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Short-Term Recovery of Residual Tree Damage during Successive Thinning Operations

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Abstract: In this study, damage to residual trees during thinning performed by motor-manual felling and whole tree skidding was studied in a loblolly pine (*Pinus taeda* L.) plantation. Forest intervention was carried out in 2016 and tree wounds were studied and examined over a period of three years. The results indicated that 8% of the residual trees suffered damage, of which 52% was caused by felling operations and 48% by extraction operations. Among the damaged trees, 13% had damage to the root system, 53% to the bole, and 34% to the crown area. The average wound size at the time of occurrence was 71.3 cm^2. This was found to be reduced to 54.4 cm^2 after a three year period. Wound intensity decreased with higher wound height and increased size. Three years after wound occurrence, only 6.6% were closed, 90.6% were still open, and 2.8% were decayed. The diameter growth in damaged trees was 1.7% lower than in undamaged trees ($p > 0.05$). Damage to the root system of residual trees reduced diameter growth by 3% ($p < 0.05$). Intensive wounds (damaged wood) caused a reduction of 22.7% in diameter growth ($p < 0.01$). In addition, the diameter growth in trees with decayed wounds was 27.4% lower than unwounded trees ($p < 0.01$). Pre-harvest planning, directional tree felling, marking of the extraction path before logging operations, employment of skilled logging workers, and post-harvest assessment of damaged residual trees are essential implementations in timber plantations.

Keywords: loblolly pine; tree damage; bole wound; wound healing rate; diameter growth

1. Introduction

Timber production from forestry plantations for industrial use is increasing worldwide. The loblolly pine (*Pinus taeda* L.) is one of the main species used for forestry plantations and it represents an important resource for agroforestry in northern Iran [1]. The main purpose of these plantations is to reduce pressure on naturally growing forests through timber production. This species in the Guilan province, northern Iran, shows a high average growth rate of 23.9 m^3 ha^{-1} per year [2]. This is the reason for the success of these plantations, which according to available statistics, cover about 2350 ha in northern Iran [2].

Silvicultural planning for these plantations suggests to conduct two thinning treatments to decrease tree competition and increase stand growth and wood quality [3]. Forest managers usually cut the trees in these forest plantations with negative morphological and technological features during thinning treatment. Some examples of these are bifurcation, sinuosity and scar tissue. Pruning could be also practiced so as to favor the obtaining of wood with a low amount of knottiness [4]. The general purpose of thinning is to enhance the growing space for maximum volume in production, thus increasing overall timber quality. Moreover, thinning reduces competition among the remaining trees, reduces the risk of fire [5] and helps to maintain a healthy forest [3].

However, forest managers are usually concerned about the potential damage to residual trees caused by thinning interventions [6] and/or selective cutting [7–9]. Various researchers have found that logging operations during thinning frequently caused numerous cases of damage to the remaining trees, with variable intensity [10,11]. The frequency and intensity of wounded trees during logging operations can have a detrimental impact on stand growth [8]. Tree wounding is the most common type of logging damage, representing more than 90% of the total damage [12,13]. Wounds on the bole of residual trees can cause negative effects on tree growth and wood quality because they are a place for disease to enter, pitch rings, etc. Moreover, wounding can cause stem deformities and significant losses in final timber volume and value [14,15]. Therefore, forest stands with a high level of damage in residual trees might not be of a sufficient value to cover management and harvesting costs caused by the reduction of stand growth and timber quality [16]. The rate of damaged trees and the extended amount of time needed for wounds to close draws attention to the technological concern of the wood quality of the final harvest. Bole wounds may reduce the amount of growth and seed production in subsequent years. In some cases, the bole may be rotted and the tree may even die [17–20]. Moreover, injuries to live trees can also create higher risks for pest infestation [21]. In the Hyrcanian forest [22], reported logging wounds affect future income by lowering the number of trees that potentially provide a higher quality of saw and veneer logs.

Another important aspect is wound closure (healing); this may be a key factor due to the fact that it restricts the colonization of wound-invading fungi [20]. Wound closure not only prevents further infection but may also stop subsequent fungal development in already infected wounds [20]. The wound healing rate is related to tree species and wound severity [21], but also to site conditions and tree age [19,20]. The age of the wounded tree and the wound location on the bole of the tree (height from ground level) are other important factors in the wound healing rate [20]. Wound characteristics, such as size, location and intensity, are the main factors influencing the wound healing rate and the future quality of the damaged trees [14,23,24]. More often in recent years, the potential damage to residual trees is a managerial concern during cyclic harvesting in the same forest stand, and closely related to environmental aspects [20]. Damage to residual trees was reported to be in the range of 36–50% in Austrian pine (*Pinus nigra* Arnold) [13], 1–46% in coniferous species [17], 14% in Corsican pine (*Pinus laricio* Poiret) [21], 13.6% in Austrian pine (*Pinus nigra* Arnold), Douglas fir (*Pseudotsuga menziesii* Franco) and Spruce (*Picea abies* L., Karst.) [25], 1.5–6% in Umbrella pine (*Pinus pinea* L.) [26], 1.3–2.1% in Scots pine (*Pinus sylvestris* L.) [27], 6–9% in Grey alder (*Alnus incana* Moench) [28], and 14% in *Sequoia sempervirens* (Lamb. ex D. Don) Endl.) [29].

Due to the large-scale plantations with loblolly pine in northern Iran, the percentage and intensity of damage to residual trees due to thinning operations deserves to be investigated. Furthermore, the ability of loblolly pine to heal wounds has not yet been studied in this context.

In this context, attention was focused on a forestry plantation with timber production as its main purpose. The main aims of this study were to: (1) evaluate the damage level and its influence on residual trees by felling and extraction operations during thinning interventions, and (2) modeling of the wound healing rate three years after thinning operations in a loblolly pine plantation.

2. Materials and Methods

2.1. Study Area

The study area was a loblolly pine plantation located in the Shaft watershed in the Guilan province, located in northern Iran (37°21′15′′ to 37°47′19′′ N and 48°37′45′′ to 49°10′6′′ E). The loblolly pine trees were planted in 1985 on 61 ha. The area of the plantation is a plateau, the elevation is 45 m a.s.l., and the annual precipitation is 1417 mm, with the heaviest precipitation in summer and fall. Average temperature in the hottest month of August is 32.7 °C, and in the coldest month of January is 3.3 °C. Soil is relatively deep (more than 90 cm) with semi-heavy to heavy texture and poor drainage. The soil type is pseudogley to gley, and the percentage of clay is more than 60%, which causes the cohesion of soil particles, and hydromorphic soils for many months of the year.

Dendrometric characteristics of the managed stand are indicated in Table 1 to understand thinning intensity. The results of t-tests showed a significant reduction in the means of tree density, dbh (diameter at breast height) of trees, height of trees, stand basal area, and standing volume immediately after thinning operations (Table 1). About 18.2% of trees (which includes 28.5% of stand basal area and 35.5% of stand volume) were felled and extracted during thinning interventions (Table 1).

Table 1. Stand dendrometric characteristics (mean ± standard deviation (SD)) before and immediately after thinning operations (year: 2016).

Stand Characteristics	Before Thinning	After Thinning	t-test Value	Intensity of Thinning
Tree density (stem ha^{-1})	1257.9 ± 21.6	1029.3 ± 37.3	41.069 **	228.6 (18.2%)
Diameter at breast height (cm)	38.4 ± 6.2	35.9 ± 5.7	2.298 *	-
Tree height (m)	23.5 ± 1.9	21.2 ± 2.2	6.117 **	-
Basal area (m^2 ha^{-1})	149.3 ± 46.2	106.7 ± 32.3	5.858 **	42.6 (28.5%)
Stand volume (m^3 ha^{-1})	2171.9 ± 769.0	1399.7 ± 507.6	6.492 **	772.2 (35.5%)

* significant at $\alpha = 0.05$; ** significant at $\alpha = 0.01$.

Trees marked for thinning were felled using motor-manual felling by chainsaw in November 2015. Chainsaw operators had more than 10 years of experience and usually attend dedicated training courses. Due to the high soil moisture in winter and to prevent future soil disturbance, the felled trees were extracted to roadside landings by a Timberjack 450 C wheeled skidder in April 2016. The weight of the skidder was 9.8 t (55% on the front and 45% on the rear axle), its width and length were 3.8 m and 6.4 m, respectively, with engine power of 132 kW. The skidder was fitted with size 24.5–32 tires, inflated to 220 kPa on both the front and rear axles.

2.2. Data Collection

The condition of the trees was examined before thinning, after felling and after extraction through 60 random square (20 m × 20 m) plots. Diameter at breast height (1.30 m; dbh) and the height of trees were measured by a dendrometric caliper in cm and a hypsometer in m, respectively. The volume of each tree was estimated using a local tree volume table based on the dbh and height of tree. On the 60 plots selected, all bole-wounded trees (106 stems) were numbered and marked. The position of each wounded tree was also identified on a topographical map using the global positioning system (GPS). The damaged trees were scattered throughout the forest. However, they were more abundant in the winching corridors and along the skid trails than in the forest. The locations of damage were recorded in three distinct parts of the trees: crown, bole, and root. Intensity, size, and height from ground level were recorded for each bole wound. Wound intensity (WI) based on the type of damaged tissue was registered in three intensity classes: bark, cambium, and wood fibers [13,20,21]. The wound size (WS) was calculated by the ellipsoid surface area [21], measuring the maximum length (WL) and width (WW) with a ruler, assuring an accuracy of ±0.5 mm. Furthermore, for improved accuracy, and in particular for irregularly shaped wounds, we prepared the wound images using a 20-megapixel camera, 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) [30]. The height of the bole wound (WH) was measured by tape as the vertical distance between the wound center and ground level, and then it was recorded as one of four classes: <0.3 m, 0.3–1 m, 1–2 m, and >2 m [12].

Three years later, in 2019, the 106 bole-wounded trees were identified in the study area. The wound characteristics were remeasured, and the condition of the wounds was reexamined and classified into one of three types: "healed", "open" but not decayed, and open but "decayed" [19,24].

2.3. Data Analysis

The wound healing rate (WHR) was analyzed considering three wound parameters (WD): (1) wound width healing rate (WWHR) (mm·year^{-1}); (2) wound length healing rate (WLHR) (mm·year^{-1}); and (3) wound area healing rate (WAHR) (cm^2·year^{-1}). The healing rate was calculated using Equation (1) [20,22,27]:

$$\mathrm{WHRj} = (\mathrm{WDij1} - \mathrm{WDij2})/\mathrm{t} \quad (1)$$

where i indicates the number of the wound, j indicates the wound parameter (width, length, area), and t is the time interval between the two measurements.

Since wound healing ability not only depends on the wound width but also on the tree diameter [20,22], the wideness ratio of each wound was calculated using Equation (2):

$$\mathrm{WWR}\ (\%) = (\mathrm{WW}/\mathrm{d}) \times 100 \quad (2)$$

where d is the diameter of the bole at the center of wound.

A neighboring undamaged loblolly pine tree with similar characteristics (i.e., dbh, height, vitality, crown class of all the trees—i.e., dominant, co-dominant subdominant, etc.) was selected for comparison with each damaged tree. The average annual diameter growth (DG) in the 3-year period of undamaged and damaged loblolly pine trees was calculated using Equation (3) as reported in [31].

$$\mathrm{DG} = (\mathrm{DBH}_2 - \mathrm{DBH}_1)/\mathrm{t} \quad (3)$$

where DG is diameter growth (mm year^{-1}), DBH1 and DBH2 are diameter at breast height at the start and end of interval (mm), respectively, and t is the time interval between two measurements (years).

After testing for normality (Kolmogorov–Smirnov test) and homogeneity of variance (Levene's test), an independent samples t-test was applied to compare the means of stand characteristics before and after thinning operations and to compare the averages of WW, WL, WHR in the felling and extraction stages. A paired t-test was applied to compare the means of diameter growth (DG) in damaged and undamaged loblolly pine trees. ANOVA and Duncan's test were applied to analyze the effects of damage location, wound intensity, and wound condition on DG. A non-parametric test (Spearman) was applied to test the relationship between the following: wound size vs. wound position, wound size vs. wound intensity, and wound position vs. wound intensity. Regression analysis was applied to test the relationships between: (i) WWHR and WH; (ii) WWHR and dbh; (iii) WWHR and WW; (iv) WWHR and WWR and (v) three variables with non-linear regression between WWHR and WH–WW. Regression analysis was also applied to test the relationships between DG and wound characteristics, and between DG and the ratio of wound width to dbh (WW/DBH). The interaction effect of dbh and wound characteristics on WWHR and DG was analyzed by ANCOVA. All analyses were performed using SPSS 19 software (IBM, New York, NY, USA) and Statistica 7.0 software (Dell, Round Rock, TX, USA).

An overview of the applied experimental design is given in Figure 1.

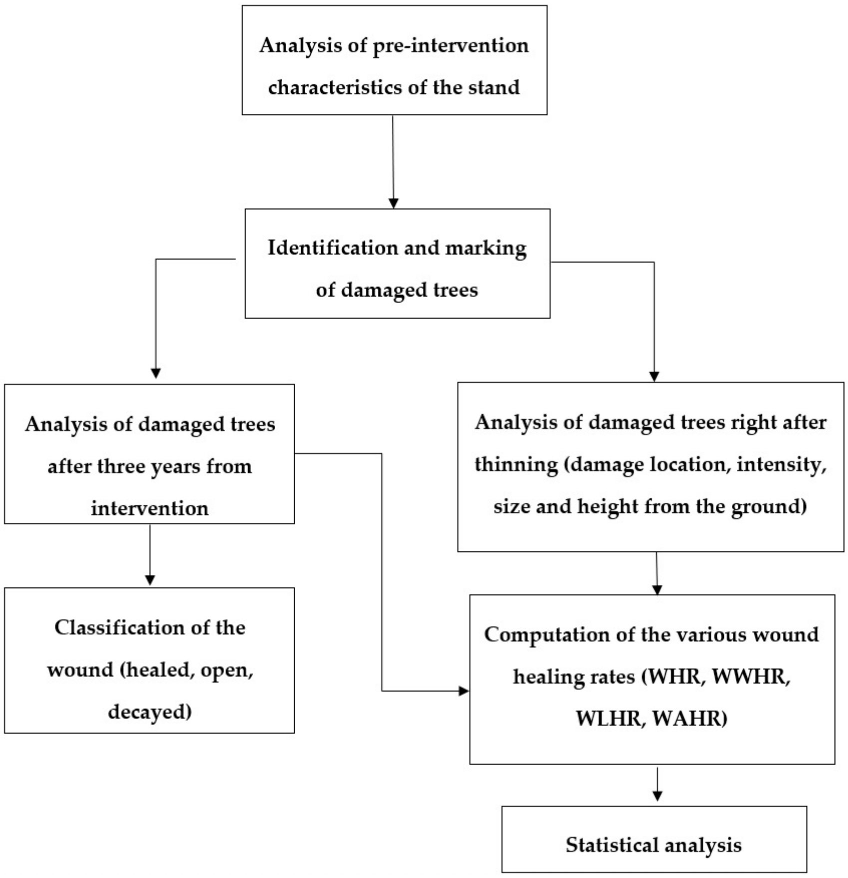

Figure 1. Schematic representation of the experimental design. WHR: wound healing rate; WWHR: wound width healing rate; WLHR: wound length healing rate; WAHR: wound area healing rate.

3. Results

3.1. Thinning Damage

Thinning operations caused damage to 8.05% (82.8 stem ha^{-1}) of the residual loblolly pine trees (Table 2); 13% of damage occurred to the roots, 53.3% occurred to the bole, and 33.7% occurred to the crown of residual trees. Out of the total thinning damage, 52.3% (104 stems) was caused by the felling operation and 47.7% (95 stems) was caused by the extraction operation. All damage to the crown (2.71% of residual trees) was caused by felling operations, and all damage to the roots (1.05% of residual trees) was caused by extraction operations. The frequency of damage to the bole (4.29% of residual trees) was higher than damage to the root and crown of residual trees. Of all bole-wounded trees (106 stems), 34.9% (37 stems) of wounds was caused by felling and 65.1% (69 stems) was caused by extraction. Results of t-tests indicated that the frequency of crown damage was higher than bole damage in the felling phase, and the frequency of bole damage was higher than root damage in the extraction phase.

The intensity of most of the wounds was severe, thus damaging the wood (46 wounds, 43.4%) (Figure 2). The percentages of wounds on cambium and bark were 25.5% (27 wounds) and 31.1% (33 wounds), respectively. The percentage of severe wounds caused by extraction operations was higher than the percentage of those caused by felling operations (Figure 1). Therefore, 41 wounds (59.4%) occurred on wood (high intensity), 16 wounds (21.8%) on cambium (medium intensity), and 13 wounds (18.8%) on bark (low intensity). More than half of all felling wounds (20 wounds, 54.1%) occurred on bark, 12 wounds (32.4%) on cambium and only five wounds (13.5%) on wood. The results of t-tests indicated that the frequency of intense wounds where the bark was removed ($t = 23.54$; $p < 0.01$) and the cambium damaged ($t = 8.62$; $p < 0.05$) were created during the felling phase and were significantly higher in frequency than those created during the extraction phase, while the frequency of wounds with wood damage intensity created during the extraction phase was significantly higher (t = 34.18; $p < 0.01$) than those created during the felling phase.

Table 2. Frequency of damage (mean ± SD) on residual trees by thinning operations (year: 2016).

Damage Location	Felling		Extraction	
	(Stem ha^{-1})	(%) of Residual Trees	(Stem ha^{-1})	(%) of Residual Trees
Root	-	-	10.8 ± 1.1 b	1.05 ± 0.12
Bole	15.4 ± 2.3 b	1.50 ± 0.17	28.7 ± 1.6 a	2.79 ± 0.37
Crown	27.9 ± 4.5 a	2.71 ± 0.24	-	-
t value	48.6 **	-	33.9 **	-
Total	43.3 ± 4.6	4.21 ± 0.35	39.5 ± 1.9	3.84 ± 0.55

** significant at α = 0.01. Different letters after means indicate significant difference between damage locations by Duncan's test at α = 0.05.

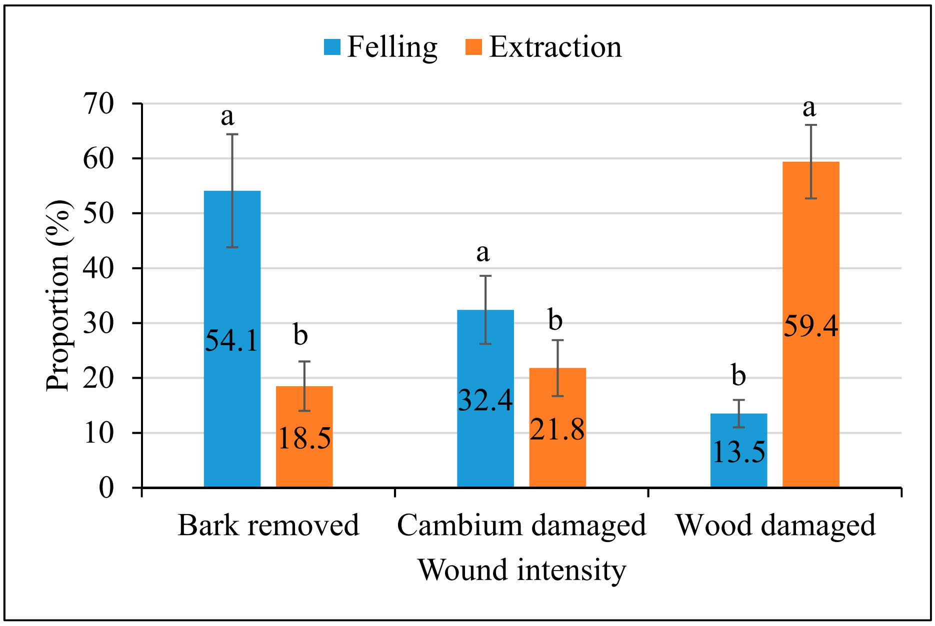

Figure 2. Proportion (%) of felling and extraction phases in the occurrence of bole wounds with different intensities.

The distribution of all recorded wounds shows that 48.1% (51 wounds) occurred at a height lower than 0.3 m from the ground, 18.9% (20 wounds) between 0.3 and 1 m height, 14.1% (15 wounds) between 1 and 2 m height, and 18.9% (20 wounds) at a height greater than 2 m. All the wounds detected at a height lower than 0.3 m were due to extraction operations, and those at a height higher than 2 m to felling operations (Figure 3). Of all felling wounds, 37.8% (14 wounds) occurred at 1–2 m in height, and 8.1% (three wounds) at 0.3–1 m. Of all extraction wounds, 24.6% (17 wounds) occurred at 0.3–1 m in height, and only one wound (1.4%) occurred at 1–2 m. Results of t-tests indicated the frequency of wounds at heights of 0.3–1 m created during the extraction phase was significantly higher (t = 7.10; $p < 0.01$) than those created during the felling phase, while the frequency of wounds at 1–2 m created during the felling phase was significantly higher (t = 39.07; $p < 0.01$) than those created during the extraction phase.

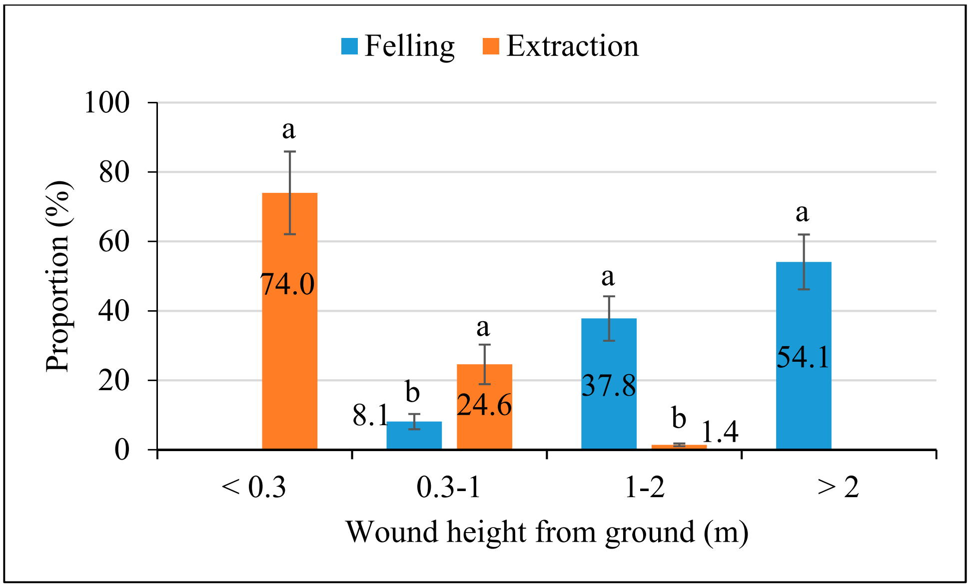

Figure 3. Proportion (%) of felling and extraction operations in the occurrence of bole wounds at different heights from ground level.

The results of the Spearman's correlation tests indicated that the wound intensity was related to wound position ($p < 0.01$) and wound size ($p < 0.05$) (Table 3). Wound severity decreased with higher wound position (height from ground level) and increased wound size. In addition, the wound size was related to the wound position ($p < 0.05$); in particular, the wound size increased with the increasing height of the wound position.

Table 3. Results of Spearman's correlation analysis for wound characteristics.

Variables	N	Correlation Coefficient	Sig. (2-Tailed)
Wound size vs. wound position	106	0.382	0.017
Wound size vs. wound intensity	106	−0.428	0.010
Wound position vs. wound intensity	106	−0.745	0.001

3.2. Wound Healing Rate

In 2019, which was three years after the wound occurrence, results showed that only seven wounds (6.6%) had closed, 96 wounds (90.6%) were still open, and three wounds (2.8%) were decayed. Among the total felling wounds, 13.5% (five wounds) were closed, 83.8% (31 wounds) were open, and only 2.7% (one wound) were decayed (Figure 4). Of the extraction wounds, 2.9% (two wounds) were closed, 94.2% (65 wounds) were open, and 2.9% (two wounds) were decayed. Results of t-tests showed that there were significant differences in the frequency of occurrence of closed wounds between the felling and extraction phases ($t = 7.15$; $p < 0.01$), and the frequency of occurrence of open wounds ($t = 4.37$; $p < 0.05$), while the frequency of decayed wounds between felling and extraction phases was not significant ($t = 0.86$; $p > 0.05$).

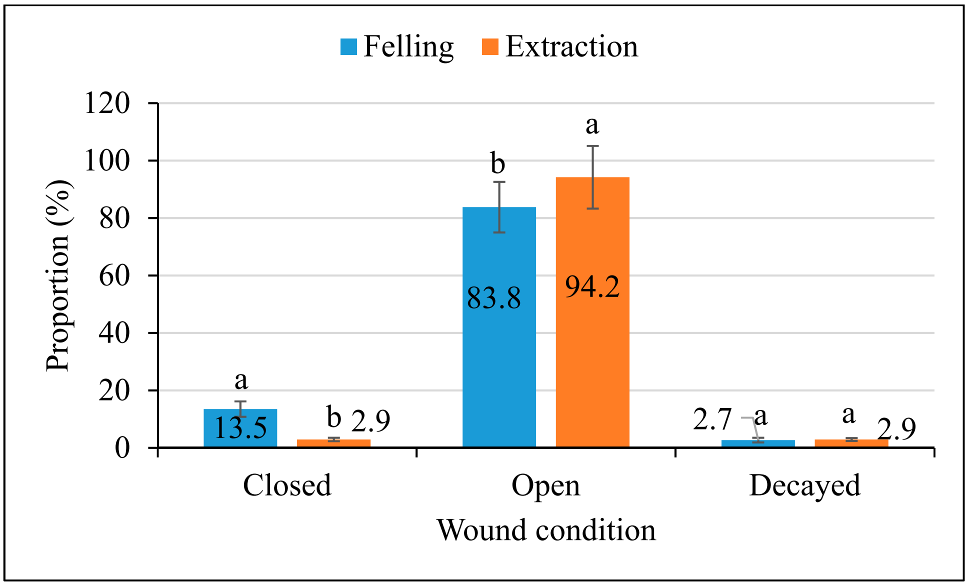

Figure 4. Condition of felling and extraction wounds three years after wound occurrence.

The average length of all wounds in 2016 was 134.8 mm and was found to be reduced to 130 mm (a reduction of 3.6%) in 2019. The average width of all wounds in 2016 was 69.6 mm, reduced to 60 mm (a reduction of 13.8%) in 2019. The average size of the wounds in 2016 was 71.26 cm^2, reduced to 54.42 cm^2 (a reduction of 23.6%) in 2019.

The results of t-tests indicated that the average length and size of the wounds caused by felling operations was higher than those caused by extraction operations at both the first (2016) and the second (2019) assessments ($p < 0.01$), while mean wound width caused by felling was not statistically different by extraction in the first assessment. The mean width of extraction wounds was significantly higher than the mean width of felling wounds in 2019 ($p < 0.01$) (Table 4).

Table 4. Dimensions and healing rates of wounds per origin (felling, extraction and total wounds) in the first (2016) and second (2019) assessments.

	Length (mm)	**Width (mm)**	**Area (cm^2)**
		Year 2016	
Felling	270.2 ± 86.1 a	64.9 ± 28.8 a	137.78 ± 32.72 a
Extraction	62.4 ± 9.8 b	72.0 ± 10.0 a	35.58 ± 6.47 b
Total	134.8 ± 18.5	69.6 ± 11.2	71.26 ± 7.86
		Year 2019	
Felling	261.7 ± 35.3 a	45.9 ± 22.5 b	95.13 ± 21.80 a
Extraction	60.8 ± 10.3 b	67.7 ± 16.7 a	32.60 ± 5.67 b
Total	130.0 ± 20.3	60.0 ± 11.7	54.42 ± 6.05
		Wound healing rate *	
Felling	2.83 ± 0.30 a	6.33 ± 1.02 a	14.22 ± 2.26 a
Extraction	0.53 ± 0.21 b	1.43 ± 0.20 b	0.99 ± 0.22 b
Total	1.6 ± 0.28	3.2 ± 0.50	5.61 ± 0.43

* mm $year^{-1}$ for wound length and wound width healing rate, and cm^2 $year^{-1}$ for wound area healing rate. Different letters after means indicate significant difference between felling and extraction by Duncan's test at $\alpha = 0.05$.

The average wound length healing rate (WLHR) was 1.6 mm $year^{-1}$, which was significantly lower than the average wound width healing rate (WWHR) at 3.2 mm $year^{-1}$ ($t = 38.4$; $p < 0.01$). The average wound area healing rate (WAHR) was 5.61 cm^2 $year^{-1}$. The average healing rates (WLHR, WWHR, and WAHR) of felling wounds were significantly higher than extraction wounds ($p < 0.01$).

The results of the regression analysis indicated that the wound width healing rate (WWHR) was related to tree dbh (R^2 adjusted = 0.5140; SE = 2.00; F = 51.28; $p < 0.01$) (Figure 5), wound wideness rate (R^2 adjusted = 0.515; SE = 1.77; F = 92.42; $p < 0.01$) (Figure 6), wound height from the ground level (R^2 adjusted = 0.364; SE = 2.81; F = 21.07; $p < 0.01$) and wound width (R^2 adjusted = 0.357; SE = 2.82; F = 59.34; $p < 0.01$).

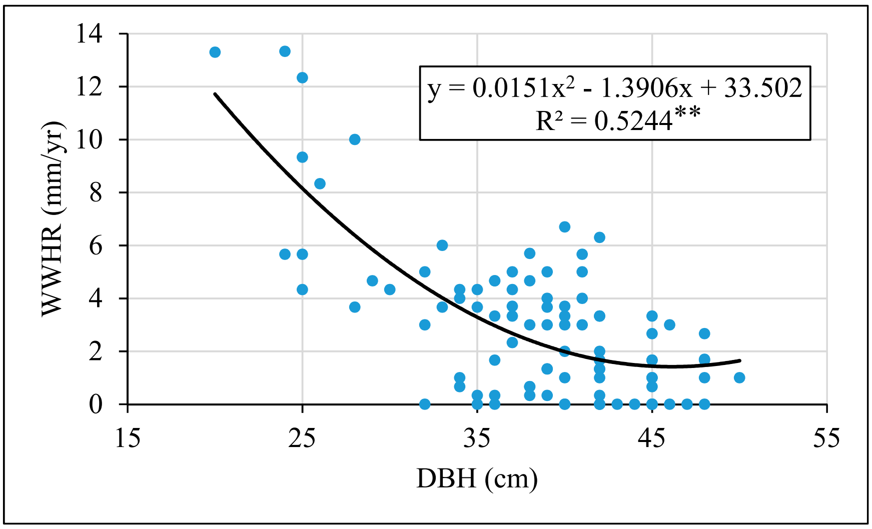

Figure 5. Relationship between wound width healing rate (WWHR) and tree dbh.

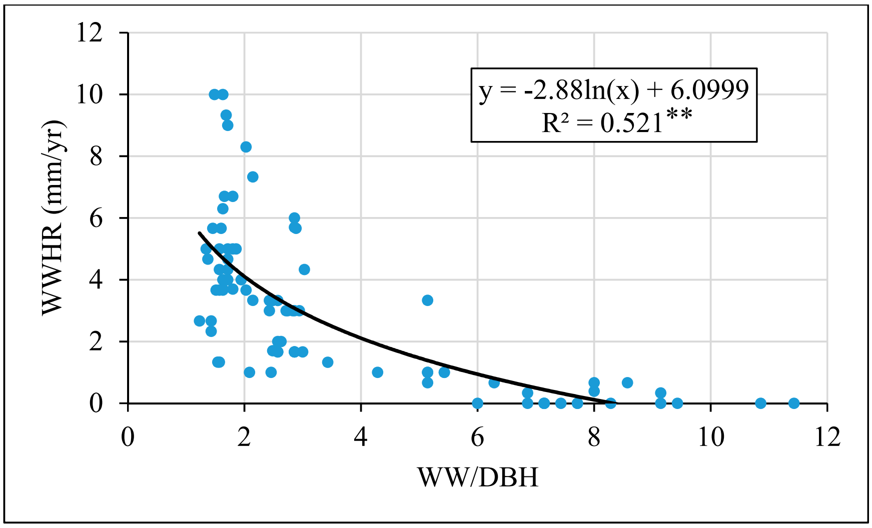

Figure 6. Relationship between wound width healing rate (WWHR) and wound wideness ratio (WW/DBH).

Moreover, a significant correlation was found concerning the regression analysis between WWHR and both wound height and wound width (Figure 7). An interesting aspect is that the regression between WWHR and both WH and WW showed higher correlation (R^2 adjusted equal to 0.57) than the single regression analysis between WWHR and both WH (R^2 adjusted equal to 0.38) and WW (R^2 adjusted equal to 0.36). According to Figure 7, the wound width (WW) was more influenced by the wound width healing rate (WWHR) than the wound height (WH). The influence of wound height on the wound width healing rate was greater in wounds with a width higher than 4 cm.

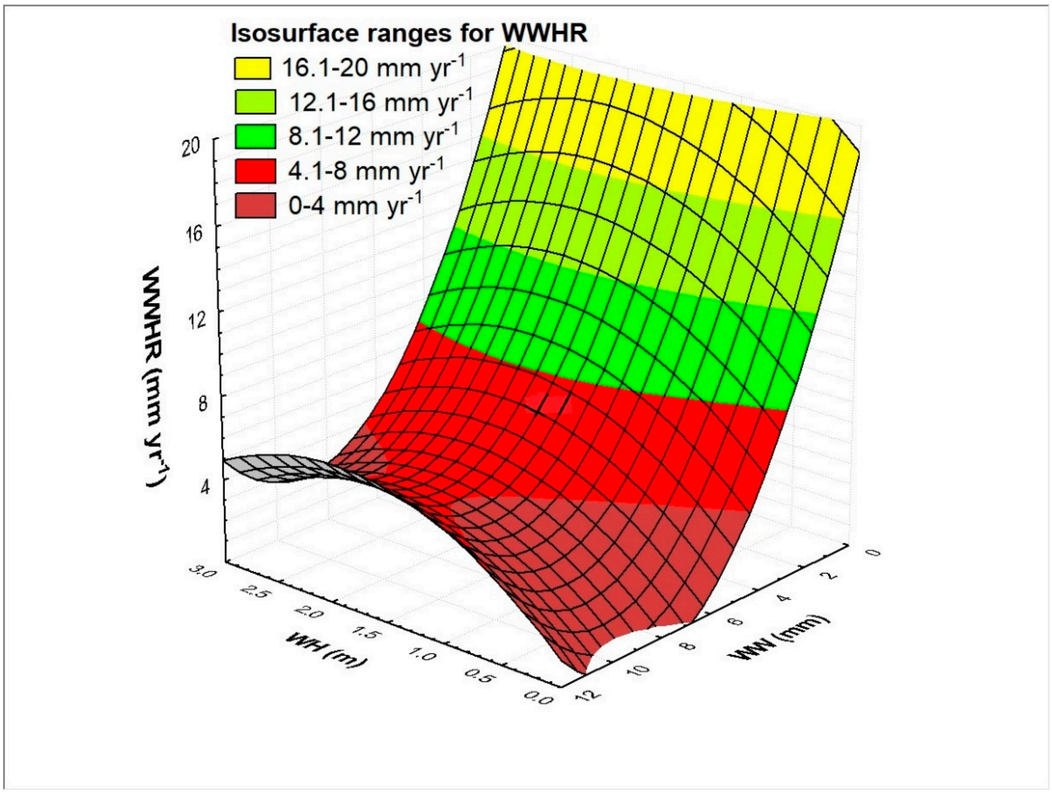

Figure 7. Relationship between wound width healing rate (WWHR), wound height from the ground (WH) and wound width (WW). Non-linear regression R^2_{adj} = 0.570; F(4; 101) = 35.744; $p < 0.001$; SE = 0.725; WWHR (mm year^{-1}) = 18.785 + 5.517 × WH − 1.433 × WH^2 − 4.481 × WW + 0.252 × WW^2.

Wound width healing rate increased with increasing wound height; decreased with increasing tree dbh; decreased with increasing wound width; and decreased with increasing wound wideness rate.

3.3. Diameter Growth of Wounded Trees

The diameter growth (DG) of damaged stems was 1.71% lower than undamaged stems, showing no statistical significance (Table 5). ANOVA results indicated damage location, wound intensity, and wound condition had a significant effect on the DG of loblolly pine trees (Table 5). Duncan's test indicated that the DG in trees with root damage was significantly lower than bole-damaged and crown-damaged trees. Duncan's test also indicated that the DG in wood-damaged trees was significantly lower than cambium-damaged and bark-damaged trees. The DG in trees with decayed wounds was significantly lower than trees with open wounds and closed wounds.

Detailed analysis and paired t-test showed that the DG of bole-wounded stems and crown-damaged stems reduced by 1.05% and 1.93%, respectively, compared to undamaged stems and that there was no statistical significance, while root damage significantly reduced the DG by 3.01%. The DG of closed and open wounds reduced by 0.36% and 0.12% (not statistically significant), while the DG of decayed wounds significantly reduced by 27.39%. The DG of wounds with intense wood damage decreased by 22.73% ($p < 0.01$).

Table 5. Diameter growth (DG; mean ± SD) of damaged and undamaged loblolly pine trees, reduction of diameter growth (RDG), and results of ANOVA, t-paired, and Duncan tests for the analysis of the effect of damage and wound characteristics (in 2016) on DG over a period of three years after thinning operations.

Damage and Wound Characteristics	N-Paired	DG of Damaged Stems (mm year^{-1})	DG of Undamaged Stems (mm year^{-1})	RDG (%)	t-Paired	*p*-Value
			Damage location			
Root	26	8.05 ± 0.97b	8.30 ± 0.64	3.01	2.195	0.038 *
Bole	106	8.48 ± 1.15a	8.57 ± 0.45	1.05	0.820	0.414
Crown	67	8.63 ± 1.31a	8.80 ± 0.82	1.93	1.293	0.201
ANOVA			F = 5.39; $p < 0.01$			
Total	196	8.48 ± 1.19	8.61 ± 0.64	1.71	1.891	0.060
			Wound intensity			
Bark	46	8.37 ± 1.08a	8.42 ± 0.57	0.59	0.824	0.201
Cambium	27	8.33 ± 1.04a	8.49 ± 0.63	1.88	1.059	0.088
Wood	33	6.63 ± 1.17b	8.58 ± 0.66	22.73	19.174	0.000 **
ANOVA			F = 7.21; $p < 0.01$			
			Wound condition			
Closed	7	8.31 ± 0.32a	8.34 ± 0.34	0.36	1.411	0.208
Open	96	8.57 ± 1.13a	8.58 ± 0.46	0.12	0.154	0.878
Decayed	3	6.23 ± 1.03b	8.58 ± 0.47	27.39	6.034	0.026 *
ANOVA			F = 6.70; $p < 0.01$			

* significant at $\alpha = 0.05$; ** significant at $\alpha = 0.01$. Different letters after means indicate significant difference among wound characteristics by Duncan's test at $\alpha = 0.05$.

The regression analysis indicated that there was a significant correlation between DG and wound characteristics (except wound length), and between DG and dbh in both damaged and undamaged loblolly pine stems (Table 6).

Table 6. Results of regression analysis between characteristics of wounds and trees with diameter growth in loblolly pine trees (WI: wound intensity, WS: wound size, WH: wound height, WW: wound width, WL: wound length, DGD: diameter growth of damaged trees, DGU: diameter growth of undamaged trees), SE: standard error.

Variables	N	R^2-adjusted	SE	F	*p*-Value
DG-WI	106	0.473	0.834	48.231	<0.001
DG-WS	106	0.186	0.974	11.851	<0.001
DG-WH	106	0.333	0.875	26.740	<0.001
DG-WW	106	0.613	0.673	79.879	<0.001
DG-WL	106	0.089	1.076	0.233	0.793
DGD- DBH	106	0.736	0.230	148.573	<0.001
DGU-DBH	106	0.452	0.859	43.866	<0.001
DG-WW/DBH	106	0.593	0.687	148.754	<0.001

The DG reduced with increasing dbh in both damaged and undamaged stems (Figure 8). The diameter growth of damaged trees was lower than for undamaged trees for all dbh values. The DG decreased with increasing wound intensity, wound size, wound width (Figure 9), and increased with increasing wound height from ground level. The DG decreased with increasing ratio of wound width to dbh (Figure 10).

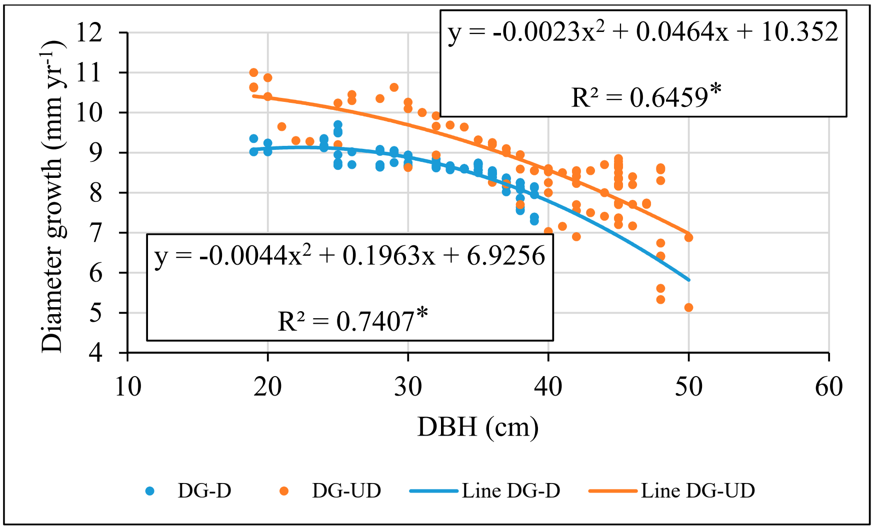

Figure 8. Diameter growth of undamaged (DG-U) and damaged (DG-D) trees in relation to tree dbh.

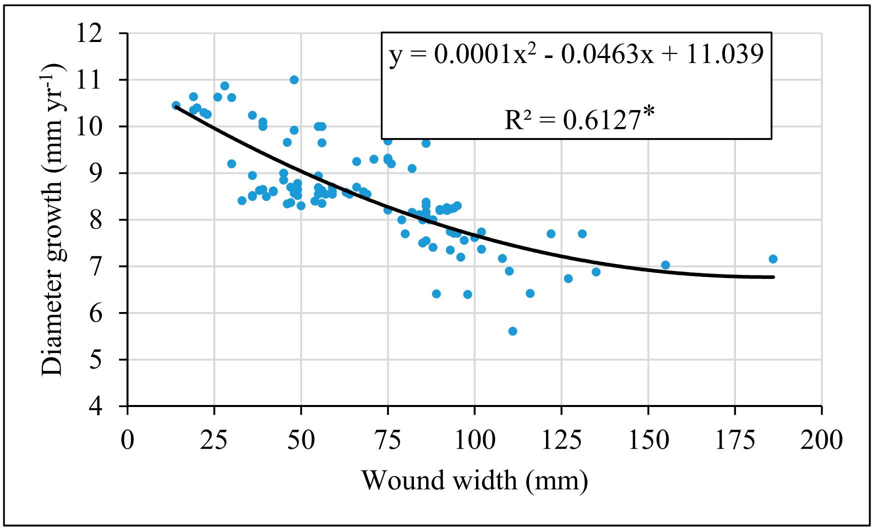

Figure 9. Wounded diameter growth in relation to wound width.

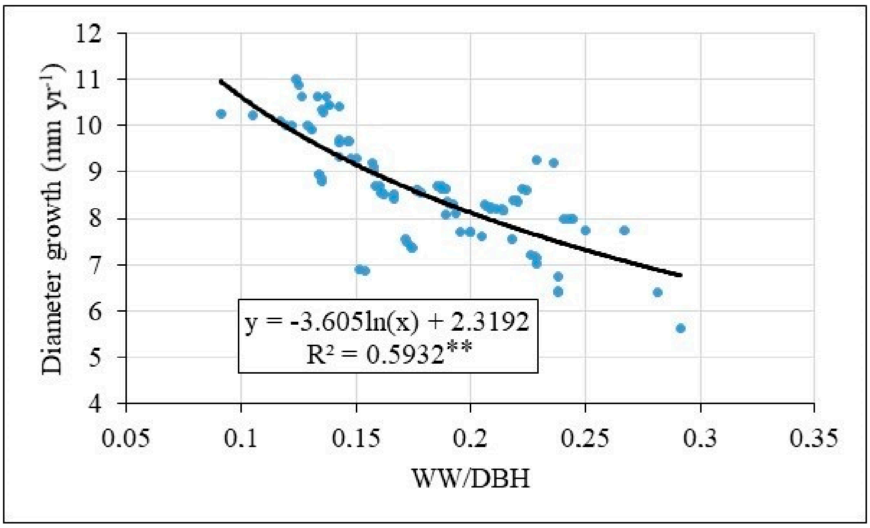

Figure 10. Wounded diameter growth in relation to the ratio of wound width to dbh.

ANCOVA results indicated interactions between dbh and WI, dbh and WH, dbh and WW; WI and WS, WI and WH, WS and WH had significant effects on both WWHR and DG, while the interaction between WW and WH had no significant effect on either WWHR and DG. The interaction between dbh and WS had significant effects only on DG (Table 7).

Table 7. ANCOVA results for the interaction of independent variables on wound width healing rate (WWHR) and diameter growth (DG) of loblolly pine stems; dbh: diameter at breast height, 1.30 m; WI: wound intensity; WS: wound size; WH: wound height; WW: wound width.

Variables	WWHR (mm year^{-1})		DG (mm year^{-1})	
	F-Value	*p*-Value	F-Value	*p*-Value
Dbh-WI	2.630	0.003	3.168	0.001
Dbh-WS	1.313	0.214	2.635	0.003
Dbh-WH	4.522	0.000	5.187	0.000
Dbh-WW	2.653	0.002	2.677	0.002
WI-WS	5.841	0.001	44.494	0.000
WI-WH	7.289	0.000	60.024	0.000
WI-WW	15.478	0.000	34.274	0.000
WS-WH	5.440	0.001	44.842	0.000
WW-WH	1.738	0.071	0.728	0.695

4. Discussion

4.1. Thinning Damage to Residual Trees

Results indicated that a high percentage of residual trees were damaged (8.05%) by thinning operations in a loblolly pine (*Pinus taeda* L.) plantation. The common maximum threshold value of thinning damage to residual trees is 5% in European forests [32,33]. Obviously, the maximum mentioned mostly concerns coniferous stands, however, in the case of broad-leaved stands, it is generally higher (e.g., in a black alder *Alnus glutinosa* Gaertn. Stand, it was 8.3%; 62.6% in extraction operations, and 37.4% during felling) [28].

There is a wide range of damage percentage to residual trees (1.3–50%) following thinning interventions [13,17,21,25,26,32–34]. Such substantial differences are mostly linked to: (i) differences in the definition of a damaged tree, and (ii) differences in stand structure, logging systems, and the skill of operators.

It is interesting to note that higher mechanization levels did not lead to increased damage in every case. Therefore, this stresses how important it is for forest operators to have proper training and skills [28]. The lack of such know-how seems to be the most outstanding cause of substantial damage to residual stand.

Focusing on high mechanization levels [24] showed that a harvester caused more damage than a forwarder (63.8% vs. 28.6%). However, the forwarder caused larger scars on residual trees compared to the harvester (178.7 cm^2 vs. 143.9 cm^2). This information could be very useful for the correct planning and assessment of cut-to-length (CTL) forest yards. Dembure et al. [29] compared damage level to residual trees by semi-mechanized tree-length harvesting and by fully mechanized cut-to-length (CTL) harvesting during commercial thinning of a 12-year-old slash pine (*Pinus elliottii* Engelm.) plantation in South Africa. They reported a significant reduction in residual stand damage frequency (from 5.2% to 2.9%) and severity (28% smaller wounds) in mechanized CTL harvesting [29].

Our results showed that the share of damage to residual trees caused by felling and extraction operations was almost equal (52% by felling and 48% by extraction). In some research, the share of damage during felling operations is reported to be higher than during extraction [29,35], while in some other studies, the share of damage that occurred during extraction operations is higher than felling [3,10]. The main reason for differences in the causes (felling and extraction) of damage is related to the applied logging systems. Picchio et al. [3] reported that damage to standing trees was mostly caused by skidding and bunching (81.2% of damaged trees); about 14.5% of trees were damaged by felling and only 4.3% showed injuries due to both felling and bunching/skidding. It was also reported [25] that the majority of contacts (68%) and damage (65%) occurred at the felling phase and were caused by trees as they were felled. Felling and processing accounted for more than 90% of contacts and are the most important work operations in contact modeling.

When thinning was performed with a farm tractor-based one-grip harvester, two thirds of the damage was caused during felling and processing. More than 90% of damage was superficial, and 65% of the damage was smaller than 50 cm^2 in size [36]. The percentage of harvested volume is another important aspect directly related to the amount of damage to residual stand [37]; therefore, adequate planning and management of each intervention (silviculture treatment, harvested volume, forest yard organization, etc.) are essential for carrying out sustainable forest operations. In Indonesian forests, Sist et al. [37] indicated that with a felling intensity of 8 stems ha^{-1} or less, reduced-impact logging (RIL) techniques only damaged 25% of the original tree population while 48% were damaged with conventional techniques.

4.2. Wound Healing Rate

Our results indicated that the wound width healing rate (WWHR) in loblolly pine trees (*Pinus taeda* L.) three years after wound occurrence was 3.2 mm year^{-1}. The values of WWHR were related to tree dbh, wound height from ground level, wound width, and wound width rate. Information about findings from previous studies on WWHR are reported, including: 2–4 mm year^{-1} in *Picea abies* (L.) H.Karst [23], 2–4 mm year^{-1} in mixed broadleaves [27], 6–10 mm year^{-1} *Fagus sylvatica* L. [38], 3.7–4.1 mm year^{-1} in *Fagus sylvatica* L. [39], 10 mm year^{-1} in *Quercus robur* L. [40], 12 mm year^{-1} in *Fraxinus americana* L. [41], 13–15 mm year^{-1} in *Eucalyptus* spp. [42], and 20 mm year^{-1} in *Acer saccharum* Marshall [43].

As reported in previous studies, the loblolly pine WWHR is similar to that of Norway spruce but substantially lower than that of broadleaved species. According to the average wound width (69.6 mm) and the average WWHR (3.2 mm year^{-1}), it will take about 22 years for the complete closure of bole wounds. However, if the data of felling and extraction wounds are considered separately, the years needed to close the wounds are different. The time required to close the wound is approximately 10 years considering both the area and the width of the wound for felling injuries. The time to heal wounds occurred during extraction is longer—36 and 50 years, respectively. The reason for this huge difference is related to the damage intensity. Effectively, extraction damage was found to be of high intensity for nearly 60% of the wounds. The frequency of the highest damage intensity during felling was 4.4 times lower than that of extraction in this loblolly pine plantation. This is key information which is also needed for better planning of future forestry interventions. Vasaitis et al. [44] reported that it took 3.6, 5.5, 10.4, 12.7 and 14.7 years on average to occlude wounds ranging in size from 1 to 5 cm wide, respectively. The data from this study are consistent with the findings detailed in previous literature.

4.3. Diameter Growth of Wounded Trees

The results indicated that mechanical damage on residual trees by thinning operations caused a reduction of diameter growth by 1.7% over a short-term period (three years). Reduction in diameter growth (RDG) following logging wounds was reported to be 8.1% in beech trees (*Fagus orientalis* Lipsky) [19], 13.3% in alder trees (*Alnus subcordata* C.A. Mey.) [22], and 43.5% in lime trees (*Tilia begonifolia* Stev.) [45] in the Hyrcanian forests. It has been previously reported that wounded trees showed no growth decrease in a pine plantation [21], but the wounded trees may die over time [3,45].

The level of the severity of wounds had a significant effect on the reduction of diameter growth. Our results indicated that wounds being closed or open wounds had no significant effect on diameter growth. However, decayed wounds caused a significant reduction in diameter growth. Decayed wounds caused up to a 51.4% reduction in diameter growth in lime trees [44]. The amount of RDG in decayed wounds in beech trees was reported to be 15.3% [20]. Diameter growth was related to the ratio of wound width to dbh in wounded trees. These findings are in line with previous research results [20,22,46].

5. Conclusions

Thinning is a crucial operation in forest management which also has important effects on the understory, fauna and soil. This kind of intervention is even more important in coniferous plantations which exist for the purpose of timber production, such as loblolly pine plantations in Iran. Damage to residual trees in such interventions is unavoidable. However, the effort to limit such damage is a key issue for sustainable forest management considering the phytosanitary conditions caused by the damage.

The first step towards limiting residual stand damage is obtaining comprehensive understanding of the issue. The aim of this short-term study was to give the details and facts necessary to reach this understanding. Our main findings from this study were:

About 8% of residual trees were damaged during thinning operations.

About 4.3% of residual trees were damaged at the bole area.

Intensive wounds on the bole of residual trees were mostly created during the timber extraction phase.

Most bole wounds were severe, deeper than the bark and on the lower parts of the bole.

The wound healing rate was related to wound characteristics and the dbh of the tree.

The wound healing rate decreased with increasing wound width.

The wound width healing rate (3.2 mm year^{-1}) was twice as fast as the wound length healing rate (1.6 mm year^{-1}).

The effect of thinning damage on the diameter growth of remaining trees was not significant, but caused a 1.71% reduction in diameter growth.

More than 50% of wounds created during extraction operations significantly reduced diameter growth.

The effect of bole wounds on diameter growth depended on their severity, location and size, and tree dbh.

The ratio of wound width to dbh was a predictor of declining tree diameter growth.

Wounds greater than 100 mm in width significantly reduced diameter growth.

Wounds with wood damage significantly reduced diameter growth.

It takes about 22 years for all wounds to reach occlusion.

Our results are consistent with previously published scientific papers on this topic concerning damage percentage and healing rate. From the results obtained here, the main aspects are described which can be implemented to reduce residual tree damage during thinning interventions. In particular, a key issue is the skill level of forest operators, which needs to be improved through dedicated training. This is fundamental from the point of view of sustainability. It is worth noting that forest workers who have an appropriate level of skill will result in lower costs, less impact on the environment and a higher level of security in worksite.

It is imperative that plantations consider taking every measure to minimize logging damage to residual trees as a priority. Pre-harvest planning and marking of the extraction path before logging operations are among these measures that must implemented in plantations.

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