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ORIGINAL RESEARCH

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Detailed Analysis of Residual Stand Damage Due to Winching on Steep Terrains

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Abstract

Damage to the remaining stand on steep terrain can be quite severe and is usually difficult to control during winching. Timber skidding, especially by agricultural tractor, is a common solution in small-scale forestry. One of the factors influencing remaining stand damage is winching on steep terrain, although, to date, this has only been studied in general. Limiting stand damage is possible when the factors causing the damage are well-known. Therefore, the aim of this paper was to study in detail the impact of slope steepness on different types of damage in the stand after winching, focusing in particular on: (1) the share of trees with damage (including natural regeneration), (2) the size of the wound, (3) the number of wounds per tree, (4) wound intensity, and (5) the position of the wound on a tree. Field observations were carried out in three beech (two in Italy and one in Iran) and two pine stands (in Italy), in which four classes of slope steepness were selected for each stand. After timber harvesting, damage to the remaining stand as well as to any natural regeneration was recorded. It was found that the share of wounded trees was directly related to slope steepness, although this was less obvious in the natural regeneration. On steeper slopes, there were larger wounds and, on average, there were more wounds per tree. Wound intensity also depended on the gradient of the slope. The size, understood as diameter at breast height, of the remaining trees on the slopes also had an impact on the wound characteristics: on thicker trees, bigger wounds were detected and a higher number of them. However, thicker trees were less often wounded. Wound position on a tree did not depend on slope steepness but it may have been related to stand density and size of winched timber.

Keywords Logging damage · Cable skidding · Ground slope · Thinning · Selection cutting

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Introduction

Damage to the remaining stand can be caused by both felling and extracting, regardless of the technological level of the machines or experience of the operators. However, it is extracting that usually causes more severe damage to the remaining trees, especially when winching and skidding are applied (Nikooy et al. 2010; Tavankar et al. 2015a). In small-scale forestry, the use of agricultural tractors is a popular form of timber extraction (Spinelli and Magagnotti 2012), although light winches are also considered as very suitable (Kaakkurivaara and Stampfer 2018; Štícha et al. 2018). Unfortunately, skidding usually inflicts considerable damage on the remaining stand (Behjou 2014).

Damage on trees occurs when moving timber from the felling area to the landing (Cambi et al. 2015, 2016; Froese and Han 2006; Kosir 2008; Picchio et al. 2012; Tavankar et al. 2015a). In particular, the winching of trees or logs in thinning increases the probability of residual stand damage (Conway 1982; Picchio et al. 2012; Marchi et al. 2014) as well as in selective cutting treatment (Nikooy et al. 2010; Tavankar et al. 2013). Generally, the skidding of long wood in thinning operations causes more damage than the extraction of shorter wood by forwarders (Bembenek et al. 2013b) or by agricultural tractors (Bembenek et al. 2013a). The tree length system (TLS) usually causes a higher level of damage in comparison with the short wood system (Cudzik et al. 2017).

Impact of Forest Characteristics on Damage

The amount or level of damage caused to residual trees during selective cutting treatment and cable skidder logging operations depends on a number of factors, including forest characteristics, such as: the amount of timber removed during harvesting (Sist et al. 1998; Fjeld and Granhus 1998), stand density and basal area (Bettinger et al. 1998), skid-trail spacing (Gullison and Hardner 1993; Vasiliauskas 2001) and road density (Iskandar et al. 2006). It is also important to highlight that all the damage may not always be caused by logging activities—a recent study confirmed that on steep slopes, a considerable number of trees may be damaged by rock fall (Mihelič et al. 2018).

Behjou (2014) found that, generally, medium and lower harvesting (thinning) intensity is observed in small-scale forestry, and this is associated with a lower level of stand damage. There are also examples, in small-scale forestry and rural areas, where high thinning intensity occurs: >100 m^3 ha^{-1} (Spinelli and Magagnotti 2012) and >250 m^3 ha^{-1} (Picchio et al. 2012). In these cases, as found by the authors, the level of stand damage was as high as 30%. Moreover, although low intensity thinning or selection cutting may limit the level of damage, low intensity also leads to lower productivity (Mederski et al. 2016a) and higher forest operation costs (Mederski et al. 2018).

Non-forest Aspects Influencing Damage

Other variables having an impact on the damage caused by skidding are mainly logistic factors that are other than forest characteristics: the level of planning in the logging operation (Pinard and Putz 1996), the type of logging machines (Han and Kellogg 2000), the season in which logging takes place (Limbeck-Lilenau 2003), and the skills of the operators (Pinard et al. 1995).

The topography, and the slope in particular, could have an influence on the level of damage to the remaining trees, as observed in previous studies (Bragg et al. 1994; Pinard and Putz 1996). This was later also confirmed by Limbeck-Lilienau (2003) and Tavankar et al. (2015a). However, these selected studies only provided a general indication that a larger slope gradient may cause a higher level of damage. An example of a detailed study of damage to remaining stands is available in the literature, although it was carried out in lowlands (Bakinowska et al. 2016). The paper presents the different probabilities of tree damage, related mainly to the harvesting system. In particular, a low damage probability was observed in the short wood system (SWS) and higher in the full tree system (FTS).

Objectives

Taking into account the above-mentioned studies, the objective of the research presented in this paper was to find out if there was a different level of damage to the remaining stand and regeneration during log winching on four particular slopes with differing gradients. The research focused on: (1) the share of trees with damage (including natural regeneration), (2) the size of the wound, (3) the number of wounds per tree, (4) wound intensity and the type of damage, and (5) the position of the wound on a tree. Furthermore, it was expected that the results obtained in this study would help to improve winching operations by limiting unnecessary damage to remaining stands in hilly areas.

Materials and Methods

Forest Sites, Timber Preparation and Extraction

For representative data collection, five different stands were selected in areas with similar slope characteristics and comparable forest operations based on winching and skidding. Under study were three beech stands and two pine stands in which extraction was carried out either by tractor or skidder, both equipped with winches (Table 1). To limit the influence of the operators' skills, teams of workers with a minimum of 15 years' experience of winch-skidding extraction were used on all the study sites.

The sample plots were selected in areas that had similar conditions for winching and skidding. The mean winching slope gradient varied from 30 to 37%, while

Table 1 Main characteristics of selected areas, stands, machine specifications, skidding and winching parameters

	Sample plot									
	FA1		FA2		FA3		PI1		PI2	
Area description										
Region	Veneto (Italy), Pian Cansiglio forest		Tuscany (Italy), Amiata Mountain forests		Nav (Iran), Nav Mountain forests		Umbria (Italy), Peglia Mountain forests		Tuscany (Italy), Amiata Mountain forests	
Coordinates	46°03′46″–46°03′28″N 12°22′13″ to 12°22′36″E		42°54′01″–42°53′35″N 11°37′42″–11°38′15″E		37°38′34″–37°42′21″N 48°48′44″–48°52′30″E		42°46′53″–42°46′43″N 12°12′40″–12°12′50″E		42°53′46″–42°54′59″N 11°38′07″–11°36′27″E	
Elevation of sample plots, m a.s.l.	1000–1200		1100–1300		1050–1350		450–550		950–1000	
Annual precipitation, mm	1500		1400		950		900		1300	
Annual mean temperature, °C	9.5		10.0		9.1		15.0		12.0	
Mean winching slope, %	30		35		30		35		37	
Skidding slope, %	0–35		0–18		0–33		0–25		0–21	
Stand characteristics										
Predominant species	European beech (*Fagus sylvatica*)		European beech (*Fagus sylvatica*)		Oriental beech (*Fagus orientalis*)		Black pine (*Pinus nigra*)		Black pine (*Pinus nigra*)	
Age in years	120		110		Uneven age		60		90	
Silvicultural treatment	Preparation cutting, THB		First shelterwood, THA		Selection cutting		THA		First shelterwood, THB	
Management type	Even age high forest, shelterwood system		Even age high forest, shelterwood system		Uneven age high forest, selection cutting		Even age high forest, shelterwood system		Even age high forest, shelterwood system	
Before/after thinning	BTH	ATH	BTH	ATH	BTH	ATH	BTH	ATH	BTH	ATH
Mean DBH, cm	39.5	41.0	41.1	41.3	30.5	29.5	22.1	22.4	38.9	41.4
Mean H, m	26.5	26.7	27.8	27.9	19.7	19.0	16.9	17.1	28.1	28.4
Stocking, $m^3\ ha^{-1}$	524.0	397.1	792.3	578.4	296.3	215.7	450.3	147.4	687.5	481.3
Basal area, $m^2\ ha^{-1}$	39.6	29.8	56.5	40.7	22.6	19.8	40.2	14.8	62.7	43.9
Density, trees ha^{-1}	339	226	428	305	309	290	1040	375	528	326
Mean tree volume, m^3	1.55	1.76	1.85	1.90	0.96	0.74	0.35	0.36	1.30	1.48

Table 1 (continued)

	Sample plot									
	FA1		FA2		FA3		PI1		PI2	
Large saplings (≥ 1 cm, < 10 cm DBH) trees ha^{-1}	–	–	–	–	229	171	184	110	250	245
Saplings (≥ 1 m tall and < 1 cm DBH), trees ha^{-1}	–	–	–	–	541	405	430	256	489	396
Seedlings, trees ha^{-1}	–	–	–	–	818	613	1433	853	1756	1125
Regeneration[a], trees ha^{-1}	–	–	–	–	1588	1189	2047	1219	2495	1766
Machine specifications and skidding parameters										
Machine used, kW	SAME farm tractor, 70		Caterpillar 518C skidder, 103		Timberjack 450C skidder, 185		Carraro Campese tractor equipped with skidding devices, 55		Caterpillar 518C skidder, 103	
Maximum length of winch cable/cable diameter, m/mm	100/14		80/18		60/20		120/9		80/18	
Machine weight, t	4.5		9.7		9.8		3.0		9.7	
Machine size, length/width, m/m	5.1/2.8		6.2/3.6		6.4/3.8		2.8/1.7		6.2/3.6	
Maximum winching distance, m	80		60		50		95		60	
Maximum skidding distance, m	280		180		580		80		220	
Share of logs (number) winched downhill out of all winched logs, %	60		54		84		15		21	

BTH before thinning, *ATH* after thinning, *THB* thinning from below, *THA* thinning from above

[a]Regeneration refers to all young trees: large saplings, saplings and seedlings

skidding was carried out on skid roads with slopes from 0 to 35% (Table 1). All the stands were located in mountain areas at elevations between 450 and 1350 m a.s.l. Annual precipitation for the regions was between 900 and 1500 mm, and the mean annual temperature ranged from 9.1 to 15.0 °C. Four study sites were located in Italy (one in the northern part and three in the central part) and one in Iran (in the northern part).

The selected stands were dominated either by beech or pine, and according to the main species, they were marked as: FA1 and FA2, even-aged mixed forests with a majority of *Fagus sylvatica*; FA3, uneven-aged mixed forest dominated by *Fagus orientalis*; and PI1 and PI2, even-aged pine forests with a dominance of *Pinus nigra* (Table 1). Before silvicultural treatment, the main tree characteristics (DBH—diameter at breast height and H—height) were collected on 10 circular sample plots, with diameters ranging from 10 to 13 m and totalling 3% of the stand area (from 0.7 ha to 1.4 ha). The trees were divided into those for cutting (marked) and those to remain. In the beech-dominated stands, the trees had a mean DBH from 30.5 to 41.1 cm, and heights ranging from 19.7 to 26.5 m. The mean DBH of the pine stands ranged from 22.1 to 38.9 cm, and the mean height varied from 16.9 to 28.1 m. Sample plots in FA3, PI1 and PI3 also had natural regeneration with a cover of approximately 1600–2500 trees per hectare (Table 1).

In all of the even-aged stands and both of the pine stands (FA1, FA2, PI1 and PI2), thinning was applied, from below or from above, in accordance with the management plans (Table 1). In stand FA3, selection cutting was applied, which was considered similar (from a forest operations' perspective) to the thinning in the other stands.

On study site PI1, a full tree system (FTS) was used: after felling, whole trees were winched and skidded. In the other stands, the timber was prepared according to the short wood system (SWS): the felled trees were delimbed and bucked into assortments, leaving the tree tops. In plots FA1 and FA2, the trunks were cut into logs 4.4 m in length, while in PI2 the trunks were cut into 6.0 m logs. In FA3, the logs were of irregular length, and, depending on the quality and dimensions of the tree trunks, varied from 7.8 to 15.9 m.

In all of the sample plots, the work procedure was the same. Skidding was provided by three people: the machine driver and two assistants, a winch operator and one more worker for cable release and the hooking of logs. One full skidding cycle included six regular phases: (1) travelling empty—begins when the skidder/tractor leaves the roadside landing area and ends when the skidder/tractor arrives at a suitable position (closest to the felled tree) on the skid trail; (2) winch cable release—begins when the operator releases the winch cable and ends when the choker setter is next to the felled tree; (3) tree/log hooking—begins when the operator wraps the chain around the tree/log and connects the chain with the choker (for all the trees/logs) and ends when the winching phase starts; (4) winching—begins when the operator starts to winch and ends when the all trees/logs reach the winch shield at the skid trail edge; (5) skidding—begins when the tractor/skidder with the load starts to move and ends when the machine arrives at the roadside landing; and (6) unhooking—begins when the choker setter opens the load and ends when all the trees/logs are free of the chains.

The machines used for extraction were two tractors equipped with winches (controlled mechanically in FA1 and with an electro-mechanical system in PI1), while in the remaining stands, skidders were used with an electro-mechanical winches (Table 1). In the beech forest FA1, extraction was carried out by a SAME farm tractor, powered by a 70 kW engine. A smaller, 55 kW Carraro Campese tractor (equipped with skidding devices) was used in the younger PI1 stand. In the other beech stands, FA2 and FA3, skidders were used: a Caterpillar 518C (103 kW), and a more powerful Timberjack 450C (185 kW), respectively. In the PI2 plot, the same Caterpillar 518C carried out extraction as in FA2. The maximum winching distances ranged from 50 to 95 m, while the skidding distances (without winching) ranged from 80 to 580 m (Table 1).

In each stand the number of logs winched uphill and downhill (through winching corridors) were in different proportions (Table 1), although, on average, for all five stands, nearly 50% of the winching was up and down the hill. The SWS was applied on four areas (FA1, 2, 3 and PI2) and in these cases the skidding was downhill only. The FTS was applied on PI1 area and the skidding was uphill only.

In all cases, harvesting, skidding and data collection were carried out in the last decade, although always at the turn of spring and summer.

Methods

In each study site, four winching corridors (WINs) located on different slope gradients were randomly selected. The potential trajectories of all the WINs were measured using GPS, then numbered and recorded on GIS and a map. The whole length of each WIN was classified into one of the slope steepness classes (SSCs): SSC1 ≤ 15%, 15% < SSC2 ≤ 30%, 30% < SSC3 ≤ 45%, and SSC4 > 45%. To do this, each WIN was divided into 10-m sections, and the slope of each section was measured separately using a clinometer. Afterwards, the arithmetic mean was calculated for each WIN and it was sorted into one of the SSCs.

Before winching, the logs were measured: the number, length and diameter were recorded in order to obtain the volume under bark.

The DBH of all the stand trees (DBH ≥ 7.5 cm) and regeneration (DBH < 7.5 cm) were measured and recorded before and after winching operations within a distance of 25 m on both sides of the winching corridor's centre line. The residual stand and regeneration damage was also monitored during each winching operation, and recorded as: wounded, broken bole and/or uprooted. Damage recorded directly after felling was separated from that caused by winching. For each tree with damage, the following were recorded: DBH, wound severity (bark squeezed, bark removed, wood damaged), as well as position and size of wound. The maximum length and width of each wound was measured (using a ruler with an accuracy of 1 mm) to obtain the wound surface area (WSA) using the formula for an ellipse (Picchio et al. 2011; Marchi et al. 2014). Four classes of WSA were differentiated based on the wound healing rate, in accordance with two previously cited papers (Tavankar et al. 2015b, 2017): WSA1 < 25, 25 < WSA2 ≤ 100, 100 < WSA3 ≤ 200 and WSA4 > 200 cm^2. The position of the wound was determined by tape measurement of the height between the wound centre and the ground. Following this, the wound position (WP) was categorised as: WP1 (superficial roots), WP2 ≤ 0.3 m (stump area, or tree collar), 0.3 < WP3 ≤ 1 m and WP4 > 1 m. This categorisation was used as, according to Meng (1978, in Limbeck-Lilenau (2003) and Vasiliauskas (2001), the highest risk for decay is when injuries are in the area of the root collar. Damage to superficial roots and above the root collar (> 0.3 m) are considered less attractive for wood-destroying fungi (Meng 1978).

Data Analysis

The winching areas (A_i, m^2) were computed as:

$$A_i = \cos\alpha \times w \times L_i \tag{1}$$

where: α was the mean of the slopes in slope steepness class i, w was the width of the sample areas = 50 m (25 m to each side of the corridor centre line) and L_i was the length of the winching corridor in slope class i (m).

The volume (V, m^3) of the winched logs was calculated using Huber's formula:

$$V = A_m \times l \tag{2}$$

where A_m was the mid-point cross-sectional area of the log (m^2), and l was the length of the log (m).

Division into slope classes was performed in order to obtain similar stand and timber characteristics in terms of harvesting intensity, number of winched logs and mean log dimensions (diameter, length, volume), i.e. FA1 had similar characteristics in all four slope steepness classes (in %): < 15, 15–30, 30–45 and > 45 (Table 2).

The residual stand damage (%) with respect to the ground slope and damage (of all kinds), wound characteristics and DBH classes, were compared using a non-parametric Chi square test. After tests for normal distributions of the data (the Kolmogorov–Smirnov test), the size of the wounds and how many there were per tree were analysed using ANOVA and the Duncan test (also with respect to the ground slope classes). Non-parametric correlations among the variables were performed using the Spearmann test, followed by a detailed parametric test to check the possibility of building a non-linear regression between the slope and the other variables. All the analyses were performed using SPSS 19 software.

Results

General Winching Damage

The total forest area affected by the winching operation and considered in this study was 19.25 ha and it varied from 0.32 to 1.60 ha in the analysed sample plots (a mean of 0.96 ha) (Table 2).

The total damage in all the analysed stands was substantial and varied from 40 to 67% (Table 3). The greatest percentage of stand damage was observed in FA1. In

Table 2 Description of sample plots divided into slope steepness classes

Sample plot	FA1	FA2	FA3	PI1	PI2	FA1	FA2	FA3	PI1	PI2	FA1	FA2	FA3	PI1	PI2	FA1	FA2	FA3	PI1	PI2
Slope steepness class (%)	< 15					15–30					30–45					> 45				
Area (ha)	0.91	1.40	0.32	0.89	1.60	1.60	1.00	0.85	0.92	1.23	1.05	0.96	0.89	0.89	1.12	0.75	0.95	0.33	0.94	0.65
Harvesting intensity (% of number of trees)	33	29	6	64	39	33	29	6	64	39	32	28	6	60	37	31	28	6	61	37
Harvesting intensity (% of volume)	24	27	27	67	30	25	28	27	68	30	24	26	27	65	28	24	26	27	62	28
Number of winched logs (stem)	150	185	5	595	395	268	196	15	600	324	208	251	18	521	297	168	215	7	601	224
Mean middle diameter of winched logs (cm over bark)	28.3	27.2	56.3	21.3	30.1	28.1	28.2	50.6	20.5	28.5	27.9	27.5	49.1	21.1	30.2	28.4	27.8	46.9	20.8	30.1
Mean length of winched logs/trees (m)	6.2	5.5	13.5	15.8	8.6	6.5	6.1	11.8	16.3	9.2	6.3	5.4	12.4	15.4	8.9	6.9	6.7	11.7	14.8	8.5
Mean volume of winched logs (m^3 over bark)	0.39	0.32	3.10	0.56	0.61	0.40	0.38	2.40	0.54	0.59	0.39	0.32	2.30	0.54	0.64	0.44	0.41	2.00	0.50	0.61

Table 3 Share of trees with damage on designed sample plots

	Sample plot	Remaining density, stems per ha[1]	Damage (%)			
			Wounded	Broken bole	Uprooted	Total damage
Stand	FA1[a]	228	66	1	0	67
	FA2[b]	304	50	1	0	51
	FA3[c]	298	27	7	6	40
	PI1[c]	383	50	6	2	57
	PI2[a, c]	331	39	4	3	45
Regeneration	FA1	–	–	–	–	–
	FA2	–	–	–	–	–
	FA3[a]	1588	22	8	17	47
	PI1[b]	2047	13	11	29	53
	PI2[a]	2495	20	23	6	50

Lower case letters in superscript show statistically significant differences based on results of ANOVA test followed by Tukey test

[1]Number of stems per ha is different to that in Table 1, as in Table 3, stems per hectare are for sample plots only, not for whole stands

similar stand and harvesting conditions in FA2, the situation was only slightly better, with 51% of the trees showing damage.

The lowest damage was in FA3, where a significantly lower number of trees was harvested, but logs were of large sizes in comparison with the logs in the other stands (Table 2). The trees were mainly wounded (bark removal), with broken boles, but were rarely uprooted.

The total damage to regeneration was also considerable and amounted to 47–53% (Table 3). Saplings were mainly wounded and uprooted, whilst the smallest share of saplings had broken boles.

Impact of Slope Steepness on Damage Intensity

The number of trees with wounds increased as slope gradient became steeper (Table 4). Uprooted trees followed the same trend. More trees with broken boles were observed on steeper slopes only in plots FA3 and PI1. A larger number of saplings with wounds were observed on steeper slopes in the pine stands (PI 1 and PI2) only, while the same was observed with uprooted regeneration (Table 4).

Further statistical analysis (Spearman's correlation) showed that the mean wound size, share of wounded trees, number of wounds per tree depended on slope steepness and DBH of residual damaged trees (Table 5). The wound intensity depended only on slope steepness. However, the position of the wound on a tree was not correlated with slope gradient.

A non-parametric analysis (Table 5), to find out the relation between slope steepness or DBH and the other main variables, highlighted some statistically significant positive trends. However, a more powerful statistical parametric analysis, such as the ANOVA test and the non-linear regression analysis, confirmed that only wound size

Table 4 Share of trees with damage with respect to slope steepness class and type of damage

Slope steepness class (%)		Damage (%)														
		Wounded					Broken bole					Uprooted				
		FA1	FA2	FA3	PI1	PI2	FA1	FA2	FA3	PI1	PI2	FA1	FA2	FA3	PI1	PI2
Stand	< 15	52^{a}	36^{a}	17^{a}	33^{a}	28^{a}	1	1	4^{a}	2^{a}	3	–	–	1^{a}	0.5^{a}	0.1^{a}
	15–30	61^{b}	45^{b}	22^{a}	42^{b}	35^{a}	–	2	6^{b}	3^{a}	4	–	–	3^{b}	1^{a}	1^{a}
	30–45	70^{c}	55^{c}	30^{b}	56^{c}	43^{b}	1	1	7^{b}	6^{b}	4	–	–	6^{c}	3^{b}	3^{b}
	> 45	80^{d}	61^{c}	40^{c}	68^{d}	50^{c}	–	1	13^{c}	10^{c}	3	–	–	13^{d}	4^{b}	6^{c}
	ANOVA *p*	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	> 0.05	> 0.05	< 0.05	< 0.05	> 0.05	–	–	< 0.01	< 0.05	< 0.05
Regeneration	< 15	–	–	15	4^{a}	8^{a}	–	–	5	11	18	–	–	11	19^{a}	3^{a}
	15–30	–	–	22	6^{a}	18^{b}	–	–	8	8	27	–	–	17	28^{b}	5^{a}
	30–45	–	–	23	18^{b}	25^{c}	–	–	9	11	22	–	–	18	31^{b}	7^{a}
	> 45	–	–	27	21^{b}	30^{c}	–	–	11	15	25	–	–	22	38^{c}	11^{b}
	ANOVA *p*	–	–	> 0.05	< 0.05	< 0.05	–	–	> 0.05	> 0.05	> 0.05	–	–	> 0.05	< 0.05	< 0.05

Different lower case letters in superscript show statistically significant differences based on results of ANOVA test followed by Tukey test

Table 5 Spearman's correlation coefficients between slope steepness or DBH and selected variables

Variables description	Slope steepness (%)	DBH (cm)
Wound size (cm^2)	R = 0.758^s	R = 0.452^s
Share of wounded trees (%)	R = 0.746^s	R = − 0.604^s
Number of wounds per tree	R = 0.698^s	R = 0.399^s
Wound intensity	R = 0.502^s	R = − 0.106
Position	R = 0.202	R = − 0.174

^{s}Statistically significant, $p < 0.05$; no. 233

and the number of wounds per tree depended on slope steepness (Table 6) with polynomial functions. For both functions linear regressions were also found with statistical significance ($p < 0.05$) but with a low "R". Wound size and number of wounds per tree were strictly related (positively) to ground slope. Wound size showed a higher angular coefficient and deviated negatively more than the regression with the dependant variable, number of wounds per tree (which was more sensitive to slope gradient).

Detailed Analysis of Damage Distribution in the Remaining Stand in Slope Classes

In a previous analysis, the DBH and stand damages were correlated with slope classes (Table 5). This revealed that the bigger the DBH, the bigger the wound size and the greater the number of wounds per tree. In contrast, the larger the DBH, the lower the share of trees observed with a wound in the stand (Table 5). The share of wounded trees was highly and inversely correlated with the DBH, therefore further statistical analysis was conducted using ANOVA and post hoc Duncan tests. As a consequence, it was inferred that the higher the DBH class, the lower the share of trees with damage (Table 7). In addition, the differences were found to be statistically significant. Broken bole followed this dependence in three of the stands (FA3, PI 1 and PI2) and so did uprooted trees in FA3 (Table 7).

The most common size of wound was between 25 and 100 cm^2 and in different stands it represented 25–50% of cases (Fig. 1A). Bigger wounds, 101–00 cm^2, amounted to approximately 30–40%. Very large wounds were very common in FA3,

Table 6 Non-linear regression analysis: impact of slope steepness (independent variable) on wound size and number of wounds per tree (dependent variables)

Dependent variables	Regression results	Parameters	Values	p level
Wound size (cm^2)	R = 0.839; R^2 = 0.705; R^2 adj = 0.702; df (2230); $p < 0.001$; SE: 52.673	Intercept	42.87935	< 0.001
		Ground slope	6.01524	< 0.001
		Ground slope 2	− 0.03612	< 0.001
Number of wounds per tree	R = 0.808; R^2 = 0.653; R^2 adj = 0.650; df (2230); $p < 0.001$; SE: 0.854	Intercept	1.54159	< 0.001
		Ground slope	0.08192	< 0.001
		Ground slope 2	− 0.00044	< 0.001

Table 7 Share of trees with damage with respect to DBH classes and type of damage

DBH class (cm)	Damage (%)														
	Wounded					Broken bole					Uprooted				
	FA1	FA2	FA3	PI1	PI2	FA1	FA2	FA3	PI1	PI2	FA1	FA2	FA3	PI1	PI2
7.5 ÷ 20.4	81^{a}	65^{a}	41^{a}	56^{a}	22^{a}	5	5	17^{a}	9^{a}	12^{a}	–	–	16^{a}	4	12
20.5 ÷ 40.4	73^{a}	55^{b}	30^{a}	47^{a}	50^{b}	2	1	7^{b}	2^{b}	4^{b}	–	–	3^{b}	–	–
40.5 ÷ 60.4	71^{a}	49^{b}	17^{b}	20^{b}	44^{b}	–	–	2^{b}	–	–	–	–	–	–	–
60.5 ÷ 80.4	51^{b}	32^{c}	18^{b}	–	19^{a}	–	–	–	–	–	–	–	–	–	–
80.5 ÷ 100	39^{c}	23^{c}	14^{c}	–	–	–	–	–	–	–	–	–	–	–	–
> 100	–	–	12^{c}	–	–	–	–	–	–	–	–	–	–	–	–
ANOVA *p*	< 0.05	< 0.05	< 0.01	< 0.05	< 0.01	> 0.05	> 0.05	< 0.01	< 0.05	< 0.05	–	–	< 0.01	–	–

Different lower case letters in superscript show statistically significant differences based on results of ANOVA test followed by Tukey test

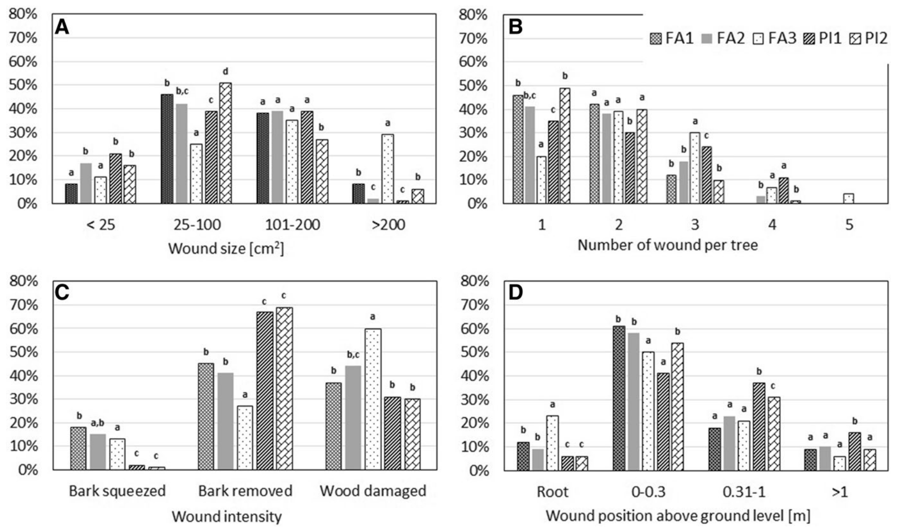

Fig. 1 Distribution of different wound characteristics in analysed stands; results of statistically significant ANOVA test followed by Duncan test; different lower case letters show differences statistically significant

at least three times more than in the other stands and the differences were statistically significant.

The number of wounds per tree also varied with between one and five wounds per tree (Fig. 1B). The most common were two wounds per tree, but trees with one wound were also well represented. There were also statistically significant differences between the number of wounds per tree in different plots (Fig. 1B), i.e. plot PI1, with WTS, had fewer trees with two wounds than in the other plots.

The most common damage was bark removed, reaching up to 70% of all of the cases in the pine stands and significantly fewer, approximately 30–40%, in the beech stands (Fig. 1C). There were also at least 30% of cases with wood damage, and approx. 12–18% of bark squeezed in the beech forests, while just a small percentage of the pine trees had squeezed bark. Only in stand FA3 were there more cases with wood tissue damage than bark removed.

The most common location of damage on the tree (approximately 40–60%) was around the root neck area (0–0.3 m) with a lower value in the pine stand where LWS was applied. In the same pine stand, a significantly higher share of damage than in the other stands was at heights 0.31–1 m and over 1.0 m (Fig. 1D).

Discussion

Wound characteristics such as size, location, and intensity are the main factors which have a strong influence on future wood quality (Meadows 1993; Han et al. 2000; Vasiliauskas 2001; Ezzati and Najafi 2010). Growing high quality trees without defects (i.e. rind gall) is in the interests of the forest owner. A post-harvesting assessment of the logging operation by accurately measuring residual stand damage may be helpful in achieving good quality timber (Stehman and Davis 1997). It is also helpful to know the risk of damage, and to control its occurrence in future operations. Unfortunately, in the study, a high level of damage was recorded in the remaining stands (40–67%) as well as in the regeneration (47–53%, Table 3).

Impact of Slope on Damage

The residual trees and natural regeneration were damaged to a large extent during winching from the felling sites to the skid roads. Skidders, and especially agricultural tractors equipped with skidding devices, used widely in small-scale forestry can be equipped with very long cables, and when the full length is used it leads to a higher probability of damage. The share of trees with damage increased as the slope in the winching areas grew (Tables 4, 5). This was probably due to the limited control of the logs, which can roll more often on steeper slopes during winching. A similar trend was observed in natural regeneration, although it was less pronounced (Table 4). The probability of small diameter trees being uprooted was higher during winching on steeper slopes, as small trees have shorter roots, and steeper slopes usually have thinner soil layer (Fazlollahi Mohammadi et al. 2016).

The share of trees with damage on slopes of more than 45% was nearly twice as large as on slopes below 15% (Table 4). A similar slope impact was also observed in relation to regeneration: there were two or three times more saplings with damage on the steepest slopes (over 45%) than on slopes up to 15%. However, the statistically significant damage to the regeneration depended on slope steepness only in the pine stands—this was not observed in the beech plot FA3 (Table 4). One of the reasons for this could have been the very small number of trees harvested in FA3, albeit of very large sizes. Again, high harvesting intensity, expressed in the number of trees, might explain the higher rate of damage (Sist et al. 1998; Fjeld and Granhus 1998).

On steeper slopes larger wounds were observed and there were more wounds per tree on average (Table 5). This could also be explained by the less predictable winching path on steeper slopes, which may lead to a less controllable trajectory of logs, especially when the logs are winched down slope. Wound intensity also depended on slope steepness (Table 5). As also found in this case, if a wound is made this will often be caused by the pulled log hitting against a remaining tree. According to Legere (2001), most winching damage to residual trees is deep and serious.

As seen in the final statistical analysis, the two significant regressions showed that the increasing gradient of a slope contributes the most to wound size and number of wounds per tree (Table 6).

In the presented research, thicker trees were less often wounded (Tables 5, 7). The size (DBH) of the remaining trees on the slopes also had an impact on the wound characteristics. On thicker trees, bigger wounds were found and a higher number of wounds per tree (Table 7). Only in FA3, ca 80% of the wounded trees had more than one wound, while in the other stands, this percentage ranged from

50 to 65%. In FA3, the biggest logs were winched, which might explain the higher number of wounds per tree.

Detailed Damage Analysis

In terms of wound size, particularly large ones were observed in FA3 (Fig. 1A), where the biggest number of wounds per tree were also found (Fig. 1B). Furthermore, in the same stand (FA3), the biggest share of wounds was found with wood tissue damage (Fig. 1C) as well as roots with damage (Fig. 1D). All of these cases can be explained by the following factors: in FA3, the biggest logs were winched and the thickest trees were in the remaining stand. Stand PI1 was also significant in terms of wound position—the largest share of the wounds was observed above 0.3 m and especially over 1.0 m. WTS was only applied in PI1—extraction with tree crowns which caused wounds higher over the ground.

Nearly 30% of the wounds in FA3 occurred with the bark removed, and in nearly 60% of the wounds, the wood tissue was damaged (Fig. 1C). Beech stands FA1 and FA2 were more homogenous in this respect: approximately 40% of the wounds occurred with the bark removed and in 40% of the wounds, the wood tissue was damaged. In both pine stands, wounds with the bark removed were observed on 65% of the trees, and only 30% had deeper damage in the wood (Fig. 1C). These differences were probably related to the thicker bark on the bottom parts of the pine trees.

Damage Complexity: Felling, Winching and Skidding

In the literature, it was found that stand damage during the winching phase was usually heavier than that during the skidding phase. In the last decade, several analyses of post-harvesting proved that residual stand damage during winching was from two to four times greater than during skidding: 32–80% and 7–24%, respectively (Danilović et al. 2015; Tatsumi et al. 2014; Stańczykiewicz et al. 2015; Tsioras and Liamas 2015; Enache et al. 2016; Jonkers and Van Leersum 2000; Solgi and Najafi 2007; Lotfalian et al. 2008; Mousavi 2008, Majnounian et al. 2009; Naghdi et al. 2008, 2009; Nikooy et al. 2010; Tavankar et al. 2010; Jourgholami 2012a, b; Tavankar and Bonyad 2014). These results suggest that particular attention should be paid to the remaining trees when winching.

Even if animal power can be used for extraction in small-scale forestry (Spinelli et al. 2010; Jourgholami 2012c; Melemez et al. 2014), in the last years the level of mechanised harvesting has generally increased (Mederski et al. 2016b), as has mechanised extraction using forwarders (Proto et al. 2018), skidders and farm tractors (Yu et al. 2017). Skidders and farm tractors, in particular, allow for an acceptable compromise between productivity and costs compared to animal power and other mechanical systems.

Consequences of Damage and Possible Avoidance Strategies

Wound size can be considered one of the most important characteristics of decay (Han and Kellogg 2000). In his work, Nyland (1986) stated that in hardwood forests, logging wounds did not influence diameter growth, but there was still a high probability of rot development due to the long process of healing. Smith et al. (1994) studied the occlusion process of logging wounds after ten years in the Appalachian forest, and reported that even smaller wounds (below 322 cm^2) needed from 5 to 10 years to heal. According to Vasiliauskas (1993), a 10 cm wide wound on Norway spruce requires from 25 to 50 years for full healing. In the end, full occlusion time mainly depends on tree increment dynamics. Welch et al. (1997) indicated that, in general, 15 years is needed for the complete healing of a Sitka spruce wound measuring up to 60 cm^2. Tavankar et al. (2019) found that, for beech trees, only 12% of wounds were completely closed after a 5-year period and 15 years were necessary for the complete closure of 80% of total wounds.

Regarding wound intensity, there were some differences between the sites: generally, the most frequently occurring damage were wounds with the bark removed as well as damaged wood (Fig. 1C). Bark stripping is a particularly unwelcome wound, which can cause fungal infection, the risk of which grows as the size of the wound increases (Mäkinen et al. 2007). Stem wound and root damage facilitates the spread of pathogens and decay formation in tree wood, which, in the end, decreases timber quality (Dimitri 1983; Shigo 1966). Damaged wood should be considered particularly serious and may accelerate the development of decay (Tavankar and Bonyad 2014).

Wounds created as a result of ground-based logging operations usually occur on the lower part of the residual tree boles (Picchio et al. 2018; Naghdi et al. 2008; Tavankar et al. 2010; Han and Kellogg 2000). However, in the presented research, a consistent amount of damage was also observed over 0.3 m, when FTS was applied. With more frequency, the analysis of wound height showed that in all the study sites, the highest absolute frequency was recorded in the stump area (0–0.3 m), ranging from 45% (FA3 and PI1) to 55% (FA1, FA2 and PI2). The location of damage on the bole of the tree is important. The most valuable timber is the butt log (Bettinger and Kellogg 1993), and this tree part should be particularly protected during winching and skidding, especially when large logs are winched (Fig. 1D). Han et al. (2000) reported that the frequency of infection and the amount of decay decreased as wound height increased.

The highest risk for decay development is in the area of the felling cut and the root collar (Meng 1978). It may happen that rot does not develop (pine has a higher resistance to fungi due to resin), however a healing wound creates a rind gall, which on the bottom part of the tree will significantly determine future log quality (Ezzati and Najafi 2010; Karaszewski et al. 2013).

Furthermore, it was found that root wounds can significantly reduce tree growth, especially if the wounds are deep (Meadows 1993). Only in FA3 did the root wounds amount to over 20%, while in the other sites, they were below 10% (Fig. 1D). In the uneven-aged stand FA3, there were trees of large sizes: harvested logs of at least 2.0 m^3 of mean volume with a median diameter of approximately 50 cm. This suggests that there were also older trees left in the stand. It is usual that older trees have superficial roots more often above ground level and they could more easily be wounded during winching or skidding.

Damage to the residual stand after logging operations may lead to serious economic loss in terms of both lower timber quality at final harvesting (Kiser 2011) and possible tree growth reduction (Vasiliauskas 2001). However, research on the effect of damage on tree growth has had contradictory results (Vasiliauskas 2001; Picchio et al. 2011, 2018).

While it is essentially impossible to harvest trees without some level of damage to some of the remaining trees, it is important to minimize damage in terms of the number of affected trees as well as the size of the damage on particular trees. The most effective way to reduce decay and avoid volume loss in residual trees is to minimize wounding during forest operations. Picchio et al. (2012) studied improved winching techniques to reduce stand damage in forests in central Italy. It was discovered that when using a snatch block, the frequency of wounded trees was reduced by one quarter (from 50 to 36%). It was also noted that the snatch block was especially effective in preventing damage to dominant trees. A detailed analysis of work cycles in the time study showed that rigging a snatch block took about 5% of the total winching time, but it allowed for a reduction in the incidence of hang-up time from 6 to 4%. Using a snatch block also resulted in a significant reduction in pulling time, most likely dependent on the smoother drag. Finally, in the winching with snatch block, Picchio et al. (2012) observed an average productivity decrease of approximately 4% with respect to the common winching.

Han and Kellogg (2000) suggested in their research that artificial tree protection rigging, such as rub pads, should be used to prevent damage on stumps and stems, even if, these solutions are not always feasible, mainly for economic reasons.

In addition, detailed planning may reduce damage to a level which is acceptable and predictable. Damage to residual stands can be decreased by good management practice: the proper planning of winching corridors and skid roads, as well as training and supervising workers (Cline et al. 1991; Wallentin 2007; Nikooy et al. 2010; Marchi et al. 2014). In fact, it has already been reported that residual stand damage can be decreased substantially by identifying the winching area before logging operations, careful road planning and the employment of skilled operators (Cline et al. 1991; Tavankar et al. 2013; Nikooy et al. 2010).

In the study sites, it was also observed during the field tests that there were two additional factors that affected winching damage. Firstly, when winching was done on areas with humps and obstacles, damage was more probable. Secondly, when there was a larger angle between the cable and the shortest route of the logs to the skid road, the damage was greater since the logs tended to tumble more frequently, thereby making it more likely that the trees would be damaged. These two factors should be also studied in future research when damage to the remaining stand on hilly areas is analysed.

Conclusion

Skidding, a popular extraction method in small-scale forestry, can cause substantial and severe damage to the remaining stand. However, this system allows for an acceptable compromise between productivity and costs compared to animal power and other mechanical systems. The results presented in this research indicated that the probability of damage was higher on steeper slopes, and therefore more care should be taken in these areas. For this reason, a post-harvesting assessment of the logging operation by accurately measuring residual stand damage may be helpful in achieving good quality timber. Areas at risk of damage can be explained to an operator in order to control their occurrence in future extractions.

In the presented research, slope steepness had an influence on several factors linked to damage to the remaining stand. First, the share of wounded trees grew as the ground slope increased, although this was less obvious in natural regeneration, especially in the case of broken boles. Moreover, on steeper slopes there were also larger wounds and there were more, on average, per tree. Wound intensity also depended on the degree of the slope.

The size (DBH) of the remaining trees on slopes also showed some influences on wound characteristics. On thicker trees larger wounds should be expected along with a higher number of wounds. However, thicker trees were less often wounded. There was no link between DBH and wound position or its intensity. Finally, wound position on a tree did not depend on slope steepness.

As steeper slope gradient indicates that there is a higher probability of damage to the remaining stand, more careful winching could limit injuries to the trees. Even if skidders and farm tractors can be equipped with a winch and cable over 100 m in length, a long winching distance can lead to even more damage to the remaining stand. Therefore, when it is possible, limiting the winching distance could be a way to control stand damage in small-scale forestry on hilly areas, where skidding is the only available extraction method. In addition, the use of the snatch block, as showed in literature, could positively improve the winching operation. Alternatively, when possible and when financially acceptable, different forms of extraction should be used, for example, cable cranes or traction-winch-supported forwarders.

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