently, due to cut-to-length technology (CTL), more roundwood of better quality is sold as short logs to sawmills, plywood and furniture manufactures. Unfortunately, not every customer will accept logs with damage on the lateral surface of roundwood (throughout the bark) caused by feed roller spikes. During mechanised harvesting, the bark of the processed logs may be removed, thus reducing the degree of protection it can offer to the wood. Regardless of species, bark adhesion is the strongest in winter and early spring, between December and April, and the weakest (nearly non-existing) in late spring and summer, between May and August (Simonov 1984, after Aniszewska and Więsik 2015), probably

because of the activity of the cambium (Uzunović et al. 1999). In mechanised logging processes, bark is usually peeled off longitudinally by the delimbing knives, which may remove strips of bark or both bark and wood. The season and the ambient temperature significantly affect resistance – as the temperature decreases, the shear strength of both the bark and wood increases (Aniszewska and Więsik 2015). Damage to the outer layers of wood associated with bark stripping is easily recognized and often criticised, even though it also occurs on logs prepared using a chainsaw (Spinelli et al. 2011) and is usually accepted. The extent of this damage may differ depending on the season of the year during which logging is performed and on the method of processing (short or long wood system). Perforation of the roundwood surface influences, for example, its technical properties, and causes the roundwood to dry out more rapidly, which is un-

desirable in paper production (Warkotsch 1994). Winter is considered a better time for logging (Lee and Gibbs 1996, Uzunović et al. 1999, Murphy and Pilkerton 2011, Murphy and Acuna 2017). During spring and summer, with a higher air temperature and moisture, secondary wood defects may occur, such as blue stain. Wood damaged on the lateral plane by the harvester is susceptible to fast and deep penetration of fungi (Lee and Gibbs 1996). As buyers expect a consistent year-round supply of roundwood on the market, logging also takes place in those months when the risk of secondary depreciation of the product is higher.

Besides weather conditions, the extent of damage may be affected by technical considerations related to the use of logging machinery and its condition. Before work, operators set up harvester computers taking into consideration tree species, type of assortment, length and diameter of assortment, as well as length tolerances. Moreover, harvester engine revolutions per minute (RPM) may be adjusted by the operator in order to reduce fuel consumption. Lower RPM means that the hydraulic pumps operate with less power, which affects the speed and torque of the feed rollers. This may in turn reduce logging output, as well as decrease delimbing efficiency, and thus potentially cause increased damage to the roundwood due to repeated attempts to delimb. As the literature indicates, bark adhesion depends on the season and it is at its lowest during late spring and early summer. Therefore, it was hypothesised that roundwood damage from feed roller spikes would be most severe in summer. It was also hypothesised that a higher RPM might cause deeper spike penetration in the wood as more aggressive rotations could cause greater damage. Thus, the purpose of this study was to investigate and highlight any differences in terms of the external damage to pine (*Pinus sylvestris* L.) roundwood from the harvester head spikes depending on the season of the year and engine RPM, as well as the significance and potential consequences of such damage. In addition, the scope of the study included an analysis of wood damage depth in three stem sections (bottom, middle and top) and pilodyn penetration tests (Giefing 1985) in areas adjacent to the damage sites. Pine was selected as the species of analysis as it is a common species cut by harvester in Central Europe and Baltic countries (Moskalik et al. 2017).

2. Material and methods

2.1 Area of study

The experimental plots were selected in a 11.95 ha pure pine stand, on sandy soil located in Dąbrowa Forest District, central Poland. The stand age was 85 years,

the mean DBH was 27 cm, the height was 22 m, and the standing volume totalled 281 m³/ha (Forest Management Plan 2007). The stand was of moderate density and of an average technical quality. The thinning intensity was 30 m³/ha. Access to the stand was provided by a network of machine operating trails, spaced 20 m apart axis-to-axis. The processed assortments were stored near the trail.

The study was performed during the four seasons at various ambient temperatures: winter (February, air temperature from 0 to +1 °C), spring (April, from –2 to +4 °C), summer (September, from +14 to +23 °C), and autumn (November, from +8 to +10 °C). During the study, all the trees were processed into industrial wood, with a length of 2.50 m.

2.2 Machine characteristics

Logging was performed using the Ponsse Beaver harvester equipped with an H60e head. The harvester had 27,000 hours of work at the beginning of the research (Table 1).

Table 1 Basic technical specifications of Ponsse Beaver harvester with H60e head

Harvester	
Year manufactured	2006
Engine	MB OM 904 LA
Engine power, kW (hp)	170 (228)
Hydraulic fluid, l	208
Software	OPTI 4G
Operating pressure, MPa	20–24
Required oil flow, l/min	240–300
Harvester head H60e	
Feed system	Bogie roller assemblies with spike rollers
Feed rollers, no	4
Gross feed force, kN	24
Feed speed, m/s	0–5
Spike length, mm	20
Spike width at base, mm	15
Hydraulically movable knives, no	3
Largest opening, mm	600

The work was performed by one operator who worked day and night shifts interchangeably in each season. The operator had 500 hours of experience on

the harvester. Firstly, the harvester head measuring system was calibrated (to obtain an accurate length and diameter) by a Ponsse technician giving instructions to the operator, who performed the subsequent calibrations.

2.3 Study design and measurements

The wood damage from the feed roller spikes, understood as wood damage depth, was tested with respect to the following criteria:

⇒ season of the year in which the logging was performed: winter, spring, summer, or autumn

⇒ harvester engine RPM (two of the most common setups): low (1600 RPM) or high (1750–1800 RPM)

⇒ section of the stem from which the log was cut: bottom, middle, or top. The bottom section was the first butt log, the middle section was any log located between the butt and top log, and the top section was the last log with a diameter of at least 7 cm overbark at the top end.

The wood damage depth was measured using the depth gauge of a Mitutoyo digital caliper. To obtain an accurate depth, the bark was removed and then a chisel was used to detach a chip of wood damaged by the feed roller spikes according to methods described in earlier research (Karaszewski et al. 2016b). The measurements were performed in the middle of a log from each tree section: bottom, middle and top. The six most severe damage points (the widest openings) were measured on each log. The caliper was also used to measure the thickness of the bark (with phloem) near the damage depth measurement site (one site being six neighbouring measurement points). The damage depth and bark thickness measurements were performed at an accuracy of 0.01 mm. For further analyses, the mean and maximum damage depths from each measurement site were used. The mean bark thickness was used to analyse the impact of the parameter on wood damage depth. Additionally, the overbark log diameter was measured at the damage depth measurement site, using a caliper with a precision of 1 mm.

Wood susceptibility to mechanical damage was tested using a Pilodyn 6J. This instrument has a steel cylinder (penetrator) of 2.5 mm in diameter and 600 mm in length, used for measuring the penetration depth in wood at a constant energy of 6 J. Pilodyn tests were performed on the cut logs, with and without bark, at the damage depth measurement sites. The penetration depth with bark was understood as the total length of penetration through the bark and wood

tissue. Penetration depth without bark was measured only in the wood tissue, after manual removal of the bark. Pilodyn penetrations were taken twice for each type: with and without bark, and mean values for each group (with and without bark) were calculated.

2.4 Statistical analysis

An analysis of variance was performed preceded by the Fligner-Killeen test for variance homogeneity and Pearson's test for distribution normality. Post hoc tests were performed using Tukey's test. If conditions for parametric analysis of variance were not met, the Kruskal-Wallis test and Dunn's test would be used. A significance level of α=0.05 was used for all the analyses. A Pearson's correlation matrix was calculated for the mean and maximum damage depths, log diameter, bark thickness, and pilodyn penetration depth with and without bark. Statistical analyses were provided using the R 3.3.1 software (R Core Team 2017).

3. Results of the study

The depth of wood damage from the feed roller spikes was analysed on a total of 102 stems, cut into 306 logs (Table 2). In total, 1836 measurements of wood damage depth and 1836 measurements (306 logs x 6 measurement depths per log) of bark thickness were taken. A total of 612 Pilodyn penetration depth measurements were performed with bark and without bark. The mean depth of wood damage by the harvester head spikes at all the points of measurement was 4.1 mm, while the maximum depth of wood damage at all these points totalled 5.3 mm.

Table 2 Log parameters by stem section

Logs	n	Length cm	Mid diameter cm±SD	Bark thickness mm±SD
Bottom	102	250	20.8±3.4	7.9±2.5
Middle	102	250	16.3±2.6	2.6±1.1
Top	102	250	12.3±2.5	2.0±0.6

The analysis of variance showed a significant interaction between the three parameters – season, harvester engine RPM, and the stem section, which impacted the mean damage depth (p=0.0468). The damage depth was the greatest in summer, at a lower RPM, and in logs cut from the top stem section (mean depth = 6.0 mm, maximum depth = 7.2 mm), while the least damage was caused in winter and autumn, at a
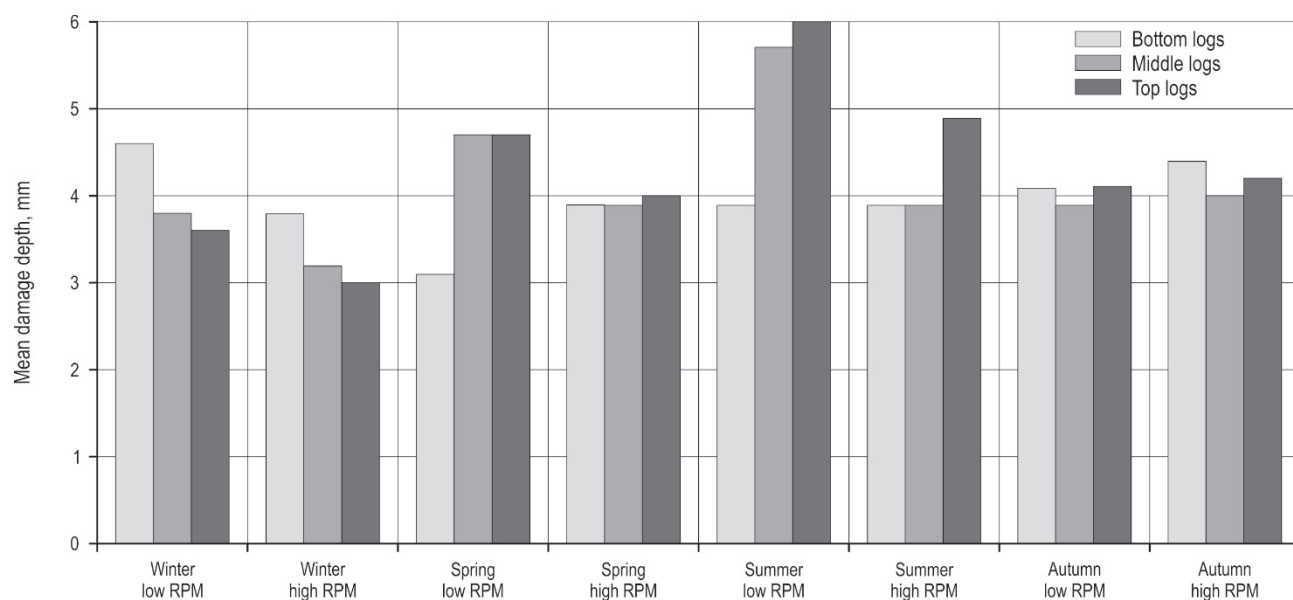
Fig. 1 Mean damage depth by season

higher RPM, in logs from various sections (mean depth = 3.0 and 3.1 mm, and maximum depth = 4.7 and 3.9 mm, respectively; Fig. 1).

An analysis of all three factors showed a complex system of interrelations. In order to present clear differences, the factors were considered independently, in relation to season, engine RPM and section of the stem.

The mean damage depth varied according to the season and ranged between 3.7 mm in winter and 4.7 mm in summer (Table 3). The maximum damage

depth ranged from 5.0 mm in spring to 5.8 mm in summer (Table 3).

The damage depth was greater at a low RPM, both in terms of the mean (+0.4 mm) and maximum values (+0.6 mm, Table 3).

The mean and maximum damage depth on the processed pine stems differed axially and reached from the bottom to the top: 3.9, 4.1 and 4.3 mm on the butt, middle and top logs, respectively. The maximum depth was 1.1–1.4 mm greater than the mean values (Table 3).

Table 3 Mean and maximum wood damage depth according to harvesting season, engine RPM and stem sections (with basic statistics: minimum, maximum values and standard deviation SD)

| Criteria	Sample size no of logs	Depth of damage							
		Mean value mm	Min. mm	Max. mm	SD	Maximum value mm	Min. mm	Max. mm	SD
Winter	60	3.7	2.0	7.1	1.0	5.3	2.5	9.0	1.5
Spring	78	4.0	2.2	6.6	0.9	5.0	2.7	7.9	1.1
Summer	78	4.7	2.4	7.2	1.2	5.8	3.3	9.8	1.6
Autumn	90	4.1	2.0	6.8	1.0	5.2	2.7	8.3	1.2
Low RPM	147	4.4	2.0	7.2	1.1	5.6	2.7	9.8	1.4
High RPM	159	3.9	2.0	7.0	1.1	5.0	2.5	8.7	1.4
Bottom logs	102	3.9	2.0	7.1	1.1	5.0	2.7	9.0	1.4
Middle logs	102	4.1	2.0	6.6	1.0	5.3	2.5	8.9	1.2
Top logs	102	4.3	2.0	7.2	1.1	5.7	2.5	9.8	1.4
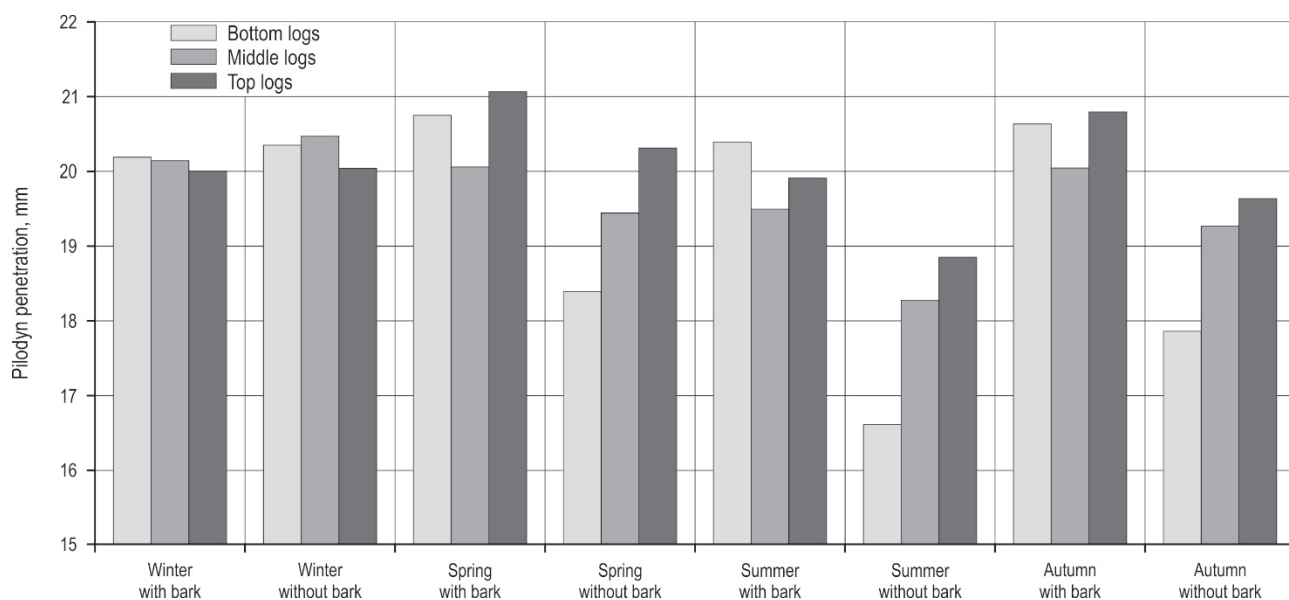
Fig. 2 Pilodyn penetration depth with and without bark by season for bottom, middle and top logs

The mean pine bark thickness was 4.2 mm when combining all stem sections. The bark thickness decreased from the bottom to the top of the stem (Table 2).

The shallowest penetration depths with bark (20.1 mm) and without bark (18.0 mm) in all the sections were found in summer (Fig. 2). In winter, the penetration depth with and without bark was similar and considerable in all sections (20.3 mm and 20.4 mm, respectively). The penetration depth without bark tended to be the shallowest in the bottom logs, greater in the middle logs, and the greatest in the top logs (Fig. 2). Statistical analysis confirmed significant differences in the pilodyn penetration depth without bark between the bottom and middle logs ($p<0.0001$), and between the bottom and top logs ($p<0.0001$). The

penetration depths with bark were more similar, and significant differences were found between the bottom and middle logs ($p=0.0020$), as well as between the middle and top logs ($p=0.0287$).

No correlation was found between the mean or maximum damage depth and pilodyn penetration depth. As the bark thickness increased, the damage depth of the wood decreased, though the relation was weak, at $r=-0.2$ (tab. 4). As expected, the bark thickness increased along with log diameter, with $r=0.7$.

4. Discussion

4.1 Seasons

The wood damage depth differed in the analysed seasons (Table 3), but in all the cases, its value varied widely, as reported in previous studies for pine and spruce (Nuutinen et al. 2010, Karaszewski et al. 2016a), birch (Nuutinen et al. 2010) and alder (Karaszewski et al. 2016b).

With regard to seasons, the wood damage depth was found to be shallowest at low air temperatures (between –2 and +4 °C), in terms of both the mean and maximum depths (Table 3). The decreased wood damage depth in winter might also have been due to better bark adherence during this season. Bark adherence to the wood affects the impact of the delimbing knives on their bark shaving, or may affect the presence of bark on the log. When the bark can be stripped with less force, as is the case during the late spring and summer in Europe, the delimbing knives may debark

Table 4 Correlation matrix

Characteristic	Mean damage depth	Maximum damage depth	Mean bark thickness	Diameter
Mean damage depth	1.0	0.9	–0.2	–0.3
Maximum damage depth	0.9	1.0	–0.2	–0.3
Diameter	–0.3	–0.3	0.7	1.0
Pilodyn penetration with bark	0.1	0.1	0.1	0.1
Pilodyn penetration without bark	0.0	0.1	–0.3	–0.2

the log and, as a consequence, the harvester head spikes scar the exposed wood. However, if the bark remains on the assortment after delimbing, the resistance of the bark during the short initial contact with the spikes prevents deeper damage to the wood itself. According to Murphy and Pilkerton (2011), bark loss from processed wood may be five times higher in late spring and early summer than in winter. In order to limit bark loss, rubber rollers have been suggested as an alternative to the steel ones used in the present study (Lee and Gibbs 1996; Murphy and Acuna 2017). However, currently this is not a popular choice under European conditions. Suggestions for: 1) a decrease in the length and increase in the number of feed roller spikes, aimed at improving the contact surface between the roller and wood (Warkotsch 1994), and for 2) the monitoring of machine performance (Gerasimov and Seliverstov 2010) are reflected in new technical (Sowa et al. 2013) and organizational solutions (Błuszakowska and Nurek 2016).

As expected, bark thickness changed axially, and was greatest in the bottom section. The depth of wood damage was negatively correlated (weakly) with bark thickness, although the least damage was found in the bottom logs, where the bark was the thickest, and the most damage was found in the top logs, with the thinnest bark. These results are comparable to the findings and observations made by Nill et al. (2011), who reported a decreasing susceptibility to damage in tree species, which tend to form thicker bark layers. According to Nill at al. (2011), among deciduous species, beech, which has a relatively thin periderm layer, was the most susceptible to damage during logging. Moreover, in coniferous tree stands, species with thick bark, such as Douglas fir, pine, or larch, were much less susceptible to damage than spruce, which has a relatively thin bark. However, damage seen in the thin-barked fir and spruce differed significantly, which indicates that there are other significant factors affecting a species' susceptibility to damage. Despite the similar bark thickness, fir was more resistant to damage during logging than spruce (Nill et al. 2011). This is supported by the findings of Kohnle and Kändler (2007), who pointed to the potential significance of anatomical bark features, such as sclerenchyma cells, often found in fir bark (but not in spruce bark), which may offer better resistance against spike penetration.

4.2 RPM

At a lower engine RPM, the feed rollers of the harvester head caused significantly more damage while processing the logs than at a higher RPM (Table 3). A lower RPM slowed the movement of the spikes on the round wood surface. As a result, this probably gave the spikes more time to penetrate the wood tissue, and, therefore, the damage was more severe compared to the cases when a higher RPM was applied. The larger mean damage found in the top logs (compared to the logs from other stem sections, Table 3) was consistent with observations by other authors (Uzunović et al. 1999, Gerasimov and Seliverstov 2010, Karaszewski et al. 2016b), although this finding was likely not only due to the branching of this section, but also due to its thinner bark and the lower mechanical resistance of the juvenile wood (Tomczak et al. 2010). This was confirmed by the pilodyn tests (Fig. 2), with statistically significant differences between the bottom, middle and top logs. Van der Merwe et al. (2015) reported yet another reason for the larger damage found in top logs, pointing to the relationship between the frequency of the feed roller movement along the processed stem (which is usually the greatest for top logs) and increased wood damage, also associated with fibre loss.

4.3 Pilodyn

In order to investigate possible associations between wood resistance to penetration and damage depth, pilodyn tests were performed. The pilodyn penetration depth in fresh pine wood is only slightly affected by moisture content (Giefing and Kokociński 1991), which motivated the choice of pilodyn as a testing instrument. Contrary to expectations, the pilodyn penetration in the wood without bark was deepest during winter (Fig. 2). This divergence between the initial assumptions and findings was also reflected in the lack of correlation between the parameters studied, which was also true in the case of pilodyn penetration with bark (r=0.1 in both cases; Table 4).

The maximum wood penetration depth for Pilodyn 6J is 40 mm (Giefing 1985). Pilodyn penetration depth is correlated with wood density in coniferous trees (Giefing and Jabłoński 1988), and in dry wood it is correlated with its hardness, r=–0.70 (Giefing and Romanowska 1992). However, pilodyn penetrates wood at a constant energy of 6 J, while the pressure of harvester head feed rollers can be higher or simply variable, which may also explain the unexpected results and lack of correlations. Summarising the pilodyn penetration tests, it should be concluded that factors other than resistance to pilodyn penetration were associated with wood damage depth, and that the instrument did not satisfactorily simulate the damage caused by harvester head spikes.

Aside from the scientific investigation of the differences in mean and maximum damage depth, practical implications can be derived from the assessment.

Damage on the roundwood surface is a natural consequence of harvester use and has a negative impact on wood quality (i.e. there is a risk of blue stain rendering the wood unattractive after further processing). Although the differences between damage depths in each season were statistically significant, the observations may be considered of little importance. In fact, although a spike damage depth between 1.0 and 1.5 mm may be insignificant for most timber-sector customers, the fact that damage occurs is important. In practice, such defects caused by harvester-related damage (spike damage) up to 2 cm depth, defined by technical specifications for medium-sized logs, are considered allowed in some European countries. These results provide an opportunity for further development of harvester heads (feed rollers in particular) for coniferous and broadleaved species in lowland forests (Moskalik 2002a, Moskalik 2002b, Więsik et al. 2005, Mederski et al. 2016, Moskalik et al. 2017) and highland forests (Visser and Stampfer 2015, Enache et al. 2016).

5. Conclusions

The following conclusions were drawn from the results:

⇒ The wood damage caused by the harvester head spikes depended on the analysed factors: the season of the year in which the logging work was performed, harvester engine RPM and the stem section from which the log was processed. These factors had a varying impact on wood damage and their interaction was statistically significant.

⇒ The wood damage depth differed according to the season. The damage was the deepest in summer and the shallowest during winter and springtime.

⇒ Contrary to the hypothesis, deeper wood damage was found at 1600 RPM: a mean of 4.35 and a maximum of 5.61 mm, respectively. When 1750–1800 RPM was used, spike penetration was shallower: 3.92 and 5.04 mm (mean and maximum), respectively.

⇒ The wood damage depth differed axially: the least damage was found in the bottom logs (mean 3.9 mm, max. 5.0 mm), more in the middle logs (mean 4.1 mm, max. 5.3 mm), and the most damage was found in the top logs (mean 4.3 mm, max. 5.7 mm).

⇒ The pilodyn penetration depth was not correlated with wood damage depth. However, the penetration depth increased axially from bottom to top, which was consistent with the axial increase in damage from the harvester head spikes (without considering the bark).

⇒ In practical terms, seasonal differences in the depth of damage from feed roller spikes may have little impact on customers' decisions. They may be more significant in the case of plywood processing, where the outer layer is the most valuable, or when the roundwood is used as the final product. The use of a lower harvester RPM results in lower surface roundwood quality – a higher RPM should be used to limit damage to the surface of the roundwood from feed roller spikes.

6. References

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