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Moisture Content of Fresh Scots Pine Wood in Areas near Damage Caused by Harvester Head Feed Rollers

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Abstract: By damaging bark, mechanized harvesting deprives wood of its natural mechanical barrier. This study concerns the effect of this damage on the changes in moisture content that occur near the damaged areas of Scots pine (*Pinus sylvestris* L.). This study was carried out using 45 randomly selected 11 m long logged pine stems. Additionally, the effect of bark thickness on the depth of damage was measured. To determine the influence of the location of the damage and bark thickness on the wood moisture near the damaged region, wood samples were collected from two sections. The first was located one meter above the log's base, while the second was located one meter from the end of the log. Two increment cores were taken by a Pressler borer in each section: one from the damaged wood zone and the second from the undamaged wood zone. The average bark thickness one meter from the base of the log was 11.2 mm, which decreased to 1.8 mm in the samples taken one meter from the top of the log. The average depths of the damage caused by feed roller spikes in the two sections were 3.9 and 3.8 mm, respectively, indicating that there was no significant effect of bark thickness on the depth of the damage. The wood samples collected near the damaged wood zone (DW) had about 13 percent lower moisture content than those taken from the undamaged zone (UDW). This difference was statistically significant. We observed greater mean moisture content closer to the top of the log for both the samples taken near the damaged zone and the samples taken from the undamaged zone. One meter from the base of the log, the moisture content difference between the DW and UDW was 9.8 percentage points, which was statistically insignificant. By contrast, significantly lower moisture content (−16%) was observed in the DW one meter from the top of the log.

Keywords: timber; mechanized harvesting; wood moisture; blue stain; wood defects

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1. Introduction

The process of harvesting timber using only machines, for example, harvesters and forwarders, is termed fully mechanized harvesting. In comparison to motor-manual felling and processing via chainsaw, multifunctional machines (i.e., harvesters) allow for an increase in work productivity while boosting occupational safety and reducing environmental impacts [1–4]. Moreover, according to Latterini et al. [5], various authors have proven that in some cases, fully mechanized harvesting may even have a lower impact on biodiversity than the use of lower mechanization levels. On the other hand, mechanized harvesting can also have negative impacts on the environment such as soil disturbance [6,7] and felling and extraction damage inflicted on the remaining trees [8–10]. Soil damage may reduce forest growth, and the damage inflicted on the remaining trees can range from lower timber quality to mortality [5,8]. On the other hand, Spinelli et al. [1] proved that mechanization significantly increases harvesting productivity. Moreover, the appropriate adjustment of the settings of the machines used in the cut-to-length (CTL) harvesting method may positively affect fuel consumption and decrease CO_2 emissions [11].

The demand for forestry equipment, including harvesters, has been increasing in the last few decades [12,13], and this trend will probably grow even further [14]. The growing utilization of these machines is largely related to increased harvesting efficiency and ergonomic aspects like safer working conditions for the operators. For example, in Poland in 2016, harvesters were applied for only 13% of total harvested timber [15], while in 2021, this value reached 46% [16].

The main operational component of a harvester during logging is the head. This is a multi-operational tool for felling, delimbing, cutting, and even measuring trees [17]. The harvester head consists of five main units: a positioning unit, a cutting unit, two to four feeding rollers, a delimbing unit, a length-measuring wheel, and two additional units, namely, a marking unit and a parceling unit [18]. The compositional material and design of the head have a great influence on both work productivity and the degree of damage inflicted on the processed logs [19]. A harvester's feeding rollers have spikes on their surfaces that help to move the trees during processing. The spikes on the rollers vary in terms of height, thickness, and position on the rollers. The most common feeding rollers are made of steel [17]. As an alternative to entirely steel rollers, rollers enriched with rubber are also used, and these rubber components improve the friction applied to the timber during processing. According to Węgrzyn et al. [20], this type of design has the potential to reduce the damage inflicted on the wood and to better protect against vibration. Nevertheless, steel rollers have a higher operating efficiency than rollers incorporating rubber elements [17,21].

When logging with a harvester, damaging the bark and wood surface is unavoidable. According to the literature, we can distinguish three types of damage during wood processing: bark loss [22], chips in the ends of the bucked logs [23], and damage inflicted on the wood surfaces of the processed logs caused by feed rollers. This kind of damage is due to the movement of the head feed rollers during the cut-to-length process. Deep damage may reduce the amount of high-quality timber harvested [17]. Damage depth is affected by several factors, such as species, bark thickness, the harvesting system employed, roller and spike size, roller speed (measured in revolutions per minute—RPM), and even season of the year [24]. In one study, the deepest damage was observed in summer [24]. It was also shown that the depth of damage is affected by the location on the stem. In general, logs on the lower part of the stem suffer the least damage [24,25]. Apart from lowering the economic value of the damaged logs [26], deep damage to timber caused by feed rollers can create ripe conditions for blue stain development [27]. Lee and Gibbs [28] pointed out that blue stain occurs more frequently in the case of logs processed by harvesters than by chainsaws. Similar findings were reported by Szewczyk et al. [29]. This phenomenon can be related to the fact that the damage caused by the feeding rollers of the harvester head can partially remove bark, thus depriving wood of a natural barrier [30].

Blue stain is a discoloration of sapwood typically caused by ophiostomatoid fungi. These fungi develop in the damaged regions of freshly felled timber, especially pine and spruce logs [31,32]. Blue stain is visible in the form of blue, grey, or even black streaks on the sapwood and has only aesthetic implications for infected timber [33]. However, even this color alteration can lead to decreased prices for the damaged logs [34].

According to the literature on this topic, wood damage can increase the incidence of blue stain in comparison to semi-mechanized felling and processing [28,29]. Based on this, we speculate that there is a correlation between the moisture content (MC) of damaged wood and the development of discoloration, especially blue stain. Therefore, the objectives of this study were as follows:

(I) Investigate the effect of the harvester head feed rollers' spikes on the moisture content near the damaged regions of Scots pine (*Pinus sylvestris* L.);
(II) Examine if the distance from the base of the log and bark thickness have an impact on the depth of the damage and the moisture content in damaged zone.

We made the following hypothesis: (i) in the zone near the damage caused during harvesting, the moisture content of wood is lower than that in the undamaged zone; (ii) bark thickness and the distance of the damage from the base of the log do not influence moisture content.

2. Materials and Methods

2.1. Study Design

This study was conducted in two stands located at logging plots in western Poland (GPS coordinates N: 52°40′29″; E: 16°47′29″). The stands were predominantly populated by Scots pine (*Pinus sylvestris* L.) and have similar ages (89 and 94 years old). The two stands are located in regions with similar edaphic conditions corresponding to a fresh coniferous forest growing on podzolic soil. The average diameter at breast height in both the parcels was 30 cm, with an average tree height of about 25 m. The study was conducted on randomly selected logged pine stems obtained via clear-cutting interventions carried out in the two cutting blocks. In total, 45 logs were selected. All the trees were cut by two harvesters: PONSSE Ergo (Ponsse, Vieremä, Finland) and Timberjack 1270D (H. Serup Olesen A/S, Brande, Danmark). The head of PONSEE—H7 was equipped with 3-feed-roller system with a 30 kN feed force and 5 m/s maximum feeding speed. The maximum cutting diameter for this head is 640 mm. The second harvesters' head—HD 758—was equipped with 4 feed rollers with a feed force of up to 30 kN and a feeding speed of up to 5 m/s. The maximum cutting diameter of the head was 720 mm.

To minimize the effects of air drying, samples were collected immediately after trees were logged and cut to 11 m length. To determine the influence of the location of the damage along the log and the bark thickness on the moisture content near the damaged zone, samples were collected from two sections. The first section (I) was located one meter from the base of the log, while the second section (II) was located one meter from the end of the log. These parameters were considered while accounting for the fact that the moisture content of wood can vary when moving vertically along the stem [35,36] and that the bark thickness of Scots pine varies, ranging from thick bark near the bottom of the tree to very thin bark on the upper parts of the stem [37]. Two increment cores were taken using a Pressler borer (Haglöf Sweden AB, Långsele, Sweden) in each section (Figure 1a–c): one from the damaged wood zone (DW) and the second from the undamaged wood zone (UDW). Each sample was collected from the sapwood zone without bark and was about 3 cm in length and 5.15 mm in diameter. In total, 180 wood samples were collected. In places where damaged wood samples were collected, we also measured the depth of the damage caused by feed roller spikes and the bark thickness around the damaged area, with an accuracy of 0.01 mm, using an electronic Vogel caliper (Vogel Germany GmbH & Co., KG, Kevelaer, Germany). For future analyses, these results were rounded off to the nearest tenth of a millimeter.

2.2. Measurement of the Properties of the Wood

After labeling, the mass and length of samples were measured on-site immediately after every tree had been logged. The mass was calculated using an electronic scale with an accuracy of 0.001 g (Steinberg Systems SBS-LW-200A, Berlin, Germany). Length (L) was measured with an accuracy of 0.01 mm using a certified Vogel caliper (Vogel Germany GmbH & Co., KG, Kevelaer, Germany). The diameter (D) of each sample was ascertained by referring to the details provided by the manufacturer, who reported a value of 5.15 mm (Haglöf Sweden AB, Långsele, Sweden). Subsequently, the volume of samples was measured using the dimensional method suggested by Pérez-Harguindeguy et al. [38].

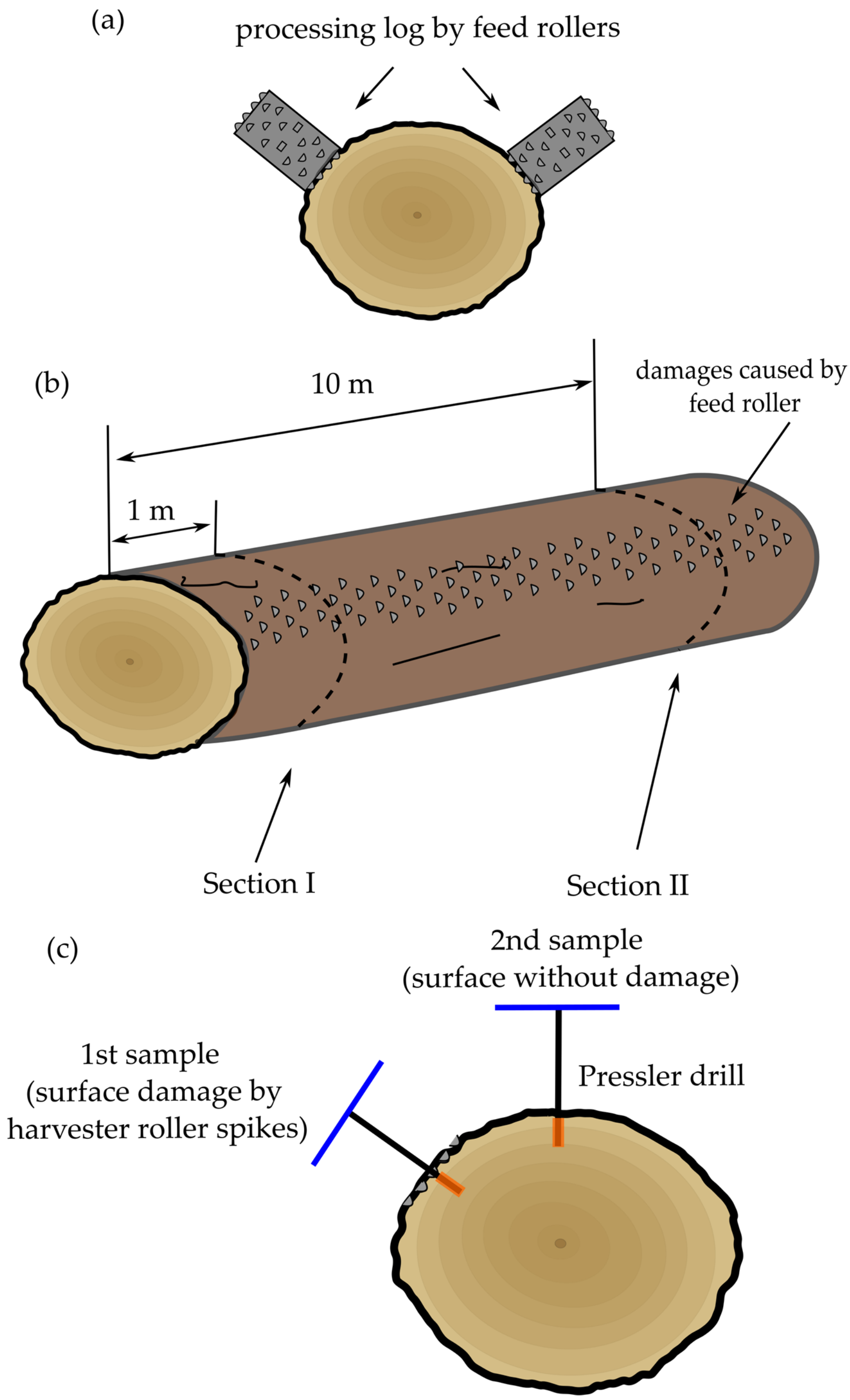

Figure 1. Labelling of samples of harvested logs: (**a**) log's processing, (**b**) section localization, and (**c**) collection of samples.

Based on the measured length and diameter, the volume of each sample was calculated using Equation (1)

$$V = \pi \times (0.5 \times D)^2 \times L \qquad (mm^2) \qquad (1)$$

where: V—volume; D—diameter of the sample = 5.15 mm; L—length of the sample.

Once the field measurements of the fresh wood had been taken, all the samples were transported to the laboratory. The next step involved the placement of the samples in an electric muffle furnace at 105 °C to be oven-dried. Drying continued until 0% water content and a constant sample mass was reached. Samples were then weighed and measured in their dried state. Based on these measurements, we specified absolute moisture content (MC) using Equation (2) according to the standard provided in [39]:

$$MC = ((mm - ms)/ms) \times 100 \quad (\%) \quad (2)$$

where: mm—mass of fresh sample; ms—mass of dry sample.

2.3. Statistical Analyses

To compare loss in moisture content values, the data were analyzed statistically. The first step consisted of using the Shapiro–Wilk test to verify the normal distribution of the data. This test assumes that a statistically significant result makes it possible to reject the hypothesis of the normal distribution of data. Accordingly, as the assumption of normality had been rejected, we applied the non-parametric Mann–Whitney U test. All statistical tests were performed with a significance level $\alpha = 0.05$. The Statistica 13.1 (TIBCO Software Inc., Palo Alto, CA, USA) and R (R Core Team, 2021) software products were used for calculations and visualizations.

3. Results and Discussion

3.1. Mean Absolute Moisture Content

The average absolute moisture content of wood was 84.10% for the UDW and 71.17% for the DW (Table 1). This result is similar to the wood absolute MC of the undamaged wood of birch and oak observed by Tomczak et al. [40] and Tomczak et al. [41].

Table 1. Descriptive statistics of absolute moisture content (%). DW: damaged zone and UDW: undamaged zone. SD: standard deviation; Q25: first quartile; Q75: third quartile.

Type of Wood	Mean	SD	Min	Max	Q25	Median	Q75
DW	71.17	26.67	29.53	141.71	51.40	63.91	87.56
UDW	84.10	30.85	42.86	161.67	58.87	80.00	102.84
Mean	77.63	29.47	29.53	161.67	53.52	70.77	96.18

The wood samples collected from the damaged zone (DW) of the logs were characterized by an approximately 13-percentage-point lower moisture content value than that of the undamaged zone (UDW). The differences observed between the two zones were highly statistically significant. There are no previous findings in the literature that might explain the lower MC in the damaged zone. These results might have been precipitated by the spikes of the harvester head feed rollers having squeezed out water. The compression force applied by the feed rollers of the harvester head on the tree stem is high in order to ensure operational efficiency, i.e., the rapid transportation of the felled trees. Therefore, the wood was exposed to compressive force at many points along with subsequent mechanical damage. This can be partially corroborated by the study conducted by Lee and Gibbs [28], who reported that the damage caused during harvester processing increased the drying of stacked timber.

3.2. Bark Thickness and Damage Depth

The average depth of the damage caused by the feed roller spikes was 3.9 mm. This is shallower than that reported in the results presented by [17,25], who noted a depth of damage in pine timber ranging from 4.2 mm to 8.7 mm. The depth of damage depends on many factors, such as the roller and spike size or the roller speed. According to Nuutinen et al. [17], the quality of wood can be impaired by deep damage. Under Polish regulations [42], the depth of damage that downgrades the quality of roundwood assortment is 20 mm for both softwoods and hardwoods. The deepest damage in our study was noted at about 12.2 mm and was located in the first section, which was situated one meter from the base of the log. Therefore, according to the Polish regulations [42], no measured damage during our study affected the quality of the wood. Karaszewski et al. [24] stated that the damage caused by harvester-feeding rollers should be lower in the lower part of the stem. However, in our study, no statistically significant difference was found between the damage in the two sections, despite the fact that the bark in the higher part of the stem was significantly thinner, as is common for Scots pine (Table 2).

Table 2. Bark thickness and damage depth arranged by section.

			Bark Thickness [mm]				
Section	Mean	SD	Min	Max	Q25	Median	Q75
I	11.2	5.7	5.1	30.5	7.7	9.1	12.2
II	1.8	1.4	0.7	8.0	1.0	1.3	1.8
All	6.5	6.3	0.7	30.5	1.4	5.8	9.1
			Depth of damage [mm]				
I	3.9	2.3	0.7	12.2	2.5	3.6	4.9
II	3.8	1.9	1.3	10.6	2.7	3.4	4.3
All	3.9	2.1	0.7	12.2	2.5	3.5	4.6

3.3. Absolute Moisture Content for Each Section

Higher average moisture content was noted in the second section, which was located closest to the top of the tree, amounting to 86.4%, while in the first section, an average value of 69% was noted. This finding is due to an increased moisture content level in the vertical span from the base of the log to the top of the tree [43,44]. We also observed greater differences between the DW and UDW in the second section. The differences in this section, located in the 10th meter of the log, amounted to app. 16.1 percentage points and were statistically significant, while the differences obtained in the first section amounted to 9.8 percentage points and were statistically insignificant (Figure 2).

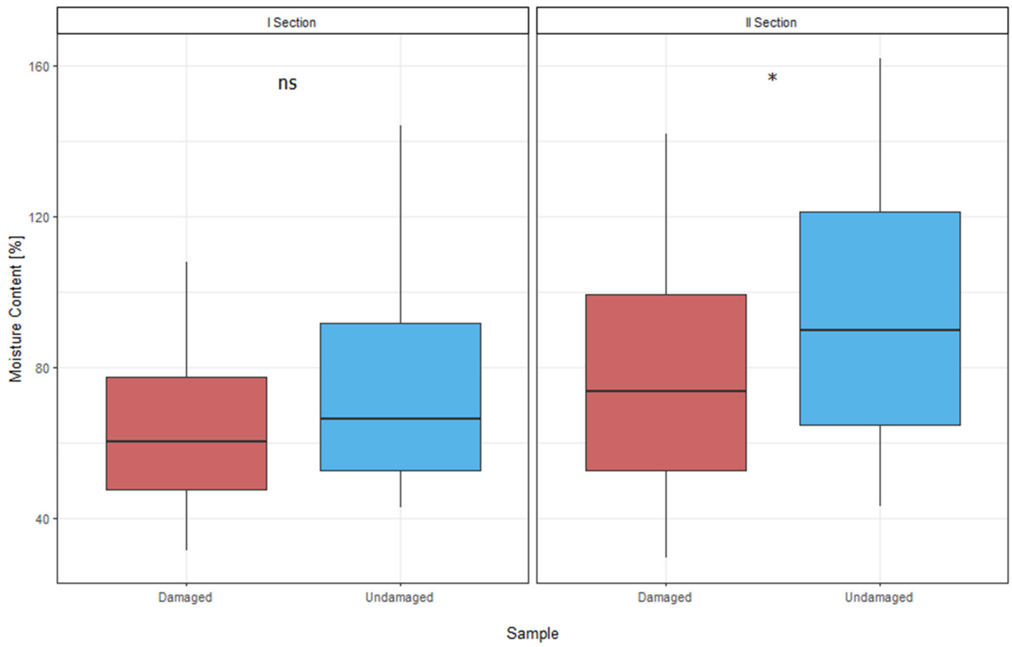

Figure 2. Distribution of moisture content in the sections of large-sized wood assortment examined, which have been arranged by wood type. The significance of the differences is marked * for p value < 0.05, and ns for no significant differences according to the results of the Mann–Whitney U Test. Whiskers correspond to minimum and maximum values, boxes represent the 1st and 3rd quartile values, and midlines indicate the median.

3.4. Possible Consequences for the Quality of Wood

Differences in moisture content have no influence during processing. On the other hand, they may cause discoloration, such as that engendered by blue stain. It has been proven that in places where damage occurs, a breeding ground for blue stain is created [27,45]. The problem of the faster occurrence of blue stain in timber harvested by harvesters has been recognized. However, it is not clear why this happens. In this study, we tried to answer the question of whether damage caused during harvester-based log processing provides better conditions for fungal development, except with respect to creating open damage on a log's surface. Wood is a hygroscopic material, and the stems of freshly cut trees have high moisture content. Immediately after felling, wood begins to dry out. After logging, we noticed many areas with lower moisture on the surface of the stem. We think that the loss of moisture creates the conditions for the quicker development of discoloration, especially blue stain, in the damaged areas (Figure 3a,b). Lee and Gibbs [28] established that logging with a chainsaw (motor-manually) precipitates less blue stain than logging with a harvester. The results reported by Millers et al. [46] confirm our hypothesis. At an average air temperature of 18 °C, for instance, the first signs of blue stain on logs (logs) processed by the harvester appeared after 17 days, while they appeared after 23 days on logs prepared by means of a chainsaw. Typically, however, the authors relate the amount of blue stain to the amount of bark damage. Bark limits natural drying, so even partial debarking of the stem by a harvester head significantly accelerates moisture loss [47,48].

(**a**) (**b**)

Figure 3. (**a**,**b**) Blue stain in damaged zones.

Bark is a tree's natural protection against blue stain. The fungus penetrates the wood in exposed areas, i.e., on the log faces, sometimes through severed branches, and also through bark damage, including damage caused by the feed rollers of the harvester head. Fungi penetrating from the periphery of the stem proceed to create a greater number of infection foci and develop in all directions. Infection arising from areas of bark damage is, therefore, more dangerous than infection that spreads from the frontal section.

In principle, blue stain does not affect the mechanical properties of wood. It is true that some species of fungi, e.g., *Aureobasidium pullulans*, rot cellulose and may attack the cell membrane, causing the wood to absorb moisture more easily, but this has no technical significance for wood used in building and construction. It only reduces the aesthetic appearance of wood; however, this implies the generation of a serious economic impact [34].

3.5. Perspectives of Future Studies

The main aim of this study was to confirm two hypotheses about the connection between mechanized harvesting and changes in the absolute moisture content of logged timber and the possible lowering of wood quality. We noticed significant differences in moisture content between the damaged and undamaged wood, especially when the bark was thinner. Therefore, the obtained results can be helpful not only in understanding the specific influence of MC on the occurrence and severity of stem damage [30], but also with respect to determining the impact of mechanical damage on the development of secondary damage caused by wood discoloration. According to the current literature, damage can increase the incidence of blue stain in comparison to semi-mechanized felling and processing [28,29]. Based on this, we conclude that the MC in damaged areas can significantly impact the development of discoloration, especially blue stain. Future confirmation of this theory will provide an opportunity to address the development of fungi that precipitate the degradation of wood quality.

4. Conclusions

The results presented herein concern timber of the most popular species in Central Eastern Europe, namely, Scots Pine, which is perfectly suitable for fully mechanized harvesting. We found statistically significant differences between wood samples from the damaged zone and undamaged zone. We also divided logs into two sections and found statistically significant differences in only the second section, which was located ten meters from the base of the stem. No effect of bark thickness on damage depth was found. We observed greater differences in moisture content between the DW and UDW in the second section. It is difficult to explain the role of the direct impact of feed roller damage on wood discoloration. However, we think that it may provide a condition for fungal development at many locations by creating open damage on a log's surface. In summary, we consider that the loss of moisture content in the damaged zones of the log is one of the factors for the quicker development of discoloration, especially blue stain in pine wood. However, this statement should be confirmed in future studies.

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