Damage to Trees from Wood Extraction in Motor-Manual Wood Harvesting Technologies in Thinning of Pine Stands

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Abstract

The purpose of this research was to assess the damage caused by the extraction of wood harvested with chain-saws in thinnings in pine tree-stands, 35, 52 and 69 years old. Two methods of wood extraction were applied, in one case the wood was dragged with an agricultural tractor or a horse, and in the other case wood was extracted with a 10-ton forwarder. The investigations were conducted in Oborniki Forest District in western Poland. The horse and tractor skidding was carried out in variants with strip-roads or without them, while the extraction of wood with the forwarder was on strip-roads only. The distance between the strip-roads was 30 m, while their widths were about 1.5 m for the horse, 2.5 m for the agricultural tractor and 3.5 m for the forwarder. The analysis presented in the paper focused on the shares of the damaged trees and differences in the numbers and frequencies of wounds in damage classes, related to the technology applied. The damage was divided into classes according to three criteria: depth (1-bark, 2-phloem, 3-wood), the wound place (stem, root crown, roots), and the damage causing factor (machine/horse, the wood/payload). The damage on trees in all the damage classes was statistically more significant in technologies with wood skidding than in technologies with wood forwarding, whereas the damage to the phloem was more frequent in the technology with the forwarder (no class 3 damage to the wood was observed). When the wood was skidded with the horse or the tractor, the wounds to the root crowns were statistically more frequent, while during the forwarding the damage to the stems dominated. As to the factor causing the damage, in the case of the forwarding operation, the machine was the main cause; while in the case of wood skidding the damage was usually caused by the wood (payload).

Key words: thinning, skidding, damage, horse, agricultural tractor, forwarder

Introduction

Despite a clearly visible increase in the number of harvesters used in Poland in the latest decade (Mederski et al. 2016), the majority of wood is harvested with motor-manual methods, with chain-saws used for felling and tree processing, and skidders, agricultural tractors or even horses for wood extraction. In these technologies, the damage is mainly caused in course of wood extraction (Porter and Porter 1998, Fröding 1987), cited from Johansson et al. (2000), Tavankar and Bodaghi 2011, Tavankar et al. 2013) and the resulting injuries may lead to diminished wood increment (Isomäki and Kallio 1974, Tavankar et al. 2017) and lower quality of wood in final fellings (Kieser 2011). One of purposes of sustainable forestry is to limit damage from tree felling and wood extraction (Sist and Nguyen-Thé 2002). Some damage in wood harvesting operations is unavoidable and it can affect even a considerable percentage of trees (Vasiliauskas 2001). Both the numbers of damaged trees and the size of the wounds depend on the time of the year (Wästerlund 1986, Sirén 2001, Limbeck-Lilienau 2003), the method of harvesting (Spinelli et al. 2010, Marchi et al. 2014), strip roads (Fries 1976, Gullison and Hardner 1993, Athanassiadis 1997, Kosir 2008) and skills of machine operators (Froehlich 1976, Crome et al. 1992, Jourgholami 2012).

The damage to trees occurs mainly in tree stands, where thinning operations are performed, especially in technologies with long wood skidding (Jourgholami 2012, Tavankar et al. 2015). The cut-to-length wood harvesting method (Pulkki 2004) with wood extraction realized by forwarders was introduced to Poland in the mid-1990s. Today, this way of wood extraction is more and more often used, and the proportion of wood dragging and skidding is consistently diminishing.

A commonly used measure for assessing the damage to trees is the percentage of trees with wounds. Other measures, like synthetic (Suwała 1999) or weighted coefficients (Sosnowski 1999, Karaszewski et al. 2013) are used more seldom. The damage assessment may also focus on the relations or links of the damage to factors that can potentially cause them (Bobik 2008, Bembenek et al. 2013a, b).

The purpose of this paper was to assess the damage to trees caused by wood extraction performed with primitive methods (dragging by a horse or agricultural tractor) and more modern ones, e.g. extracting wood with a forwarder. Also, the effects of strip roads were studied, when using simple wood extraction methods, with tractors or horses moving on strip roads or directly among trees in the tree stand.

Materials and Methods

The experiments were carried out in Oborniki Forest District (Figure 1), in western Poland, in 35, 52 and 69-year-old pine tree-stands, planned for thinning operations. In each stand four experimental plots were established and marked, on which the wood was harvested and then extracted with different technologies. In each technology the trees were felled with chain-saws. In all the tree-stands the following technologies were used:

Figure 1. Location of the research area, Oborniki Forest District

- LW-H-NoS – long wood (LW), skidding with a horse (H), no strip roads (NoS),
- LW-AT-S – long wood (LW), skidding with an agricultural tractor (AT) on strip roads (S),
- SW-F-S – short wood (SW), extraction with a forwarder (F) on strip roads (S).

Moreover, a LW-H-S variant (horse skidding of long stems on strip roads) was investigated in the youngest stand, and a LW-AT-NoS variant (skidding long stems with a tractor without strip roads) was tested in the two older stands.

Table 1. Characteristics of the investigated stands

Age [years]	Technology	Plot area [ha]	Number of trees after thinning [pcs./ha]	Trees removed		Thinning intensity [%]*
				Number [pcs./ha]	Tree volume [m^3]	
35	LW-H-NoS	1.27	2258	1608	0.012	17.6
	LW-H-S	0.99	2232	1646		18.2
	LW-AT-S	0.82	2152	1865		20.4
	SW-F-S	1.19	2073	2040		23.8
52	LW-H-NoS	1.51	895	246	0.11	10.9
	LW-AT-NoS	1.56	895	246		10.9
	LW-AT-S	1.83	871	298		12.8
	SW-F-S	1.78	854	314		14.4
69	LW-H-NoS	0.87	754	206	0.16	11.1
	LW-AT-NoS	0.87	754	206		11.1
	LW-AT-S	1.26	744	241		13.1
	SW-F-S	1.52	802	235		12.9

* percent of removed timber

The agricultural tractor was not equipped with a winch. Its weight was 2,170 kg, and it was 3.6 m long and 1.8 m wide. The weight of the forwarder was 11,000 kg, and its length and width were 9 and 2.7 m, respectively. The long wood was on average 7.7 m long in the 35-year-old stand, and 13 and 14 m long in the older stands. The logs forwarded with the forwarder were 2.4 and 2.5 m long in the youngest stand, and 1.8, 2.4 and 2.5 m long in the 52 and 69-year-old tree stands. The distance between the strip roads was ca. 30 m, and their widths were ca. 1.5 m (horse), 2.5 m (tractor) and 3.5 m (forwarder). Due to the lack of a winch on the tractor, in the case of the LW-AT-NoS (long wood with tractor, no strip roads) in the 35-year-old tree stand, the delimbed tree stems were first manually brought to the strip road and then hooked to the tractor with chains. In the same variant, but in the older tree-stands and in the LW-H-S (long wood with horse on strip roads) variant in the youngest tree stand, the tractor or the horse left the strip roads in order to approach the lying wood, and the extraction was realized partly among trees in the tree-stand and partly on the strip road. The worker extracting the wood with the horse had three years of experience, the agricultural tractor operator had been working for 7 years and the operator of the forwarder had four years of experience. The tree stands, where the trials were conducted, are characterized in Table 1. Because in the technologies used the tractors or the horse moved on the strip roads and partly among the trees, the damage to the trees was assessed with the full inventory method (the entire area of the experimental plots was covered by the assessment) (Jourgholami 2012, Badraghi et al. 2015). The damaged trees on the plots were counted and qualified, according to the classification used by Giefing et al. (2012), which was reduced to three classes reflecting the depth of the wounds (class 1 – bark, class 2 – phloem, class 3 – wood). Also, the position of the wound on the tree (stem, root crown, roots) as well as the cause of the damage (machine used, horse, wood being extracted) were analysed. The root crown was the first 30 cm aboveground segment of the stem (Yilmaz and Akay 2008). Altogether, 2,185 cases of tree damage were assessed.

Next, the proportions of the damaged trees were also broken down according to the cause of the damage, the wound depth and the position of the wound on the stem. In order to statistically verify the results obtained, the relations between:

• the technology and the damage type,

• the technology and the position of the wound (stem, root crown or roots), and

• the technology and the causing factor (machine/horse or the load) were assessed.

In the case of the LW-H-NoS, LW-AT-S and SW-F-S technological variants, used in all the tree stands, and the LW-AT-NoS variant in the 52 and 69-year-old stands, relations between the stand age and the damage observed were analysed. In those cases, in which the relations were visible, the significance of differences in damage frequency between all the technologies and all stand ages was analysed pairwise. A chi-square test (sometimes with Yates's correction) was used, less often Fisher's exact test (Łomnicki 2006), and the computations were performed using Statistica 12 software package (StatSoft 2014). The level of significance was $\alpha = 0.05$.

Results

The damage to the trees that was found in course of the research was limited to the bark and the phloem (classes 1 and 2), and no damage to the wood (class 3) was observed. The shares of the damaged trees in damage classes 1 and 2 showed large differences between the youngest stand and the older ones. Regardless of the stand age, large differences between the SW-F-S variant and the others were found (less damage in the young stand and in the SW-F-S method – Table 2). Similarly, the SW-F-S technology caused the least damage to the root crown zone. Among the remaining technological variants, the LW-AT-S in the 52-year-old stand caused the most damage to the root crown zone, with over 3 % of the trees showing wounds.

At each stand age the connection between the technology used and the damage to the trees was statistically proven (p = 0.000) (Table 3). In general, the statistical analysis showed that the damage was statistically more frequent in variants with skidding compared to variants with forwarding. They were more frequent in variants in which the agricultural tractor was used compared to variants with the horse and in the variant with the agricultural tractor with no strip roads compared to the same variant, in which the wood was skidded on strip roads.

Also, the frequency of wounds reaching the phloem was linked to the technology applied (p = 0.00) which was true for the results observed in each of the stands as well as for the results from all the stands combined (Table 3) The wounds in the phloem zone were statistically more common in the SW-F-S technology than in the other variants, and in the variants with the tractor (LW-AT-NoS and LW-AT-S) compared with the variant with the horse (LW-H-NoS).

The research also confirmed a relationship between the position of the wound (stem, root crown, roots) and the technology used (regardless of the age, the p = 0.00). In general, the stems were more often damaged than the root crowns when the wood was extracted with the forwarder, compared to skidding with the tractor or the horse. It was also found that skidding wood with the tractor moving in the stand without strip roads compared to that on strip roads caused statistically more damage to the stems than to the root crowns.

Statistically significant relations for almost all of the analysed pairs of technologies were also found between the technological variants and the direct cause of the damage (skidding machine, horse, the payload) (p = 0.00) (Table 3). No significant relations were only found between the LW-H-S and LW-AT-S variants in the oldest tree stand. In the youngest stand in the LW-H-S and LW-AT-S variants the damage was caused by the pay-

Table 2. Damage characteristics, by quantity

Age [years]	Damage	Share of damaged trees by technology [%]				
		LW-H-NoS	LW-H-S	LW-AT-NoS	LW-AT-S	SW-F-S
35	in damage classes 1-3	6.1	5.9	-	10.4	1.2
	in damage class 2	0.5	0.7	-	0.7	0.5
	on root crown	0.4	0.6	-	0.4	0.2
	causing factor - machine	-	-	-	-	100
	causing factor - payload	100	100	100	100	-
52	in damage classes 1-3	25.4	-	24.2	23.9	1.2
	in damage class 2	2.4	-	4.8	4.6	0.5
	on root crown	2.4	-	2.5	3.2	0.2
	causing factor - machine	-	-	56	20	75
	causing factor - payload	100	-	44	80	25
69	in damage classes 1-3	22.0	-	30.5	25.3	0.6
	in damage class 2	1.1	-	4.1	4.7	0.1
	on root crown	0.4	-	2.4	2.8	-
	causing factor - machine	-	-	42	29	100
	causing factor - payload	100	-	58	71	-

Table 3. Results of statistical analysis of relations between technology and the damage class, place of damage and the causing factor

Age [years]	Pair of technologies tested	*p* values of χ^2 test for different damage aspects			
		all damage classes	damage class 2	place of damage	damage causing factor
35	LW-H-NoS vs. LW-H-S	0.744	0.286	0.820	**0.040**
	LW-H-NoS vs. LW-AT-S	**0.000**	0.471	**0.003**	**0.013**
	LW-H-NoS vs. SW-F-S	**0.000**	**0.000**	**0.000**	**0.000**
	LW-H-S vs. LW-AT-S	**0.000**	0.079	**0.004**	-
	LW-H-S vs. SW-F-S	**0.000**	**0.000**	**0.000**	**0.000**
	LW-AT-S vs. SW-F-S	**0.000**	**0.000**	**0.005**	**0.000**
52	LW-H-NoS vs. LW-AT-NoS	0.475	**0.000**	**0.000**	**0.000**
	LW-H-NoS vs. LW-AT-S	0.351	**0.000**	**0.000**	**0.000**
	LW-H-NoS vs. SW-F-S	**0.000**	**0.001**	**0.000**	**0.000**
	LW-AT-NoS vs. LW-AT-S	0.843	0.823	**0.000**	**0.000**
	LW-AT-NoS vs. SW-F-S	**0.000**	0.070	0.310	**0.002**
	LW-AT-S vs. SW-F-S	**0.000**	0.141	**0.002**	**0.000**
69	LW-H-NoS vs. LW-AT-NoS	**0.000**	**0.008**	**0.000**	**0.000**
	LW-H-NoS vs. LW-AT-S	0.124	**0.000**	**0.000**	**0.000**
	LW-H-NoS vs. SW-F-S	**0.000**	0.358	**0.000**	**0.000**
	LW-AT-NoS vs. LW-AT-S	**0.022**	0.153	0.368	0.152
	LW-AT-NoS vs. SW-F-S	**0.000**	1.000	**0.040**	**0.003**
	LW-AT-S vs. SW-F-S	**0.000**	1.000	**0.021**	**0.001**
all stands	LW-H-NoS vs. LW-AT-NoS	**0.000**	**0.000**	**0.000**	**0.000**
	LW-H-NoS vs. LW-AT-S	**0.000**	**0.000**	**0.000**	**0.000**
	LW-H-NoS vs. SW-F-S	**0.000**	**0.000**	**0.000**	**0.000**
	LW-AT-NoS vs. LW-AT-S	**0.000**	0.511	**0.000**	**0.000**
	LW-AT-NoS vs. SW-F-S	**0.000**	**0.000**	**0.003**	**0.000**
	LW-AT-S vs. SW-F-S	**0.000**	**0.000**	**0.000**	**0.000**

values in bold mean that differences are statistically significant

load only. A comparison between the forwarding and the skidding operations showed that in the case of the forwarding more damage was caused by the machine rather than by the payload, while for the skidding operation the opposite was the case. The tractor caused the damage more often than the horse. When skidding with the horse, the payload in the form of tree stems was the main cause of the damage. When comparing technologies using the same skidding agent working either on the strip roads or in the tree stands without strip roads (LW-H-NoS and LW-H-S in the youngest stand and LW-AT-NoS and LW-AT-S in the elder stands), the factor causing the damage was the skidding agent in the variants with no strip roads, while in the variants with strip roads the damage was mostly caused by the skidded wood (payload).

According to the methodology applied, for each of the technologies studied the relation between the age of the stand and the damage level was analysed (all put together and in class 2). A valid relationship was found for the technologies with long stems being skidded (LW-H-NoS, LW-AT-S and LW-AT-NoS: $p = 0.00$), but not in the case of the SW-F-S technology ($p = 0.32$). In the case of the LW-H-NoS and LW-AT-S technologies, the damage was statistically more frequent in the older stands than in the youngest one ($p = 0.00$). Such differences were not found between the 52 and 69-year-old stands (LW-H-NoS: $p = 0.09$, LW-AT-S: $p = 0.43$). In technologies where the wood was extracted with the tractor, the damage was more common in the 69-year-old stand than in the 52-year-old one. In the case of the LW-H-NoS and LW-AT-S technologies a statistically significant relation was found between the stand age and the damage to the phloem ($p = 0.00$), while such a relation was not found for the SW-F-S and LW-AT-S technologies (SW-F-S: $p = 0.11$, LW-AT-S: $p = 0.49$). In the case of the LW-H-NoS technology significant differences in the frequency of class 2 wounds were only found between the youngest stand and the 52-year-old one ($p = 0.00$), but neither between the youngest and the oldest stands ($p = 0.11$) nor between the 52-year-old and the 69-year-old stands ($p = 0.05$). In the case of the LW-AT-S technology, the damage to the phloem was significantly more frequent in the elder stands than in the youngest one ($p = 0.00$). The 52 and 69-year-old stands showed no statistically significant differences in the frequency of this type of damage ($p = 0.89$).

Discussion

The results showed a differentiated level of damage from wood extraction. The damage level was affected both by the method of wood extraction as well as by the age of the stand. The technology using a forwarder caused the least damage, usually caused by accidental contact of the machine with the trees. The wood extraction by forwarders is an integral part of the cut-to-length method and many researchers stress a relatively low level of damage in the stands, where this technology is used (Hakkila 1995, Siren 2000, Limbeck-Lilienau 2003, Slamka and Radocha 2010). It is noteworthy that in the case of the other technologies, there was less damage when the wood was dragged with the horse than with the tractor. Higher levels of damage caused by the horse were reported long ago (Worhington 1961, Hunt and Krueger 1962), while Wang (1997) and Naghdi et al. (2009) reported more damage caused by skidders compared with mules. Dragging delimbed stems with an agricultural tractor in the oldest tree stand without any strip roads caused damage to over 30 % of the trees, whereas the same extraction method in a stand with skid roads (LW-AT-S) caused damage to over 25% trees. Similar results for skidding with a tractor in young fir and Douglas fir stands in California were reported by Aho et al. (1983). An insignificant difference between the variants with the strip roads and the ones without them (in the 53-year-old stand it was even smaller) resulted from the fact than in the LW-AT-S variant the tractor partly moved on the strip roads. Noticeable differences between the variants with and without strip roads in mechanized wood harvesting technologies were reported by Ostrofsky et al. (1986). The results suggest a need to limit machine movements among trees in the stand if there are strip roads present (agricultural tractors should be equipped with winches). The damage caused by the skidding variants, presented in this paper is in general larger than that found in scientific literature. For instance, in 37 and 42-year-old stands, Porter (1994) found 3 % of the trees damaged by horse skidding and less than 5 % damaged by a cable skidder. Suwała (2003) found that horse skidding and skidding by the tractor with a winch caused damage to 2.5 % and 5.3 % of trees in an early thinning and 4.4 % and 7.9 % in a late one, respectively. Slightly larger values were found by Erler (2005), who reported 10 % of trees damaged by horse skidding and 15 % by skidding with a tractor with a winch.

There are opinions in literature that stress methodological difficulties, when comparing results of the research into damage on trees (Sowa and Stańczykiewicz 2007). These difficulties result from different tree damage classification methods (Athanassiadis 1997, Walczyk and Duszyński 2007). It is our opinion that the above-mentioned difficulties can be enhanced by frequently encountered imperfect descriptions of the damage classifications used in the research and of the wood harvesting technologies, especially wood extraction which is the main cause of the damage in motor-manual technologies (Suwała 2003, Zastocki 2003). In this paper, the depth of the damage also reflected the scratches on the bark (class 1) which do not lower the value of the trees, but their frequent presence contributed to the increase in the participation of damaged trees. The share of this type of damage, depending on the technology used and the age of the stand, varied between 60 and 90% (Figure 2) Proportions of the trees with scratched bark at a level of over 50% in the whole technological processes were reported by Karaszewski et al. (2013) and Bembenek et al. (2013a). According to Butor and Schwager (1986), cited from Tsioras and Liamas (2010), damage to bark does not result in fungal infections. Disregarding such damage would result in damage level below 5 % for technologies with the extraction of long wood and 1.5 % for wood extraction with a forwarder. Similar results are reflected in literature (Hakkila 1995, Suwała 1995, 1999, 2003).

The research has shown a considerable difference in the proportion of the damaged trees, when using technologies with wood skidding, between the youngest and the two older tree stands, and the damage was statistically more frequent in the older stands than in the youngest one. Although results found in scientific literature often suggest the reverse (Wallentin 2007, Bobik 2008), this indicates a relation between the tree damage frequency and the dimensions of the extracted stems rather than a link between the tree damage extent and the number of trees remaining in the stand after thinning. These results are consistent with those reported by Suwała (1999), who proved a positive relationship between the

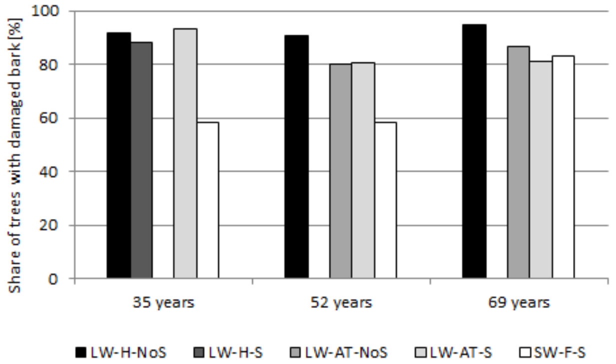

Figure 2. Bark damage in different technologies and stand ages

volume of the harvested trees and the damage intensity, but did not find any relationship between the damage coefficient and the number of trees remaining after thinning. A positive relation between the damage and the stand age (and the number of trees per area unit) was found for the technology with wood skidding, but not for wood forwarding (SW-F-S). Different results were reported by Karaszewski et al. (2013), who found significant differences in damage frequency between age classes for the short wood technology and a lack of them in the long wood method. Also, Heizman and Grell (2002), in their research on tree damage when thinning using the cut-to-length technology, reported larger damage values in denser stands.

Damage in the area close to the root crown is extremely dangerous to trees (Parker and Johnson 1960, Aho et al. 1983, Żółciak 1997). An analysis of this type of damage, presented in this paper, showed that, regardless of the tree stand age, there was a relationship between the damage and the technology, again with wood skidding rather than wood forwarding leading to significantly more frequent damage. The presence of damage to the root crown area during wood dragging with a winch, and on the lower part of the trees stem when extracting with a skidder was reported by Danilović et al. (2015) and by Jourgholami (2012) who investigated the damage when dragging the wood with a skidder winch to the strip road and then skidding on the strip road. The majority of the damage (71% to 81% depending on the wood length) occurred up to a height of 1 m, and the wounds were considered to be deep.

An interesting result was more frequent damage to root crowns by the tractor in the technology variant with strip roads (LW-AT-S) than in the variant without them (LW-AT-NoS) in older tree stands. The reason for this should rather be found in the fact that the tractor was not equipped with of a winch, and as a result of this, despite the presence of strip roads, the first stage of wood extraction had to take place inside the stand and only after bringing the wood to the strip road could continue the extraction on the strip road. Also, there were more entry points at which the tractor entered the strip roads, which was accompanied by violent changes in the driving direction (thus increasing the probability of damage to root crowns), compared to the technological variant without strip roads, where the tractor chose the shortest and if possible, the straight way to the landing.

Conclusions

1. Wood extraction with the forwarder moving exclusively on strip roads led to the least damage on trees. This technology caused statistically significantly lower frequency of damage in all damage classes except for the damage to the phloem, in which case the wood extraction by skidding led to less frequent damage.

2. Technologies using skidding caused damage to root crowns statistically more often, compared to wood extraction in the form of forwarding. Wood skidding with the agricultural tractor caused damage to root crowns statistically more frequently than skidding with the horse. Also, wood skidding with the tractor moving on strip roads led to more frequent damage to root crowns than skidding with the tractor in a stand without strip roads.

3. The wood extraction machine was statistically more often the causing factor of the damage in technologies with wood forwarding, compared to those with wood skidding. In the case of wood skidding, the agricultural tractor caused the damage more often than the horse, and the tractor moving in the stand without strip roads left more trees damaged than the tractor going on strip roads.

4. In the short wood technology no statistically significant effect of the stand age on the damage was found. In the other technologies, the damage was statistically more frequent in older stands than in the youngest one.

5. The role of strip roads in reducing the damage is rather limited when the machines extracting the wood leave the strip roads. If the strip roads are present, the machines should not leave them, because it can lead to more damage in the root crown area.

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