

Article

Assessment of Wound Recovery and Radial Growth 10 Years after Forest Operations in Hardwood Stands

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Abstract: Damage to the residual stand caused by forest operations can have detrimental impacts on the biological processes of stand growth. This study shows the details from monitoring damages related to manual motor ground-based timber operations in a mountain mixed hardwood forest. The harvesting system was cut-to-length, and logs were extracted by wheeled cable-skidders. Data were collected from the remaining trees immediately after logging and 10 years after the logging session. The parameters assessed included stem injury, radial growth increment and wound healing rate for five hardwood species of commercial interest. The number of injured trees represented 15% of the residual stand, 23% of the wounds were related to the felling operation and 76% to extraction. Wound height, wound size and damage to bark, due to felling, were larger than those in extraction, while wound width and damages to cambium and wood caused by extraction were larger than those triggered by felling. Ten years after harvesting, average longitudinal and radial growth increments were reduced by 38% and 24%, respectively. Wound healing rates ranged from 12.90 mm yr^{−1} for extraction wounds to 19.70 mm yr^{−1} for felling ones within 10 years. On average 73% of all wounds were still unrecovered and 17% of these were decayed, while only 10% were fully healed within a 10-year recovery period. The analysis showed that the best recovering performance among damaged trees was mostly achieved in shade-intolerant species with a diameter less than 40 cm, located in the dominant canopy layer with a wound size smaller than 100 cm². In addition to the significant effect on log quality, the ecological longevity of residual trees has major implications for pre-planning harvesting operations that can preserve the quality and value of residual trees. Understanding the damage inflicted upon residual trees is essential to reduce economic losses, improve planning of harvest operations and, ultimately, ensure a sustainable harvest of mixed hardwood stands in mountain regions.

Keywords: cable skidder; diameter growth; residual tree; selective harvesting; wound recovery



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1. Introduction

Disturbances related to forest operations are practically unavoidable, and they can involve forest soil, natural regeneration and residual stand [1–4]. Stem injuries (scarring, tree fork or stripping of bark), and bending or breaking of crown branches can occur during felling, while root collar damage, injury to cambium and sapwood exposure are common types of damage to the residual stand that can occur during forest operations [5–7]. Most often, damage to the remaining trees results from inaccurate inventories, caused by lack of information on stands and physical terrain conditions, poor planning and the use of inexperienced operators [8–12].

Even with high mechanization and good coordination, damage to the remaining trees is sometimes unavoidable [13–15], especially in mountain harvesting operations in mixed hardwood stands under single or group selection cutting regimes [16,17]. This is mainly related to the fact that harvesting operations in such stands are carried out generally in steep terrain via ground-based skidding systems, with restricted maneuvering space, especially when moving felled trees. These are conditions in which large amounts of damage often occur, not only to standing trees but also to established regeneration [18,19].

Several factors, such as silvicultural treatment [20], method or intensity of harvesting [13], method of wood processing [21] and species composition [5], determine the intensity and extent of harvesting damage. Other determinant factors are harvest season, available equipment and the layout of skidding trails [21]. These factors influence the frequency and level of damage to residual trees and future healing processes. The frequency of damaged trees and its intensity during harvesting operations can have detrimental impacts on the future growth of stands [16,22]. When a tree is injured, whether its stem or root is affected, certain eco-physiological features decline and anatomical reactions can potentially occur, such as stem deformation, reduced growth and seed supply, which in some cases result in decreased tree vigor, or even tree mortality [23,24]. Some authors have pointed out that the result of the visibility of the wood stem (i.e., peeling of the bark or exposure of the cambium) is the formation of the pitch ring and decay, which allows easy access to organisms and diseases [5,25]. Other negative consequences are retarding tree growth and degrading future financial value up to 20% at the time of the final harvest [21,26]. In temperate forests, harvest injuries can be managed by limiting the felling operation to the dormant period and scheduling log extraction in dry seasons, when there is less risk of stand damage and soil disturbance. Some authors have emphasized posterior inventories aimed at analyzing the extent and severity of stand damage, and monitoring the long lasting effects of injuries on tree growth [27,28].

The biological traits of the damaged trees (e.g., age, species) and the profile of wounds, such as severity, size and location in which wounds occurred, are also important in determining wound recovery and the future quality of the injured trees [29,30].

Three years after a bark stripping wound, Hecht et al. [31] found a higher risk of wood decay (almost three times) for the European beech when the wound occurred at the crown stem level compared to damages occurring to the basal stem. Tavankar et al. [30] concluded that fifteen years after harvesting, the size of wounds not only reduced, but also tended to recover with a mean of 17.5 mm yr^{-1} mainly for shade-intolerant species. Similar results were noted for *Fraxinus excelsior* trees in Lithuania [32].

Overall, there is a long history of research regarding damage to residual stand following forest operations, either in final felling or in thinning treatments, that shows the importance of the subject from the perspective of sustainable forest management. However, relatively few studies have so far focused on the implications of damage to residual stand in uneven-aged mountain hardwoods forest, where semi-mechanized systems, operating with limited working space and single-lane skid trails, are the only option for extracting timber. In addition, the medium-term effect of harvest treatments on radial growth increment and healing of damages inflicted on residual trees has not been well-addressed [33,34].

Considering the lack of these topics in the current literature, this study investigated the midterm impact of forest operations on residual tree damage in an uneven-aged broadleaved forest in northern Iran. Specifically, the objectives of this study were the following: (i) to characterize and quantify post-harvest damage caused by forest operations (felling and log extraction) in broadleaved mountainous forests; and (ii) to analyze harvesting injuries, radial growth increment and wound healing rate of five commercial hardwood species over a period of 10 years after harvesting. In this way the authors wanted to answer the following research questions: what are the main drivers of residual stand damages in semi-mechanized forest operations in uneven-aged mountainous hardwood? What are the parameters that have a substantial influence on the recovery rates of the damage caused?

2. Materials and Methods

2.1. Study Areas

The study was conducted in the natural forest area of Nav-Asalem between 37°38' to 37°42' N and 48°48' to 48°52' E in northwest Iran. Three adjacent cutting blocks were selected. The altitude of the blocks ranged from 400 to 1200 m above sea level. The area of these blocks varies from 33 to 43 ha with a heterogeneous slope ranging from 15% to 33%. The mean annual precipitation ranges from 960–1270 mm per year and the mean annual temperature ranges between -2°C in February and $+25^{\circ}\text{C}$ in August [5]. Soil types are predominantly brown forest and the texture varies from loam clay to loam with good drainage [5,30]. The study area is placed in an uneven-aged forest. This is a broadleaved mixed forest, managed under a single or group tree selection regime. Single selection was applied in the three investigated cutting blocks. A cut-to-length harvesting system, with manual motor felling by chainsaw, was applied for directional felling and processing of trees within the stand and extraction on designated skid trails was performed with a Timberjack 450 skidder. The applied harvesting system is the most commonly used in the Hyrcanian forests. Harvesting intensity, as the proportion of removed basal area to initial stand basal area, ranged from 5.5% to 6.1%, equivalent to 8.3% to 9.1% of stand volume. The main characteristics of the three cutting blocks are given in Table 1.

Table 1. Stand characteristics and harvesting intensities in 2008.

Stand Characteristics	Block I	Block II	Block III
Altitude range (m a.s.l.)	400–800	800–1200	1200–1800
Area (ha)	33.40	41.44	43.70
Average slope (%)	15–25	20–30	19–33
Average tree DBH (cm)	22.81	21.90	22.07
Average tree height (m)	15.20	15.08	15.00
Tree density (stem ha^{-1})	271	314	305
Standing volume ($\text{m}^3 \text{ha}^{-1}$)	198.800	215.500	248.070
Harvesting intensity (% of standing volume)	8.28	8.63	9.11

2.2. Data Collection and Damage Assessment

A two-stage inventory was conducted for collecting residual stand damage data. The first inventory was right after the last timber harvesting in 2009 and included measuring and classifying damage on residual trees caused by felling and extraction operations. The second inventory was conducted in 2018 and involved measuring longitudinal and radial growth increment and determining wound healing rates 10 growing seasons after forest operations. A total number of 1490 trees were inventoried, i.e., 340 trees for felling injuries and 1150 trees for extraction injuries. A systematic grid survey network ($100 \text{ m} \times 100 \text{ m}$) was designed, consisting of delineating fixed circular plots throughout the area of interest. Each plot had an area of 0.1 ha. The geographical coordinates of each plot center were recorded. In each plot, all trees with a diameter at breast height (DBH) $\geq 7.5 \text{ cm}$ were measured with a caliper with an accuracy within one millimeter, and the species recorded. From each plot, two individual trees (one closest to the center and the other with the largest diameter) were selected to measure tree height using a hypsometer with an accuracy of 0.1 m. In each plot, the trees were labeled as healthy and damaged. For each damaged tree, several attributes were recorded, such as type of damage, damage height from the ground (vertical location), length, width, size of damage and agent, i.e., felling or log extraction (Figure 1).



Figure 1. (A) Winching wound on middle-aged beech tree at the end of period, open wound. (B) Felling wound on old maple tree (*Acer velutinum* Boiss.) at the end of period, open wound.

Three types of damages were broadly considered: crown injury, stem injury and root collar injury. The height of injury was recorded from the ground up to the center of the wound on the tree stem using a tape measure. Wound size was used as the indicator to determine the wound healing rate. We prepared the wound images using a 20-megapixel camera (Ultrasonic Brand), and the wound size was measured at the beginning and end of the period using the UTHSCSA Image Tools software for Windows (Version 3.0). It should be noted that the minimum threshold to be considered as damage was a wound area above 4.62 cm² [35]. Wound intensity was classified into three classes: bark removed, cambium or phloem damaged, and fiber exposed [30].

To evaluate recovery ability after damage, a sample of 10% of the damaged trees with at least one injury on the stem occurring in 2008 was randomly selected. These were used for conducting post-harvest inventory in 2018, including 34 trees affected by felling injuries and 115 caused by extraction. The locations of these trees within the stand were precisely recorded by the global positioning system (GPS) so that it was possible to iterate a further postharvest survey. For each damaged tree, a neighboring healthy tree with similar characteristics (DBH and species), and within the same vertical layer, was selected and its geographical position recorded. The conditions of injuries 10 years after forest operations were classified according to the recovery status as unrecovered or open, recovered or fully closed and decayed [35]. Radial growth increment of damaged trees was calculated by means of Equation (1), and wound healing rate was calculated with Equation (2):

$$Dr = (d_e - d_b) / t \quad (1)$$

$$Hr = (r_e - r_b) / t \quad (2)$$

where, Dr radial growth increment (mm yr⁻¹), d_e and d_b represent diameter at breast height (mm) at the end and beginning of the period, respectively, t is time interval between two measurements (yr). Hr is wound healing rate (mm yr⁻¹), r_e and r_b correspond to differences in wound width (mm) between end and beginning of period.

2.3. Statistical Analysis

Authors tested the normality and homogeneity of variances using the Kolmogorov–Smirnov and the Levene tests in SPSS 19.

One way analysis of variance (ANOVA) and Duncan’s test was applied to check for the presence of statistically significant differences between the characteristics of the wounds within and among the three investigated blocks. Differences between the characteristics of the wounds related to felling operation and the ones related to extraction operation were investigated by unpaired samples T-test. Paired samples T-test was applied to check for statistically significant differences between the mean values of growth increments of damaged and undamaged trees, and between wound characteristics just after forest operations (2008) and ten years later (2018). Non-parametric Chi-square test was applied to investigate the effects of tree and wound characteristics on radial growth increment, wound healing rate and wound recovery status.

3. Results

A summary of damaged trees after forest operations is presented in Table 2. For all the investigated parameters there were no statistically significant differences among the three blocks. Differences among the various investigated characteristics of each parameter were detected for all the characteristics. The proportion of damaged trees varied from 13.50% in harvest block III to 16% in harvest block II. However, the differences were not statistically significant among blocks. Among damaged trees, extraction operation was responsible for the major part of damages in all the investigated blocks, with about 70% of injuries related to extraction. The most common damage type was injury to the stem (Figure 1). A large number of damages occurred in the lower parts of the trees, i.e., between 30 and 100 cm above the ground, measuring less than 100 cm² and having a width of 11–20 cm.

Table 2. Proportion of damage after initial harvesting operation in 2008.

Wound Characteristics		Block I	Block II	Block III
Proportion of damaged trees (%)		14.80 ± 1.30 a	16.00 ± 1.51 a	13.50 ± 1.29 a
Operation	Felling	31.10 ± 2.19 aB	28.80 ± 2.16 aB	29.50 ± 2.38 aB
	Extraction	68.90 ± 4.00 aA	71.20 ± 3.9 aA	70.50 ± 4.23 aA
Position	Crown	21.30 ± 1.85 aB	20.10 ± 1.71 aB	17.80 ± 1.88 aB
	Stem	66.20 ± 4.96 aA	69.10 ± 5.23 aA	70.70 ± 5.40 aA
	Root collar	12.50 ± 1.05 aC	10.80 ± 1.03 aC	11.50 ± 1.10 aC
Intensity	Bark	17.58 ± 3.33 aC	18.73 ± 2.61 aC	18.01 ± 2.93 aC
	Cambium	28.22 ± 3.80 aB	30.08 ± 3.50 aB	29.50 ± 3.71 aB
	Fiber	54.20 ± 6.31 aA	51.19 ± 5.88 aA	52.49 ± 6.60 aA
Height from base (m)	<0.30	30.25 ± 3.71 aB	28.34 ± 3.85 aB	29.25 ± 3.70 aB
	0.31–1.00	46.70 ± 3.35 aA	47.91 ± 3.69 aA	46.02 ± 3.91 aA
	>1.10	23.05 ± 2.70 aC	23.75 ± 2.48 aC	24.73 ± 2.10 aC
Size (cm ²)	<100	39.42 ± 2.95 aA	38.90 ± 2.99 aA	40.64 ± 3.10 aA
	101–200	29.11 ± 6.10 aB	29.50 ± 5.96 aB	29.17 ± 6.20 aB
	>201	31.47 ± 3.84 aB	31.60 ± 3.92 aB	30.19 ± 3.61 aB
Width (cm)	<10	17.32 ± 3.00 aB	18.61 ± 3.18 aB	17.83 ± 2.96 aB
	11–20	65.58 ± 7.44 aA	66.30 ± 7.92 aA	66.10 ± 7.70 aA
	>21	17.10 ± 2.48 aB	15.09 ± 3.65 aB	16.17 ± 3.40 aB

Note: lowercase letters show significant differences ($p < 0.05$) among blocks. Upper case represents differences among damage categories for each block. Applied test: one-way ANOVA with Duncan test as a post hoc.

Table 3 summarizes the characteristics of wounds related to felling and extraction. The frequency of severe damages, i.e., fiber removed and cambium exposure, were significantly higher by extraction compared to felling (relative risk of 68.7/8.8 for fiber removed and 21.7/17.7 for cambium exposure). The position of the damage was significantly higher

(over three meters) by felling operation in contrast to extraction. Felling wounds were 305% longer and 137% greater in size compared to extraction wounds, while inflicted damages were 31% wider by extraction compared to felling.

Table 3. Wound characteristics (mean $\pm$ SD) following initial operations in 2008.

Wound Characteristics	Felling	Extraction
Bark (%)	73.50 a	9.60 b
Cambium (%)	17.70 a	21.70 a
Fiber (%)	8.80 b	68.70 a
Wound height (m)	3.95 $\pm$ 1.02 a	0.61 $\pm$ 0.12 b
Wound width (cm)	20.80 $\pm$ 5.20 b	27.30 $\pm$ 2.60 a
Wound length (cm)	72.50 $\pm$ 10.40 a	17.90 $\pm$ 2.00 b
Wound size (cm ²)	842.30 $\pm$ 21.00 a	355.20 $\pm$ 12.70 b

Different letters indicate statistically significant difference ($p < 0.05$) between treatments according to unpaired samples *t*-test.

Table 4 shows tree characteristics and stand attributes resulting from the occurred injuries. Ten years after forest operations radial growth increment was reduced by 15.60% and 32.50% due to damage from felling and extraction, respectively, as compared to undamaged trees. During this period, height growth of damaged trees decreased by 20.65% and 58.75% due to felling damage and extraction damage, respectively, in comparison to undamaged trees. After 10 years, the width and size of felling wounds were significantly smaller by 95% and 74%, respectively, while the width and size of extraction wounds were reduced by 45% and 17%, respectively. Wound length tended to recover but the change was not significantly different for either operation. Ten years after forest operations wounds tended to recover, mostly the felling wounds. However, more than 70% of the wounds were still unrecovered. Only 14% of felling wounds and 4% of extraction wounds were completely healed. Proportion of decaying wounds from log extractions was 2 times greater (relative risk) than the proportion of decaying wounds from felling.

Table 4. Quantitative characteristics of post-harvest damaged trees (mean $\pm$ SD) ten years after forest operations in 2008.

Attributes		Felling		Extraction	
		2008	2018	2008	2018
Stand attributes					
No. of observation		34.00		115.00	
Radial growth increment (mm yr ⁻¹)	Damaged	6.50 ± 0.4 ^{N.S.}		5.20 ± 0.4 *	
	Undamaged	7.70 ± 0.43		7.71 ± 0.40	
Height growth (m yr ⁻¹)	Damaged	0.73 ± 0.11 ^{N.S.}		0.33 ± 0.10 *	
	Undamaged	0.92 ± 0.12		0.80 ± 0.14	
Wound characteristics					
Wound width (cm)		20.80 ± 5.203	1.11 ± 0.5	27.31 ± 2.59 *	15.12 ± 2.10 *
Wound area (cm ²)		842.32 ± 21.04	217.20 ± 10.18	355.20 ± 12.66 *	293.2 ± 10.1 *
Wound length (cm)		72.50 ± 10.40	67.47 ± 10.72	17.92 ± 2.05 *	16.90 ± 2.10 *
Wound healing rate (mm yr ⁻¹)		19.70 ± 1.74		12.90 ± 0.43 *	
Recovery status (%)	Closed	14.71 ± 1.20		4.35 ± 0.93 *	
	Open	73.53 ± 5.82		73.04 ± 5.82 ^{N.S.}	
	Decayed	11.76 ± 1.05		22.61 ± 4.08 *	

(N.S.): not significant, (*): significant, significant differences ($p < 0.05$) between treatments according to unpaired sample *t*-test (felling vs. extraction) and paired samples *t*-test (damaged vs. undamaged and 2008 vs. 2018).

The relationships between stand characteristics, radial growth increment and wound healing rate are reported in Table 5. Damaged trees showed significantly lower radial

growth increment in comparison to undamaged trees (almost -30%). The DBH growth decline was significantly stronger for trees with a diameter over 65 cm. Regarding tree crown class, radial growth decline was evident for all the classes, but an evident trend of wound healing rate was shown. In particular trees in the dominant crown class there was a significantly higher wound healing rate than trees in the intermediate and, mostly, suppressed crown classes. Interestingly, all species showed decreased DBH increment between damaged and undamaged trees, except for *Carpinus betulus* L. Concerning wound healing rates of the different investigated species *Fagus orientalis* Lipsky showed the fastest recovery while *Tilia begonifolia* Stev. the lowest one.

Table 5. Radial growth increment of damaged trees and their recovery trends (mean $\pm$ SD) in relation to tree characteristics ten years after operations in 2008.

Tree Characteristics		Change in DBH Growth between Damaged and Undamaged Trees (%)	Wound Healing Rate (mm yr ⁻¹)
DBH (cm)	<40	−20.18 ***	20.92 $\pm$ 1.80 a
	41–65	−23.48 ***	18.90 $\pm$ 1.60 a
	66–90	−37.35 ***	6.09 $\pm$ 0.70 b
	>91	−38.73 ***	5.84 $\pm$ 0.50 b
Crown class	Suppressed	−25.18 ***	8.10 $\pm$ 1.20 c
	Intermediate	−27.88 ***	13.80 $\pm$ 1.20 b
	Dominant	−22.59 ***	17.00 $\pm$ 1.30 a
Tree species	<i>Fagus orientalis</i> Lipsky (oriental beech)	−22.54 ***	17.0 $\pm$ 2.30 a
	<i>Carpinus betulus</i> L. (hornbeam)	−9.09 N.S.	9.2 $\pm$ 1.20 c
	<i>Alnus subcordata</i> C.A. Mey. (caucasian alder)	−26.58 ***	18.0 $\pm$ 2.30 a
	<i>Acer velutinum</i> Boiss. (persian maple)	−20.73 ***	16.1 $\pm$ 1.70 a
	<i>Acer cappadocicum</i> Gled. (cappadocian maple)	−25.93 ***	13.6 $\pm$ 1.40 b
	<i>Tilia begonifolia</i> Stev. (lime tree)	−38.46 ***	6.2 $\pm$ 0.40 d

Note: lowercase letters indicate statistically significant differences ($p < 0.05$) among the treatments according to one-way ANOVA with Duncan test as post hoc. Results of Chi-square test for frequency of damaged trees: DBH class: $\chi^2 = 41.44$, $p < 0.000$; tree vertical layering class (crown class): $\chi^2 = 37.87$, $p < 0.000$; tree species: $\chi^2 = 95.47$, $p < 0.000$. “***” indicates significant difference at $p < 0.001$ according to Chi-square test. N.S. means “not significant”.

Table 6 analyzes radial growth increment and wound healing rates in response to various types of wound characteristics. Different types of wound intensity significantly affected radial growth increment and wound healing rates. Diameter growth increments were significantly decreased in different levels of wound intensity, ranging from -6.99% for bark removal to -38.71% for fiber damage, in comparison to undamaged trees. Radial growth increment and wound healing rates of damaged trees were significantly affected by the wound height. Wounds higher on the tree stem had less effect on radial growth increment compared to the radial growth increment of similar undamaged trees. The wound healing rate at higher heights was also greater than lower ones. With increasing wound size, radial growth increment decreased, ranging from -8% in smaller wound size (less than 100 cm²) to -45% in greater wound size (greater than 200 cm²) compared to the radial growth increment of similar undamaged trees. The greatest diameter growth increment compared to the radial growth increment of similar undamaged trees was observed for the least wide injuries (smaller than 10 cm). Similarly, the wound healing rate by size and width was greater in the classes of size < 100 cm and width < 10 cm.

Table 6. Radial growth increment and wound healing rates (mean $\pm$ SD) regarding different characteristics of wound ten years after operations in 2008.

Wound Characteristics		Change in DBH Growth between Damaged and Undamaged Trees (%)	Wound Healing Rate (mm yr ⁻¹)
Intensity	Bark	−6.99 N.S.	18.34 $\pm$ 1.80 a
	Cambium	−23.88 ***	14.21 $\pm$ 1.50 b
	Fiber	−38.71 ***	8.47 $\pm$ 1.04 c
height (m)	<0.30	−39.00 ***	9.62 $\pm$ 1.10 c
	0.31–1.00	−22.10 ***	14.51 $\pm$ 1.40 b
	>1.10	−19.50 ***	18.12 $\pm$ 1.70 a
size (cm ²)	<100	−7.80 N.S.	18.04 $\pm$ 1.70 a
	101–200	−32.93 ***	13.64 $\pm$ 1.50 b
	>201	−45.40 ***	8.10 $\pm$ 1.30 c
width (cm)	<10	−5.20 N.S.	17.94 $\pm$ 1.30 a
	11–20	−31.20 ***	14.85 $\pm$ 1.30 a
	>21	−46.70 ***	3.60 $\pm$ 1.30 b

Note: lowercase letters indicate statistically significant differences ($p < 0.05$) among the treatments according to one-way ANOVA with Duncan test as post hoc. Results of Chi-square test for frequency of damaged trees: Intensity class: $\chi^2 = 31.83$, $p < 0.000$; height class: $\chi^2 = 13.71$, $p < 0.001$; size class: $\chi^2 = 3.48$, $p > 0.05$; width class: $\chi^2 = 32.91$, $p < 0.000$. “***” indicates significant difference at $p < 0.001$ according to Chi-square test. N.S. means “not significant”.

Table 7 summarizes the status of wound healing in relation to the various investigated characteristics based on Chi-square analysis. Wounds tended to recover slower with increasing tree diameter. The highest percentage of recovered wounds was detected for the smallest diameter classes of less than 40 cm, while unrecovered wounds and decayed wounds were mainly concentrated in larger diameter classes. Concerning the effects of crown classes, in each class more than 60% of wounds were unrecovered, while 15%–30% of wounds were decayed with an increasing trend from dominant to suppressed crown class. The highest percentage of recovered wounds were found for *Fagus orientalis*, while *Carpinus betulus* and *Tilia begonifolia* showed a large percentage of unrecovered wounds (85%) and decayed wounds (36%), respectively. A high percentage of recovered wounds was observed in the case of light damage to bark, while unrecovered wounds and decayed wounds were dominant in trees whose cambiums were damaged, ranging from 26%–71%, respectively. None of the wounds at the first 30 cm from the ground level were closed, while more than a quarter of them were decayed. With increasing height from the ground, wounds tended to recover with the highest proportion over 100 cm from the base level. After a 10-year recovery period, small-sized wounds (<100 cm²) tended to recover. Nevertheless, none of the small-sized wounds (<100 m²) were decayed, while 50% of large-sized wounds (>200 cm²) were decayed. The larger the wound width the higher the revealed percentage of decayed and unrecovered wounds.

Table 7. Proportion of wound recovery status regarding various independent factors.

		Wound Recovery Status (%)			X ² Value
Stand Attributes		Recovered	Unrecovered	Decayed	
DBH (cm)	<40	23.8	52.40	23.8	0.16 N.S.
	41–65	6.50	76.90	16.6	85.15 **
	66–90	2.10	80.90	17.0	105.62 **
	>91	0.00	62.50	37.5	6.19 *
	X ² value	24.182 **	7.77 N.S.	12.250 **	-

Table 7. Cont.

		Wound Recovery Status (%)			X ² Value
Stand Attributes		Recovered	Unrecovered	Decayed	
Crown class	Suppressed	4.80	61.90	33.40	48.74 **
	Intermediate	7.30	71.00	21.70	67.22 **
	Dominant	8.50	75.60	15.90	80.57 **
	X ² value	1.143 N.S.	1.445 N.S.	6.282 *	-
Tree species	<i>Fagus orientalis</i> Lipsky	8.80	75.00	16.20	78.86 **
	<i>Carpinus betulus</i> L.	3.80	84.60	11.60	118.35 **
	<i>Alnus subcordata</i> C.A. Mey.	6.30	62.50	31.20	48.98 **
	<i>Acer velutinum</i> Boiss.	6.70	66.70	26.60	55.44 **
	<i>Acer cappadocicum</i> Gled.	7.70	69.20	23.10	60.62 **
	<i>Tilia begonifolia</i> Stev.	0.00	63.60	36.40	7.84 **
	X ² value	2.176 N.S.	4.87 N.S.	17.00 **	-
Wound Intensity	Bark	250.00	63.90	11.10	45.26 **
	Cambium	3.20	71.00	25.80	71.78 **
	Fiber	0.00	78.00	22.00	31.36 **
	X ² value	17.286 **	0.47 N.S.	6.136 *	-
Height from base (cm)	<0.30	0.00	72.70	27.30	21.160 **
	0.31–1.00	5.20	76.90	17.90	88.34 **
	>1.10	18.10	70.50	11.40	64.58 **
	X ² value	7.35 **	0.25 N.S.	6.90 *	-
Wound size (cm ²)	<100	11.70	88.30	0.00	57.76 **
	101–200	4.30	76.60	19.10	89.18 **
	>201	2.40	47.60	50.00	44.24 **
	X ² value	9.34 **	12.02 **	13.92 **	-
Wound width (cm)	<10	10.90	83.60	5.50	113.24 **
	11–20	2.50	75.30	22.20	83.54 **
	>21	0.00	68.00	32.00	12.96 **
	X ² value	4.57 *	1.70 N.S.	17.20 **	-

N.S. = not significant. * = significance at $p < 0.05$. ** = significance at $p < 0.01$.

4. Discussion

The obtained results confirmed that ground-based mechanized extraction is the major cause of damage to residual stand when dealing with semi-mechanized harvesting systems [36–38]. Felling wounds showed a higher average dimension, while extraction ones were deeper and much more frequent. As a consequence, wounds related to tree felling recovered at higher rates and caused a lower decline of diameter and height growth rates of the injured trees. Therefore, considering that the present results confirm that the deeper the wound the longer the recovery time and the higher the possibility of wood decay in the wound [34], particular attention should be put to optimizing ground-based mechanized extraction operation [39–42]. Given that extraction is the major cause of residual stand damage, increasing the quality of operator skills and improving extraction operation planning could positively influence the overall results. Better results could be achieved by decreasing of the opportunity for colonization of wound-invading fungi [43] and preventing a decrease in the quality of timber [44], but also in fostering the potential contribution of the forest stands to climate change mitigation. Carbon sequestration from trees is strongly related to stand productivity [45–48].

It is moreover worth noticing that, as expected, wounds related to extraction operation are located closer to the base of the trees, thus, affecting the quality of the most valuable part of the stem in terms of economic value [24,49].

Concerning wounded tree characteristics, high DBH trees close to the senescence phase showed a significant impact of the wound on growth and healing rates, and also a higher risk of wound decay [50]. The same was observed for wounded trees in the suppressed crown class. Crown class indeed influences not only growth rates, but also

several physiological processes, and trees in the suppressed class have lower resilience towards disturbances, including damages related to forest operations [51].

This paper's results regarding the effects of tree species on healing rates were only partially consistent with current literature. High healing rates for beech (*Fagus orientalis*) and alder were reported in the Hyrcanian forest, as well as a low healing rate for lime trees [30]). Studies carried out in Central Europe on *Fagus sylvatica* showed healing rates for damages to beech trees which were much lower than what was reported in the present study [31,52]. A technical report from the USDA (United States Department of Agriculture) highlighted high susceptibility of the *Fagus* gene to stem damage and consequent decay [53]. It seems, therefore, that the environmental context has a strong influence on the ability of a given tree species to react to damages and further research is needed on this topic.

Given the evidence observed it is recommended that future research incorporates other investigation methods, for instance tomography, to evaluate the consequences of wounds on the internal structure of the tree [54–57]. Moreover, an evaluation of the consequences and extent of damage to functional traits of trees caused by forest operations could be studied at a more detailed level to observe and evaluate the implications of these damages to trees on the forest ecosystem [58–61].

5. Conclusions

Residual stand damage is an inevitable risk of selection cutting in any harvesting system, especially in mountain conditions under ground-based skidding operations. The level, intensity and extent of damage should be minimized, to assure good timber quality and sustainable management in the future. Our results revealed that the effect of stem wounds on the radial growth increment and wound healing rates are related to different characteristics of the trees (DBH, species, crown class) and of the wound itself (position, dimension and severity). Wounds related to extraction operations are more serious and take a longer time to recover and of the impact on tree growth and risk of wound decay is more marked than in wounds caused by felling operations. Damage and injuries reduce the commercial value of the logs, affecting not only the tree growth, but also the income of the future harvest.

The obtained findings demonstrate that full closure of wounds related to forest operations is lengthy, taking more than 10 years to fully heal, especially for wounds caused by extraction. This study has made a contribution towards the improvement of the knowledge on tree response (i.e., radial growth increment and wound healing) to wounding caused by forest operations in mountain areas. These data have a wide range of information for current forest management. In particular, proper intervention planning, with a particular focus on ground-based extraction, and training of workers on machines are fundamental in the effort to limit the damage to residual stand.

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