Damage to Soil and Residual Trees Caused by Different Logging Systems Applied to Late Thinning

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Abstract

This paper concerns the evaluation of logging systems in terms of the damage to the forest ecosystem. Damages to trees and soil during late thinning conducted in foothills areas in Poland using tree-length and cut-to-length logging systems were assessed. In both stands, the test plots were located within the primary and secondary skid trails. In the study, areas occupied by skid trails were determined as well as the depth of ruts. In order to determine changes in the soil properties at selected measurement points, a soil penetration resistance and a maximum shearing stress were measured. For each logging system, the share of trees damaged during harvesting operations and location of injuries were determined. The studies have shown that a 70% larger area was required to form technological trail with CTL than with TL. After CTL, skid trails were scarred by shallow ruts, and the share of ruts with the depth between 0.16 and 0.25 was three times smaller than after TL. The average increase in penetration resistance of soil in the ruts after TL was 324% and 302% and after CTL 308% and 220%, respectively, for primary and secondary skid trail, in comparison to the values obtained in measurement points located 5 m from the trails. In TL, comparable changes of soil properties were caused by skidder wheels and by hauled wood. The research has shown a greater share of damaged trees after TL. In both logging systems, the most damage was found within the root collar and lower parts of the bole.

Keywords: logging system, soil disturbance, damage to trees

1. Introduction

The main goal of forest management is to sustain continuous development of forest ecosystems that optimally fulfil their productive and non-productive functions (Gebauer et al. 2012, Jourgholami 2012). In order to achieve this goal, forest management should combine market demand, the economy of wood harvesting and requirements for forest environment protection (Zastocki 2003).

In recent years, a continuous increase in the level of wood harvesting mechanization has been recorded. In many cases, manual felling and logging by horses and farm tractors have given way to mechanized harvesting, using specialized felling (harvester) and logging (skidder, forwarder) machines (Ampoorter et al. 2010). Widespread use of specialized forestry equipment contributes to increase in productivity and improves work safety, but in some cases could also be associated with the adverse effects on the forest environment (Magagnotti et al. 2012, Picchio et al. 2016).

Logging is an example of the strongest human intervention into forest environment, causing many threats to its individual components. Damage to the forest ecosystem arises due to felling and skidding operations, regardless of the technical means used in this process. Many reports have indicated that most damage occurs during wood transportation from the stump area to the landing (Jamshidi et al. 2008, Cambi et al. 2015, Cambi et al. 2016). Disturbance of surface layers, changes in physical and chemical properties of soils and damage to residual trees are the main consequences of logging operations (Modry and Hubeny 2003, Ampoorter et al. 2007). Soil compaction is a serious disturbance due to physical properties caused by equipment used for skidding and forwarding. As a result of soil compaction, there is a decrease in porosity and increase in bulk density (Demir et al. 2007), penetration resistance and strength of the soil (McFero et al. 2006). Soil compaction causes a reduction of the number and activity of microorganisms (Tan et al. 2008) and edaphic fauna (Marchi et al. 2016, Venanzi et al. 2016) leading to disruption of the chemical processes in the soil (Arocena 2000). The common effects on the soil from ground based forest operations are increased compaction and removal of litter mass in skid trails (Tan et al. 2008). Damage to the soil contributes to the deterioration of conditions for tree growth and reduces the site productivity (Brais 2001, Gomez et al. 2002, Smith 2003). The problem of damage to remaining trees in the stand is the subject of many scientific studies. Damage to the residual stand in forest operations often occurs during timber extraction (Vasiliauskas 1993, Wronsky and Murphy 1994, Košir 2008, Picchio et al. 2012). Most trees damaged due to forest operations are situated close to the extraction trails (Froese and Han 2006, Youngblood 2000). Mechanical injury to residual standing trees are caused by machine traffic and log dragging (Klvač et al. 2010). Damage usually occurs right after treatment, but sometimes develops over time (Legere 2001, Ezzati and Najafi 2010). Damage to residual trees during selection cutting may decrease the quality of residual trees and increase stand mortality from insect and disease infestations (Han et al. 2000, Camp 2002).

Range and size of damage to forest ecosystem during harvesting activities depends on a number of factors related to, among others, machine mass, type and size of its tires, used logging technology and number of machine passes or skidding cycles (Alakukku et al. 2003). Not without significance is also the age of the stand, where the logging operations are carried out, the amount of removal trees, season and weather conditions (Lageson 1997, Limbeck-Lilienau 2003). An important role is also played by the level of training and ecological awareness of employees (Bragg et al. 1994, Sirén 2001).

A large number of factors affecting the level of damage to the forest ecosystem make the results presented in numerous scientific works not universal. It is primarily associated with natural and technological conditions of the logging process in different countries. There are few studies dealing with the comparison of damage to the forest ecosystem by different logging technologies during late thinning in a selection cutting system. The impacts on the environment, especially on soil and residual trees, is an important aspect to be considered in planning and execution of forest operations (Picchio et al. 2016).

The aim of the study was to assess the damage to forest soil and remaining trees after logging operations in late thinning performed using tree-length and cut-to-length logging system. The specific goals were:

To determine soil disturbance through appointment of the forest area occupied by skid trails and assess damage to the surface layers of the soil;

Assess damage to trees remaining in stands, by determining the percentage of damaged trees and the location of injuries.

2. Material and methods

The research was conducted in Poland (Lower Silesia) in Forest District Międzylesie, Forest sub-district Biała Woda in two selected forest stands No. 89a and 99b. Tree-length harvesting system (TL) was studied in forest stand No. 89a. TL included felling the tree

Table 1 Description of study site

Logging system Logging method	Tree-length (TL) Chain saw + Skidder	Cut-to-length (CTL) Harvester + Forwarder
Felling category	Late thinning	
Location – stand number	89a	99b
Area, ha	9.34	6.09
Altitude, m	790–870	850–910
Slope, °	13–17	8–12
Ground cover	Herbaceous	Grass-green
Type of habitat	Fresh montane mixed broadleaved forest	Fresh montane mixed coniferous forest
Share, % – Species	80 – Spruce 20 – Beech	100 – Spruce
Stand age, year	90	85
Average diameter at breast height (DBH), m	0.38 – Spruce 0.28 – Beech	0.30
Average tree height, m	26 – Spruce 23 – Beech	23
Stocking of merchantable timber, $m^3 \cdot ha^{-1}$	476 – Spruce 76 – Beech	326
Total harvesting volume, m^3	726 (660 Spruce + 66 Beech)	449
Removal from 1 ha, m^3	77	73
Time of harvesting	Spring	

Table 2 Specification of forest machines

	Harvester Gremo HPRV Head SP 551 LF II	Forwarder Gremo 950 R	Skidder LKT 81 T
Length, mm	7490	7895	5700
Width, mm	2600	2600	2230
Weight, kg	13,970	11,185	7145
Ground clearance, mm	580	580	540
Height, mm	3445	3445	2780
Number of wheels	8	8	4
Tire dimensions	600/50×22.5	600/50×22.5	16.9-30
Outreach of boom, m	10	6.5	–

using chain saw and wood extraction by a cable skidder LKT 81T equipped with two-drum winch with pulling force of 80 kN. Cut-to-length harvesting system (CTL) was studied in forest stand No. 99b. The CTL system included a harvester and a forwarder with loading capacity of 10,000 kg. Detailed information on the location and characteristics of the test stands are presented in Table 1. Information concerning the vehicles (machines) used in the logging process are shown in Table 2.

A survey of tree damage, rutting, soil penetration resistance and maximum shearing stress was conducted after wood harvesting operations. In both tested forest stands, the area occupied by skid trails was defined. A total length of skid trails was measured with a measuring tape. Rut depth measurements were performed on primary skid trails (more than 10 passes) and secondary skid trails (less than 5 passes). The depth of the ruts was measured at the designated lengths of 100 m, divided into 2 m sections. In each stand, 10 measuring sites were randomly selected (5 measuring sites on primary and 5 on secondary skid trail). Measurements were carried out in randomly selected rut. The depth of ruts was classified as follows:

⇒ <0.05 m (shallow)
⇒ 0.05–0.15 m (medium deep)
⇒ 0.16–0.25 m (deep)
⇒ >0.25 m (very deep).

The degree of tree damage and changes in the surface layer of the soil were determined at designated test sites. Tested areas in both forest stands were representative network of circles with a radius of 12.6 m (area of ca 0.05 ha). In each stand, 10 research plots were selected (5 within the primary skid trail, 5 within the secondary skid trails). Scheme of the test site and the location of the measurement plots are shown in Fig. 1.

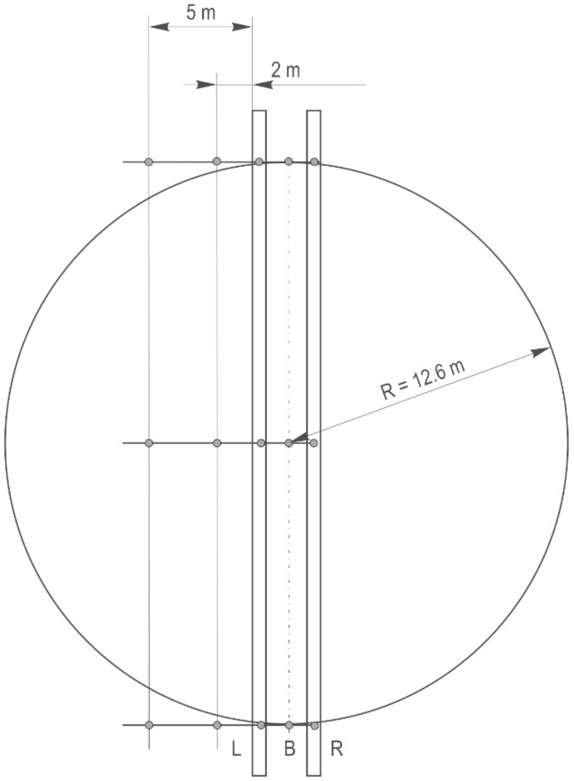

Fig. 1 The scheme of test sites – location measurement plots: L – left rut, B – between the ruts, R – right rut, 2 m from the rut, 5 m from the rut (control)

The evaluation of surface damage to the soil structure was carried out based on measurements of soil compaction (penetration resistance) and the maximum shearing stress. Compactness of soil in the layer of 0–0.2 m was measured using Penetrologger Eijkelkamp with a measuring range of 0–10 MPa and accuracy of 1 kPa. The instrument enabled the measurement and recording of data as a function of cone penetration depth. A cone with a base surface of 1 cm^2 and an angle apex of 60° was used for tests. Penetrologger was equipped with a Theta probe type ML2x to measure soil moisture with the accuracy of 1% vol. Soil humidity was measured in several points of each tested stand in the surface layer (0–0.05 m). The maximum shearing stress was measured using a shear tester with a wings probe made by Geonor company. The measuring range of the instrument was 0–260 kPa with the measurement accuracy of 2 kPa. Measurements were made at three depths: 0.05; 0.10; 0.15 m. Measurements of penetration resistance and maximum shearing stress at each plot were performed in five repetitions.

The percentage of damaged trees during logging operations was determined based on the number of damaged trees relative to the total amount of remaining trees in the stand on each test site. Mechanical damage to residual trees was classified according to their location:

⇒ root collar and bole at a height <0.3 m from the ground
⇒ bole at a height of 0.3–1 m
⇒ bole at a height >1 m.

The share of damage was specified for each class (different location) in relation to the total number of damaged trees.

The statistical analysis of the obtained results was conducted in the *Statistica 12.5* software. For the determination of factors impact, the multifactor analysis of variance (ANOVA) was used; the significance level α was equal to 0.05. Before carrying out the ANOVA tests, the terms of its applicability were verified (the normal distribution by Shapiro-Wilk test and the homogeneity of variance by Levene test). When the number of factor levels was higher than 2, the post-hoc tests (*HSD* Tukey) were conducted – these tests had to show the significant differences between each of the factor level.

3. Results

The total length of skid trails in both tested forest stands was different and amounted to 1920 m in the stand 99b and 1500 in the stand 89a. The width of skid trails amounted 3.0 m in CTL and 3.5 m in TL. Fig. 2 presents areas occupied by logging trails in the analyzed forest stands, where different systems of wood logging were used.

After TL, skid trails occupied 5.6% (0.53 ha) of the total area, trails were located at a distance of about 60 m from each other. Mechanized logging using harvester and forwarder requires a dense network of trails – after CTL, skid trails occupied 9.5% (0.58 ha) of the total stand area.

The 22–32 m distance between the trails was primarily dictated by the location of trees to be felled and to a smaller extent by the length of the harvester boom.

The soil humidity, measured during the tests, in both forest stands was comparable and amounted to 20–33% vol. Lower moisture values (20–26% vol.) was obtained in the undisturbed soil, higher soil moisture (24 –33% vol.) was observed within the skid trails and local terrain cavity.

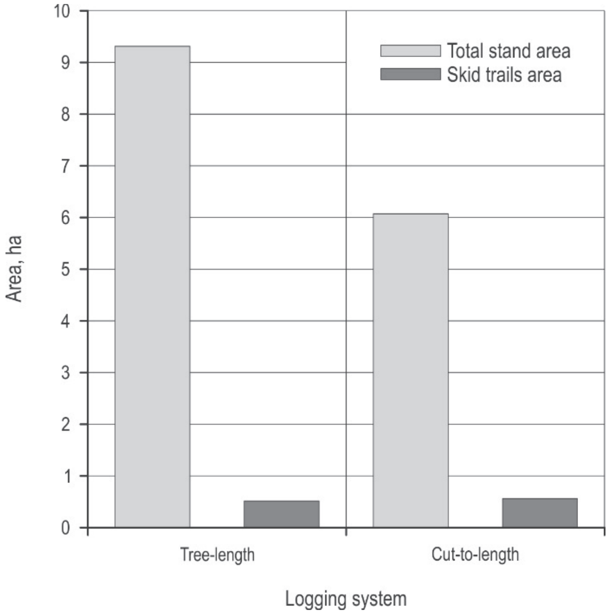

Fig. 2 The area occupied by skid trails in relation to the total area of study forest stands

The treatment effect on the share of the ruts of the total length of skid trails is shown in depth classes in Fig. 3. The data indicate that the extent of skid trails damage depends on the logging system and the number of machine passes. It was found that the greater diversity of ruts depth occurred in tree-length logging system (wood transported by skidder LKT 81T), than in cut-to-length logging system. In both logging systems, on the prevailing trail lengths shallow ruts occurred (<0.05 m); their share after TL was 49% and 64%, and after CTL 75% and 87%, respectively, on primary and secondary skid trails. In CTL, the share of ruts deeper than 0.05 m was significantly smaller compared to TL system. At the trails, where wood extraction with skidder was carried out, a share of ruts with depth of 0.16–0.25 m was three times greater than on the trails in stand 99b. After CTL, there were no very deep ruts (>0.25 m), while after TL, ruts in this depth class accounted for 4–6% of the skid trail length. The very deep ruts were located in the local cavity, where the ground was characterized by higher humidity. The differences in the range of skid trail damage were the result of differences in the size (width) of tires and number of wheels of forest machines. Tires with greater width had less tendency to penetrate deep into the soil. Greater number of wheels (8 wheels), in the case of forwarder, could result in a lower contact pressure. In addition, less damage to trails in CTL was probably the result of local trail surface protection by branches coming from harvesting operations.

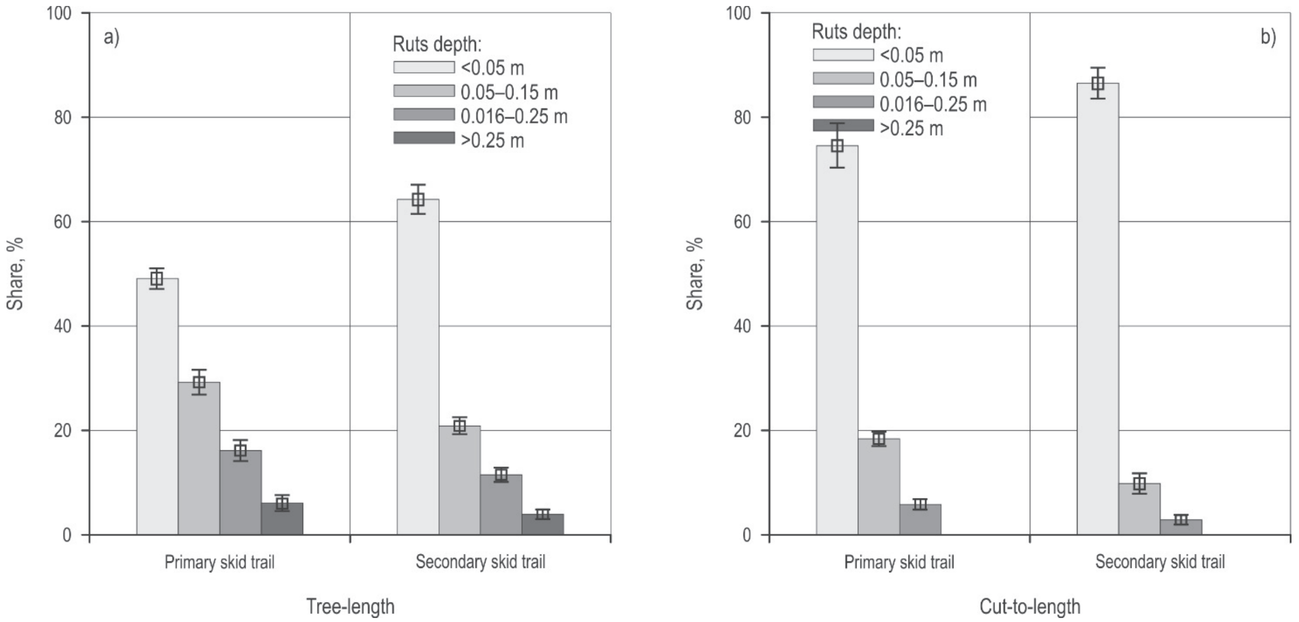

Fig. 3 The percentages of different rut depth on skid trails in tested stands (arithmetic mean ±SD); a) Tree-length; b) Cut-to-length

Fig. 4a, b and Fig. 5a, b show the course of changes in soil penetration resistance as a function of cone penetration depth in the analyzed harvest areas. Presented courses are related to measurements on research plots located at the primary and secondary skid trails. After TL (Fig. 4a, b), the maximum values of soil penetration resistance were exceeded by 5 MPa on the primary skid trail and by 4 MPa on the secondary skid trail. The average increase in soil penetration resistance in the layer 0–0.2 m, both on the primary and secondary skid trail, was similar and amounted to 324% and 302% compared to the values obtained for undisturbed soil at a distance of 5 m from the trails. Soil penetration resistance values measured at points spaced about 2 to 5 m from the trails (both primary and secondary) do not differ significantly, which indicates that the range of changes in soil properties concerns only skid trails. The largest increase in soil pen-

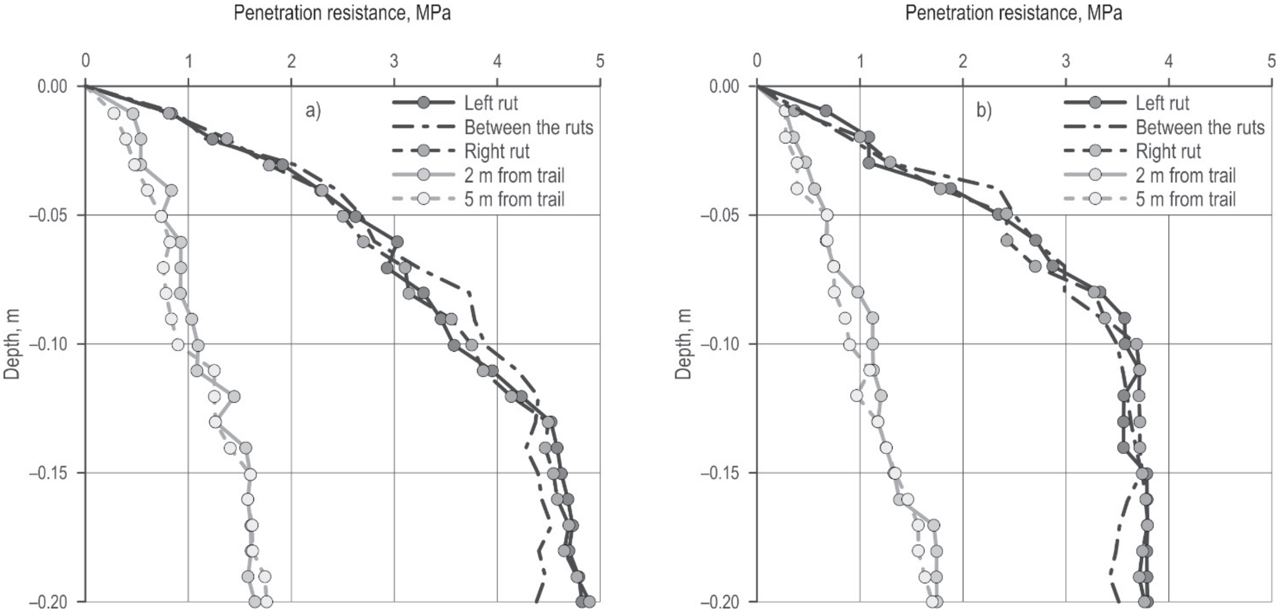

Fig. 4 Relationship between penetration resistance and soil depth in stand 89a: a) primary skid trail, b) secondary skid trail

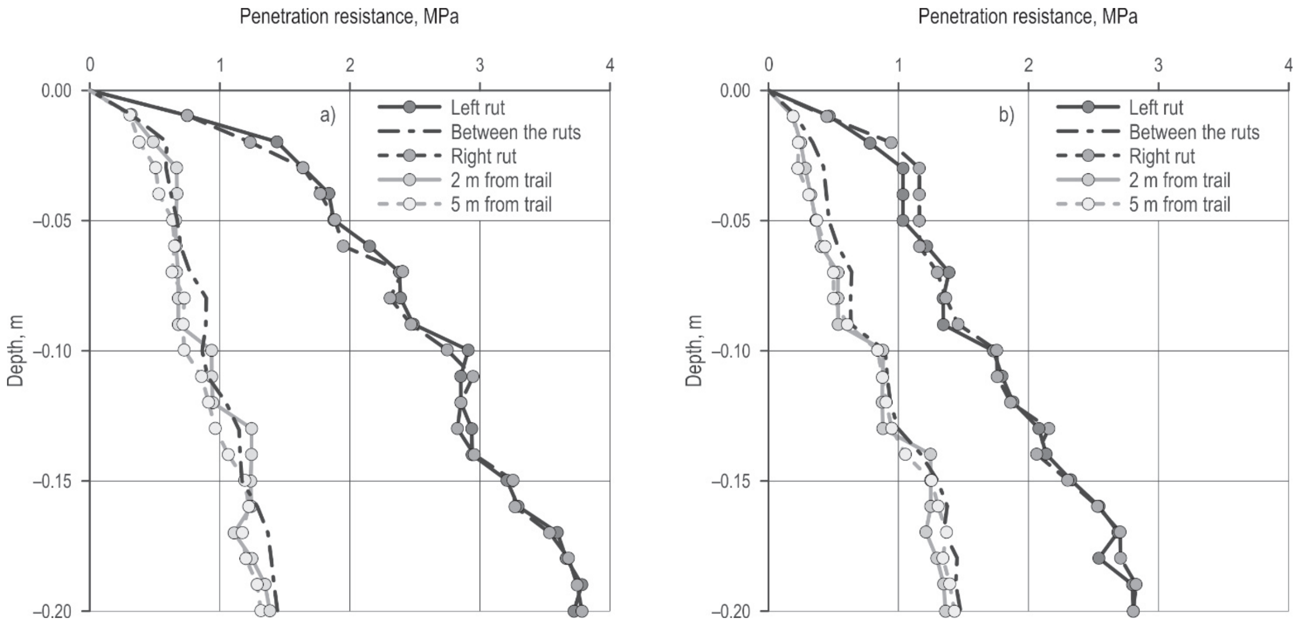

Fig. 5 Relationship between penetration resistance and soil depth in stand 99b: a) primary skid trail, b) secondary skid trail

etration resistance on the primary skid trail has been demonstrated in 0–0.13 m depth, and on the secondary skid trail in the layer 0–0.10 m. It was observed that, after TL, the impact of the skidder wheels and drawn wood led to a comparable increase in penetration resistance.

Courses of changes in the penetration resistance of the soil within the skid trails (primary and secondary) after CTL are shown in Fig. 5a, b. In case of cut-to-length logging system, the changes in soil properties were observed mainly in the ruts. The increase in penetration resistance of soil resulted from the weight of the machine and load of transported wood. The soil penetration resistance on the surface between the ruts was much lower than in the ruts, and in terms of value closer to the results obtained at a distance of 2 m from the skid trails. On the secondary skid trail, lower values were observed of soil penetration resistance than on the primary trail. In the analyzed depth range (0–0.2 m), the average increase in penetration resistance of soil in the ruts was 220% and 308%, respectively, for secondary and primary skid trail, in comparison to the values obtained in measurement points located 5 m from the trails. At a depth of 0.2 m in the ruts on the primary skid trail, the values of soil penetration resistance reached 4 MPa, while on the secondary skid trail these values do not exceed 3 MPa. After CTL, lateral range of changes of soil properties was negligible. It was indicated by the value of soil penetration resistance obtained at the measuring points outside the ruts.

Different waveform character presented in Fig. 4 and Fig. 5 indicate various susceptibility of the soil to compaction under the wheels of machines with different contact pressure.

The shearing stress strength of the soil is the parameter used to determine conditions of transferring a driving force from vehicle wheels to the ground. The values of maximum shearing stress, measured after TL, are presented in Fig. 6a, b. It was observed that the shearing stress strength of the soil, both on the surface of skid trail and beyond it, increased with the depth. Similarly as in the case of penetration resistance, the range of influence of skidder wheels and transported wood was limited to the trails surface. A higher shearing stress was found on the primary skid trail (average differences between values obtained on the primary and secondary skid trail amounted to 16%). On the primary skid trail, the highest values of maximum shearing stress were obtained in the furrow formed by hauled wood (between ruts), at depth of 0.05 and 0.10 m. On the secondary trail, used with less intensity, the highest values of maximum shearing stress in the furrow caused by hauled wood were found only at a depth of 0.05 m. The greatest increase in values of maximum shearing stress, compared to the values obtained at the control point (5 m from the trail), was observed at a depth of 0.05 m (values even higher than 700%). At greater depths (0.10 and 0.15 m), the values of the maximum shearing stress were smaller than the values obtained on the undisturbed soil. The obtained results confirmed the fact that the

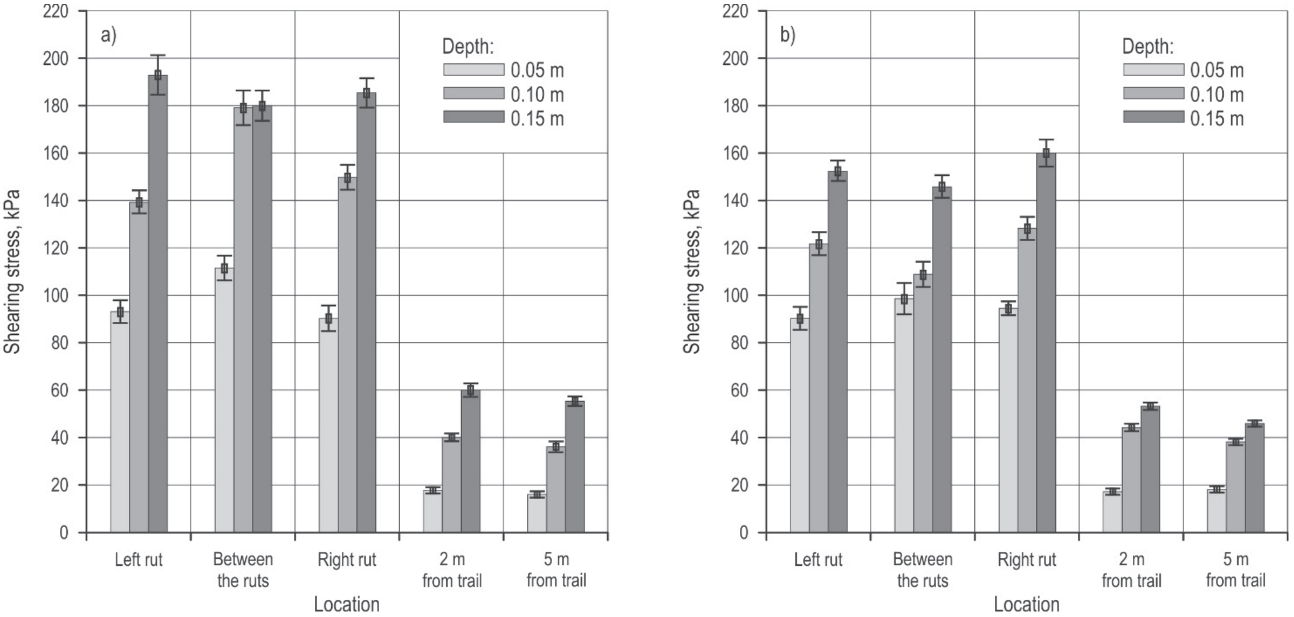

Fig. 6 The values of maximum shearing stress of soil measured in stand 89a: a) primary skid trail, b) secondary skid trail (arithmetic mean ± SD)

greatest changes in the soil structure occur in the surface layers at the contact point between the vehicle wheels and transported wood with the soil. This tendency was observed for both types of skid trail (primary and secondary).

Fig. 7 presents the values of the maximum shearing stress measured within the trails after CTL. On the secondary skid trail, the values of the analyzed parameter were significantly lower than on the primary trail. It was shown for both types of skid trail that the biggest changes of the soil structure occurred as a result of the impact of vehicles wheels (in the ruts), while on the surface between the ruts and 2 m from the skid trails the values of maximum shearing stress were significantly lower. This fact proves that the vertical impact of machinery on the soil is domi-

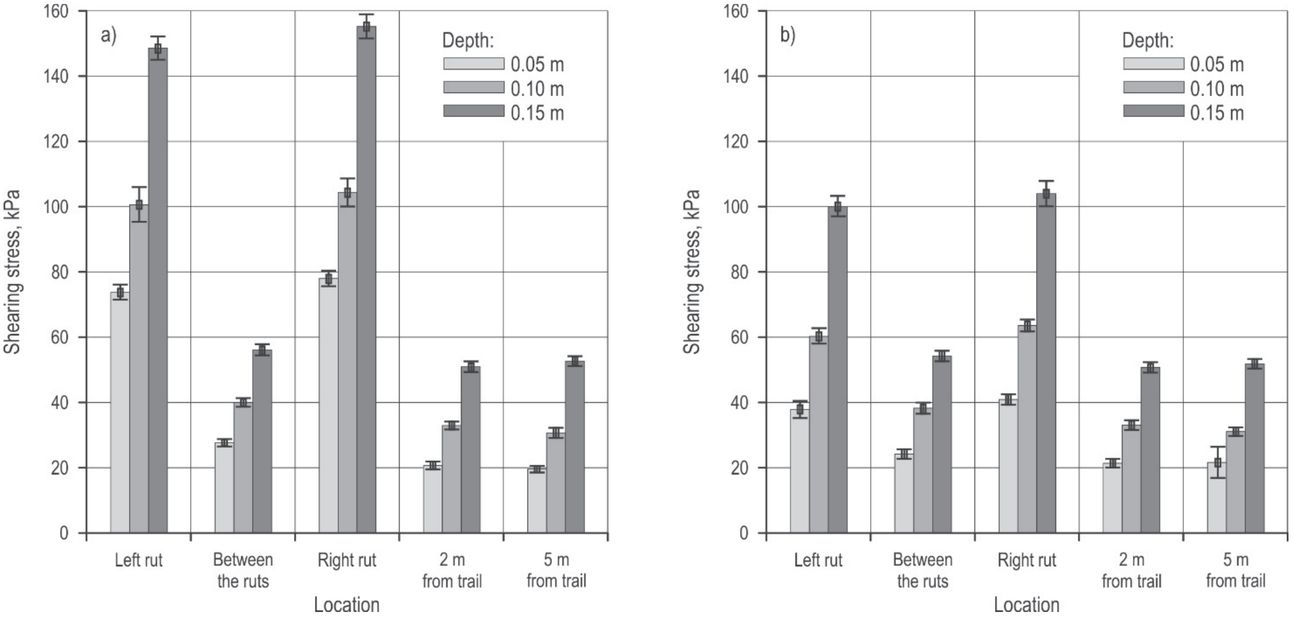

Fig. 7 The values of maximum shearing stress of soil measured in stand 99b; a) primary skid trail, b) secondary skid trail (arithmetic mean ± SD)

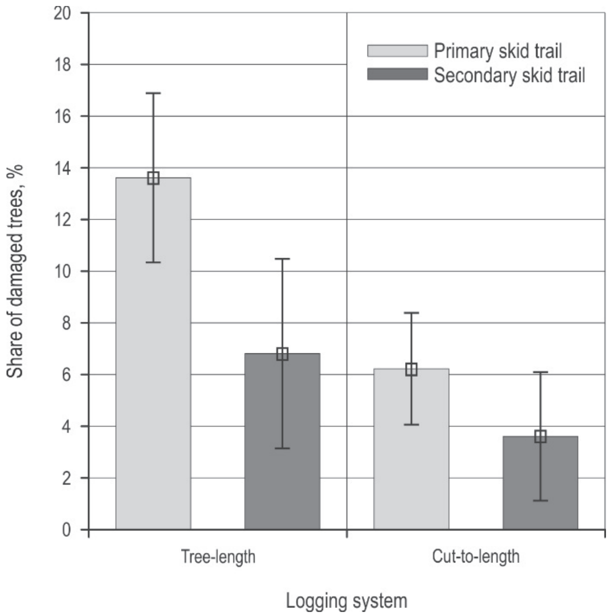

Fig. 8 Percentage share of damaged trees (arithmetic mean ± SD)

nant, while the range of lateral changes is clearly smaller. The greater the number of passes, the higher the strength of the soil and the higher the values of maximum shearing stress of soil. Increase in the values of the maximum shearing stress was aligned to all measure depths; for the primary trail it was about 285% and for the secondary trail below 200% in relation to the undisturbed soil (5 m from the trails).

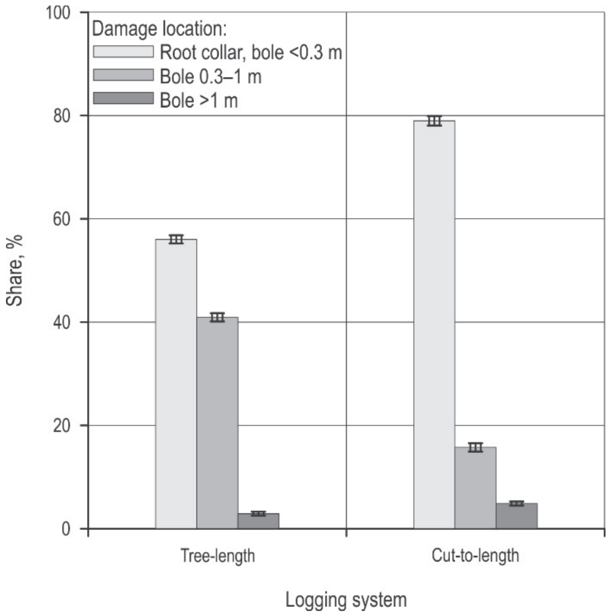

Fig. 9 Percentage share of tree damage classes (arithmetic mean ± SD)

In the designated research areas, damages to trees remaining in the stand after the harvesting operations were assessed. These damages were primarily caused by wood extraction. In stand 89a, where tree-length logging system was used, tree damages were caused by skidder wheels and hauled logs. In cut-to-length logging, the residual trees were damaged by wheels of machines (harvester/forwarder) and by hydraulic boom during loading of logs on forwarder trailer.

Fig. 8 shows the percentage of damaged trees in the area of technological trail on both analyzed forest stands. It was observed that more standing trees were damaged when tree-length logging system was used. At the research plots located within primary skid trail in stand 89a, the damaged trees accounted for an average of 13.5%. The largest share of damaged trees was 16.1% (5 trees damaged out of 31 growing trees), while the smallest share was 10% (3 trees damaged out of 30 growing trees). Within the secondary skid trail, the share of damaged trees was significantly lower – an average of 6.8% (the lowest 3.33% and the highest 12.5%). In forest stand 99b, where cut-to-length logging system was used, the share of damaged trees within the primary skid trail was 6.3%, while within the secondary skid trail the share of damaged trees was 4%.

Based on the methodology applied, damaged trees were classified according to their location. Assessment of logging technology was also conducted based on this classification. As the results obtained within the primary and secondary skid trail at both analyzed forest stands were comparable, the average values of the measurements obtained on research plots were presented. The share of individual damage class in relation to the total number of damaged trees is shown in Fig. 9. Both after TL and CTL, major damage to trees occurred on root collar and in the lowest parts of the bole, their share being 56% in tree-length logging and 79% in cut-to-length logging. This type of tree damage was caused by the wheels of forest machinery. In case of tree-length logging system, damaging the bole at a height of 0.3–1.0 m accounted for 41% (they were caused by skidder and hauled wood). In the case of cut-to-length logging system, such injuries accounted for 16% and the damages were caused by the harvester/forwarder and grapple mounted on the hydraulic arm. Damage to the bole located at a height above 1.0 m was the result of tree felling and in tree-length system, it accounted for 3%, while in cut-to-length it accounted for 5%.

The results of ANOVA tests are shown in Table 3.

Table 3 Results of statistical analysis; the significance level $\alpha=0.05$; $\bar{x}$ – arithmetic mean; SD – standard deviation

Analyzed parameter		Factor	Factor level	$\bar{x}$	±SD	*p*-value
Share of ruts depth (in total length)	<0.05 m	Logging system	TL	56.60^{A}	8.22	<0.000001
			CTL	80.80^{B}	6.91	
	0.05–0.15 m		TL	25.00^{A}	4.69	<0.000001
			CTL	14.30^{B}	4.71	
	0.16–0.25 m		TL	13.70^{A}	2.75	<0.000001
			CTL	4.50^{B}	1.71	
	>0.25 m		TL	5.00^{A}	1.41	<0.000001
			CTL	0.00^{B}	0.00	
Penetration resistance		Logging system	TL	2.38^{A}	1.09	<0.000001
			CTL	1.40^{B}	0.71	
		TL-location	Left rut	3.27^{A}	0.28	<0.000001
			Between the ruts	3.23^{A}	0.31	
			Right rut	3.25^{A}	0.27	
			2 m from trail	1.12^{B}	0.05	
			5 m from trail	1.04^{B}	0.06	
		CTL-location	Left rut	2.19^{A}	0.46	<0.000001
			Between the ruts	0.92^{B}	0.06	
			Right rut	2.20^{A}	0.43	
			2 m from trail	0.85^{B}	0.08	
			5 m from trail	0.83^{B}	0.05	
Shearing stress		Logging system	TL	95.43^{A}	56.19	<0.000001
			CTL	57.49^{B}	35.92	
		TL-location	Left rut	131.51^{A}	36.91	<0.000001
			Between the ruts	137.29^{A}	35.03	
			Right rut	134.58^{A}	35.67	
			2 m from trail	38.78^{B}	16.70	
			5 m from trail	34.98^{B}	14.44	
		CTL-location	Left rut	86.84^{A}	35.86	<0.000001
			Between the ruts	40.09^{B}	12.40	
			Right rut	90.99^{A}	36.86	
			2 m from trail	34.96^{B}	12.61	
			5 m from trail	34.56^{B}	13.88	
Share of damaged trees		Logging system	TL	10.20^{A}	4.87	0.001385
			CTL	4.90^{B}	2.60	
Share of damage classes	Rut collar, bole <0.3m	Logging system	TL	56.00^{A}	1.05	<0.000001
			CTL	79.00^{B}	1.33	
	Bole 0.3–1 m		TL	40.90^{A}	0.99	<0.000001
			CTL	15.80^{B}	1.03	
	Bole >1 m		TL	3.00^{A}	0.47	<0.000001
			CTL	5.00^{B}	0.48	

*the letters at arithmetic values denote separate homogeneous groups

Based on statistical analysis of the first parameter, it can be stated that the logging system was a significant factor. For penetration resistance and shearing stress, besides the logging system, the location of measure was also a relevant factor. In this way, the range of soil structure changes, caused by logging, could be determined. It has been shown that all factors were significant for shearing stress values and for penetration resistance values. To determine the location as a factor, post-hoc tests had to be carried out. By Tukey's *HSD* tests, conducted for TL and CTL, two different homogeneous groups have been identified. Further analysis showed that the logging system was statistically significant both for percentage of damaged trees and for shares of damages in all analyzed parts of the tree.

4. Discussion

The area occupied by skid trails in tree-length logging system with wood extraction using skidder was 5.6% of the total stand area. A larger area under skid trails was occupied in stands where cut-to-length logging system was used. The obtained results were confirmed by other authors. Jones et al. (1996) showed that the trails for skidder accounted for 5.4% and 5.3% for planned and unplanned operations, respectively. Jackson et al. (2001), in a study conducted in tropical forests in Bolivia, showed that the area occupied by the primary and secondary logging trails accounted for 19% of the study area. In this case, the skid trails were established before harvesting operations and approximately 24% of the created skid trails were not used to transport logs. Picchio et al. (2012) showed that during thinning operations, using full-tree harvesting system with wood extraction by tractor with winch, skid trails occupied 2.7% of the study area. When using cut-to-length logging system in this study, the logging trail accounted for 9.5% of the stand area. Our results are different from those presented by others authors. According to Elliasson (2005) and Wågberg (2001), the area designated for harvester and forwarder passes accounted for 12.5% and 12.1%, respectively. The study of these authors was carried out at the final felling of trees, while our research was related to areas under trails after selective felling within late thinning. Therefore, the trail network did not have to be so dense, the trails did not have to be formed at distances equal to twice the length of the harvester crane as was the case in final cutting.

Analyses of measured rut depths confirm that the rut depth increased with the increase of traffic intensity. Our results are in accordance with the findings of many researchers (McNabb et al. 2000, Eliasson and Wasterlund 2007). The deepest ruts on the examined areas were formed in land cavities, where the soil had higher humidity. This is in accordance with the results obtained by Jourgholami and Majnounian (2011), who showed that the increase in soil humidity results in a significant increase in rut depth.

The aim of the measurements of soil penetration resistance and the maximum shearing stress was to demonstrate changes in soil properties resulting from its compaction. In the present study, the values of analyzed parameters, obtained in ruts created by wheels of machines and by hauled wood, were significantly higher than the values obtained on the undisturbed soil. The maximum values of penetration resistance in the soil layer of 0–0.2 m were 4–5 MPa. Ampoorter et al. (2010) showed that the effect of the number of passes on the increase of soil compactness depends on soil humidity – the higher humidity, the greater the increase in compactness. In our research, we also observed a significant increase in soil penetration resistance and values of maximum shearing stress with the number of passes (significant differences between the values obtained on the primary and secondary skid trails with regard to the control plots).

Taking into account differences in wood harvesting circumstances, it is hard to compare the results coming from different countries. Many studies have shown that trees damaged by forest operations may range between 4–21% of the total post-harvest stand (Vasiliauskas 2001, Picchio et al. 2011). The results presented in most publications referred to pine stands. Cervinkova (1980) and Dimitri (1983) showed that different tree species vary in resistance to damage, with spruce being more sensitive than pine. As shown in this study, the percentage of trees damaged by logging operations, with the use of harvester and forwarder, is comparable with the results presented by other authors. Based on the research conducted in Latvia, Epalts (1989) indicated 6.5% of damaged trees, Froding (1992) from Sweden – 4% in pine stand and 7.2% in spruce stand, Suwała (1999) – 4.5% in thinning of pine stand.

Damage to trees after late thinning operations using tree-length logging system (felling by chain saw and extraction with cable skidder) in the foothill area in Poland (stand 89a) accounted for an average of 13.5% for the research plots located at primary skid trail and 6.8% on surfaces within the secondary skid trail. In studies of late thinning in pine forest, Suwała (1999) showed that after the operation damaged trees accounted for 12.8% of the remaining trees (the trees were felled by chain saw and extracted by cable skidder – distance between the trails was 60 m). In his studies conducted in the forests in Iran, Jourgholami (2012) showed that wood transport using a skidder in the stands caused damage to 16.4% of growing trees.

Generally, it can be stated that using of the short wood logging system (harvester and forwarder) during late thinning causes less damage to trees than using tree-length system. This is in accordance with the findings of Suwała et al. (2000). The results of researches conducted in lowlands of Poland have shown that the share of damaged pine trees in late thinning in the short-wood system is distinctly lower (4.1–5.8%) than in tree-length system (8.6–11.9%).

Our research showed that the damage to residual growing trees is mainly located in the lower parts of the bole, at the height below 1 m. Bettinger and Kellogg (1993), Athanassiadis (1997), Naghdi et al. (2008), Jourgholami (2012) also found in their study that the damage to trees during harvesting operations is related to the lower parts of the bole. This study reported major damage in the root collar and the bole at a height of less than 0.3 m (59% – in tree-length logging system and 79% in cut-to-length system). Vasiliauskas (1993) presented similar results – he showed that in spruce stands harvested by partial and shelterwood cuttings, only 15% of all tree wounds were situated higher than 0.5 m, and over 60% of the trees were damaged at the root collar and at 0.3 m height from the ground.

5. Conclusions

Cut-to-length logging system requires a denser trail network, the area under trail occupied 9.5% of the stand. In late thinning using tree-length logging system, the area under skid trails accounted for 5.6% of the total stand area. Much less damage to the trail was found in the short wood harvesting system, the ruts were shallower than after wood transportation by skidder;

The range of changes of the analyzed soil properties, regardless of the used logging system, was mainly limited to the direct impact of the vehicle wheels and transported wood. On the trails in study stand 89a, greater increase in the maximum shearing stress values and soil penetration resistance was found after wood hauling with skidder than after wood logging using harvester and forwarder;

Larger share of damaged trees was found in tree-length logging. Higher share of damaged trees was observed at the primary skid trails. Mechanical injuries of remaining trees, for both logging systems, concerned the trees growing at skid trails. These wounds were mainly located on the root collars and lower parts of the boles.

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