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Damage to Residual Trees in Thinning of Broadleaf Stand by Mechanised Harvesting System

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Abstract: This research was conducted to determine the cause, intensity and location of damage (stem, butt end, root collar, root) and the extent of damage to standing trees during felling and processing by an harvester and timber extraction by a forwarder (cut-to-length system). The research was conducted in the central part of the Republic of Croatia in the Management Unit (MU) "Bjelovarska Bilogora" during the thinning of Subcompartment 14b, area of 18.28 ha, in the stand of hornbeam (*Carpino betuli—Quercetum roboris fagetosum* Rauš 1975), age 70, and of Subcompartment 14c, area of 9.07 ha, in a stand of common beech (*Carici pilosae—Fagetum* Oberdorfer 1957) aged 79 years. The thinning intensity was 12.13% in Subcompartment 14b and 13.72% in Subcompartment 14c. Field measurements were carried out on sample plots—the first time in 2017 to determine the intensity and characteristics of the damage to standing trees with regard to the cause of the damage (harvester or forwarder), and the second time in 2018 to determine the overall intensity and features of the damage to standing trees after finishing harvesting operations. For all trees remaining in the stand after the harvesting operations, the following were determined: tree species, diameter at breast height (*DBH*), the position of the tree in the stand depending on the forest traffic infrastructure, and—if damaged—cause of damage, type of damage, the position of damage on the tree, and dimensions of damage. The intensity of the damage was expressed by the ratio of damaged and undamaged trees, with a detailed analysis of bark damage (squeezed-bark damage and peeled-bark injuries). The results of the research indicate the highest prevalence of peeled-bark injuries. In relation to the total number of standing trees, trees with peeled-bark injuries were more represented in Subcompartment 14c (39%) than in Subcompartment 14b (33%). In Subcompartment 14b, the harvester and the forwarder damaged an equal number of trees, while in Subcompartment 14c, the harvester damaged 59% of the damaged trees. In both subcompartments, an average of 83% of (peeled bark) injuries were up to 1.3 m above the ground. In both subcompartments, the most common (67%) were injuries up to 100 cm^2 in size, for which many authors claim the tree can heal by itself. Given the increasing use of harvester-forwarder systems in deciduous stands and research results that indicate possible damage to standing trees, it is necessary to pay attention to all phases of planning and execution of timber harvesting operations, thus minimising negative effects.

Keywords: bark damage; harvester; forwarder

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1. Introduction

Thinning as a treatment is a procedure that, with the help of positive selection, systematically directs the growth and development of selected trees, shapes the optimal structure of the stand following management goals, increases the quality, stability, and vitality of the stand, and prepares stands for natural regeneration [1]. In addition, the thinning removes one part of the increment accrued from the previous thinning that makes the removal of intermediate felling volume [2]. Thus, each stand, managed according to even-aged principles, is exposed to thinning several times during its rotation period. In addition to the principles of thinning, it is to be expected that the future quality of timber also be affected by the quality of performed harvesting operations. Although silvicultural operations (such as thinning) are performed to achieve positive management goals, timber harvesting operations can negatively affect forest stands, which is primarily reflected in the damage of forest soil and the remaining trees [3].

Damage to the stand can be defined as mechanical damage to the total number of standing trees in the stand after finishing operations [4]. Damage to standing trees can occur directly (mechanically) and afterwards indirectly (biologically). Previous researchers have pointed to the fact that the number of mechanically damaged trees can serve as a good indicator of the total damage to the stand [5–7]. In addition, such damage can be determined relatively easily and accurately [3].

The amount and characteristics of damage to standing trees in harvesting operations are influenced by numerous factors that can be classified into three groups: 1. working conditions; 2. choice of methods and means of work; and 3. practitioner's attitude towards harvesting operations [8]. Working conditions, which are the most varying, can change in part depending on the goals of management. These include: the felling intensity expressed by the number of trees per unit area [9,10]; the felling season, with less damage occurring during winter felling, making it preferable [11]; the density of primary and secondary transport infrastructure on which the average extraction distance depends [12]; and terrain slope [13]. Damage to the remaining stand can be caused by both felling and extracting, regardless of the technological level of the machines or the experience of the operators [14]. However, the amount and characteristics of damage depend on the combination of means and methods used in timber harvesting operations [15], whose choice is directly related to the level of planning [13], but is also limited by various working conditions. A practitioner's attitude towards harvesting operations depends on his/her experience and skills [16] and the interest of each individual in the quality of the work performed [4].

Attention should be paid not only to damage to the stand during operations, but also to the efficiency of harvesting operations. Commonly used harvesting systems in Croatia imply the use of chainsaws. The application of fully mechanised timber harvesting systems results in increased productivity, reduced physical workload, and increased work safety [17]. Efforts to rationalise and develop methods and systems of timber harvesting operations should minimise environmental effects such as damage to standing trees and forest soil [11]. When thinning is fully mechanised, it becomes technically complex, with high costs due to reduced vehicle mobility within the forest caused by limited space between trees [18], which leads to reduced productivity and increased costs [19].

The latest research on harvester application in broadleaf-dominated stands indicates different challenging factors in different European regions [20]. Since the introduction of the first privately owned harvester in Croatia in 2005 [21], the number of harvesters working in Croatia has reached 40 in 2021, four of which are owned by the state company Croatian Forests Ltd. (which manages 73% of the total forest area with a net annual cut of 5.4 mil m^3) and another four by Slovenian entrepreneurs working in Croatian territory [20]. They all work in both private and state forests, mostly in conifer plantations, stand sanitation after forest fires, clear-cuts of European black pine (*Pinus nigra* Arn.), stands ready for conversion, clear-cuts in poplar (*Populus* sp.) plantations, and sanitation felling of narrow-leaved ash stands due to ash dieback caused by *Hymenoscyphus fraxinues* (T. Kowalski) Baral, Queloz & Hosoya, but also in late thinnings and preparatory fellings of hardwood stands, often in combined mechanised and motor-manual cutting due to larger butt swelling, large crowns and thick branches [20].

A further increase in the use of fully mechanised systems is expected due to labour shortages and a needed increase in labour productivity [17], but mechanised forest operations in close-to-nature forestry are generally more complex than those in conventional conifer monoculture, and often lead to lowered harvesting productivity [22]. Although some studies indicate that a higher degree of mechanization causes a higher intensity of damage [15], application of the cut-to-length system, which includes a combination of an harvester and a forwarder, causes less damage to the forest, slower accumulation of damaged trees over time, and better distribution of accumulated damage in the stand, which ultimately increases the stability of the stand and the timber quality at the end of the management period when compared with the application of motor-manual felling and timber extraction by skidders in the tree-length and full-tree harvesting methods [23,24].

Current information on damage to residual trees following fully mechanised harvester-forwarder systems is primarily focused on young coniferous stands reporting 29.1–36.1% damaged trees, but with a mean wound area under 100 cm^2 in the thinning of a 12-year old *Pinus taeda* stand with a removal of 40% of trees in the stand [25], and 25% damaged trees in the first thinning of *Pinus taeda* stand with a removal of 50% of trees in the stand [26], to as low as 7.0% (with a 1 cm^2 bark damage threshold) in the first thinning with an intensity of 60% of the standing trees in Norway spruce dominated stand without previous marking of trees designated for felling, and 3.2% when prior marking of the trees was conducted [27]. Mechanised thinning of an uneven-aged Norway spruce dominated stand resulted in 21.5% damaged trees [28]. Late thinnings resulted in damage in 37.4% of the remaining trees in a mixed conifer stand [29] and shelterwood system regeneration felling (with 18.6 and 17% intensity) of a sessile-oak-dominated stands resulted in 20.47 and 23.36% damaged trees [30].

Depending on the intensity of the damage, further development of the stand is indirectly jeopardised if the damage to the remaining trees is such that the stability and vitality of the stand are impaired. In contrast, the intensity of the damage has a direct impact on the quality of the remaining trees, thus reducing the economic value of such stands [31]. Certainly, the quality of the timber volume at the end of the rotation period is most affected by those negative effects that occurred during forest growth, i.e., from a young age and especially during thinnings, and whose shortcomings are most pronounced at the end of the rotation period.

The question of how and to what extent injuries affect tree development has been the subject of numerous studies. Research on stand damage has investigated the extent of damage to the trees and its impact on further tree growth. As a general rule, fungal infection is not expected in the case of superficial bark damage, as in the case of peeled bark up to the size of 10 cm^2, while the possibility of fungal infection increases with increasing damage to the surface area [32–34]. However, several research results indicate that even injuries of up to 100 cm^2 can be repaired independently by the tree itself [32,34,35], and report that no fungi have been identified on such injuries [34]. The limiting value of the size of the critical injury can be approximated as the square of the diameter at the breast height of the tree [36], but the size of the area considered critical for a peeled-bark injury, which causes tree death, also depends on tree species, age, genetic predispositions, location of the injury, dimensions, and the shape of the injury (round, transverse or longitudinal) with respect to the longitudinal axis of the tree [37,38]. In addition to the size of the injury, the occurrence of fungal infection is also affected by the height of the injury from the soil, as it was found that the optimal conditions for fungal development are up to one meter from the ground [34], and the closer the injuries are to the ground, the more favourable the conditions created for the development of wood-destroying mycoses [37].

The negative consequences of damaged trees can lead to increment loss of 1–4.7% [34], and up to 8.1% loss in a mixed beech stand [39]. The loss of increment with a decrease in the quality of timber assortments results in a decrease in the economic value of stands [31,40]. For example, damage to beech bark results in air entering the wood cells, which eventually creates a specific white rot [41] that also reduces the technical value of the wood. Injuries to trees in the form of peeled bark can cause the appearance of various wood defects (colour change, frost crack, ring shake, heart shake, buckle, rot), which reduce the value of future roundwood [42–44].

In some countries, legal regulations prescribe the maximum allowable damage to standing trees. For example, in Finland, the maximum damage allowed is 15% of the remaining trees, while in Poland, the damage is allowed on 5% of the remaining trees [23] in the stand.

Given that there is growing concern to increase the quality of timber harvesting operations in order to reduce their negative effects on forest ecosystems, it is necessary to determine the consequences of the operations performed and identify and record the causes [45].

This research aims to determine the quality of fully mechanised harvesting operations (harvester-forwarder) with an emphasis on determining the origin (harvester or forwarder), location (stem, butt end, root collar, root), and the size of individual damage to the remaining standing trees after harvesting concerning their position in the stand.

2. Materials and Methods

The research was conducted in a 27.34 ha felling site located in the Forest Administration (FA) Bjelovar, Management Unit (MU) "Bjelovarska Bilogora", consisting of Subcompartments 14b and 14c (φ 45°59′59″ N and 45°59′31″ N and λ 16°44′05″ E and 16°43′38″ E) of state forests managed by the company "Croatian Forests" Ltd. (Figure 1, Table 1).

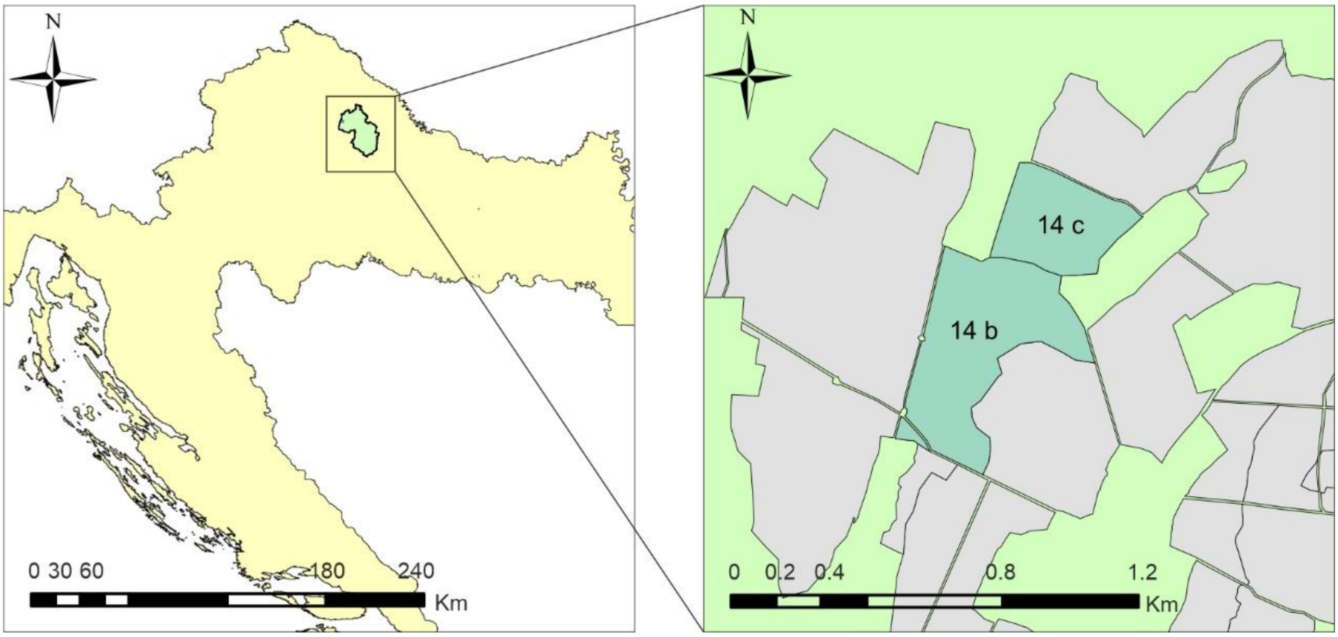

Figure 1. Study area.

On the south-west part of Subcompartment 14b (Figure 2), a landing site was positioned along the forest road of a total length of 545 m, while a secondary traffic infrastructure network in the researched subcompartments consisted of 3.46 km of trails (126.5 m/ha) and 8.51 km of harvester "ghost trails" (311.2 m/ha).

The prescribed thinning intensity in both subcompartments was around 11% of the standing volume, amounting to 34.03 m^3/ha in Subcompartment 14b and 44.98 m^3/ha in Subcompartment 14c. The thinning intensity per tree species amounted to 2.02 m^3/ha of European beech and 32.00 m^3/ha of European hornbeam in Subcompartment 14b, while in Subcompartment 14c thinning intensity of European beech was 19.96 m^3/ha and 25.03 m^3/ha of European hornbeam.

Table 1. Data on surveyed subcompartments.

Subcompartment	**14b**	**14c**
Area, ha	18.28	9.07
Age/Rotation, years	79/100	79/100
Altitude, m	100	150–175
Aspect	Western	Southwestern
Inclination, %	3–9	3–9
Soil	Luvisol	Luvisol
Phytocenosis	*Carpino betuli—Quercetum roboris fagetosum* Rauš 1975	*Carici pilosae—Fagetum* Oberdorfer 1957
Canopy coverage	Complete	Complete
Stocking	1.23	1.06
Growing stock, m^3 (m^3/ha)	5530 (291.58)	3681 (405.84)
Species composition, m^3/ha (%)	European hornbeam (*Carpinus betulus* L.) 243.71 (84) Pedunculate oak (*Quercus robur* L.) 18.16 (6) European beech (*Fagus sylvatica* L.) 17.34 (6) Sessile oak (*Quercus petraea* (Matt.) Liebl.) 3.72 (1) Black alder (*Alnus glutinosa* (L.) Gaertn.) 8.32 (3) Other hard broadleaves 0.33	European beech (*Fagus sylvatica* L.) 201.76 (50) European hornbeam (*Carpinus betulus* L.) 179.60 (44) Sessile oak (*Quercus petraea* (Matt.) Liebl.) 16.54 (4) Pedunculate oak (*Quercus* robur L.) 7.94 (2)
Number of trees, N/ha	784	540
Basal area, m^2/ha	28.88	30.98
Mean tree, cm	21.60	30.98
Annual increment, m^3/ha	7.49	9.70

The harvesting system previously applied in the researched subcompartments consisted of felling and processing by chainsaws and timber skidding. To enable the in-site travel of the harvester (and forwarder) and its reaching of the marked trees (and processed roundwood), it was necessary to establish a network of secondary transport infrastructure. Therefore, a correction of the tree selection and marking (for previously planned motor-manual timber harvesting) was performed in such a way as to include the trees located on the future "ghost trails". This resulted in omitting part of the previously marked trees to retain the prescribed felling intensity (Table 2). According to the technical characteristics of the harvester, the "ghost trails" were placed at a 20-meter distance. This enabled felling and processing of the trees situated between the "ghost trails" parallel to the felling and processing of the trees located on the "ghost trails" and the forwarding of the processed roundwood. Timberjack machines, forwarder model 1710D, and harvester model 1470D were used; the technical characteristics are shown in Table 3. Harvesting was conducted during summertime, and the absence of precipitation allowed favourable vehicle mobility.

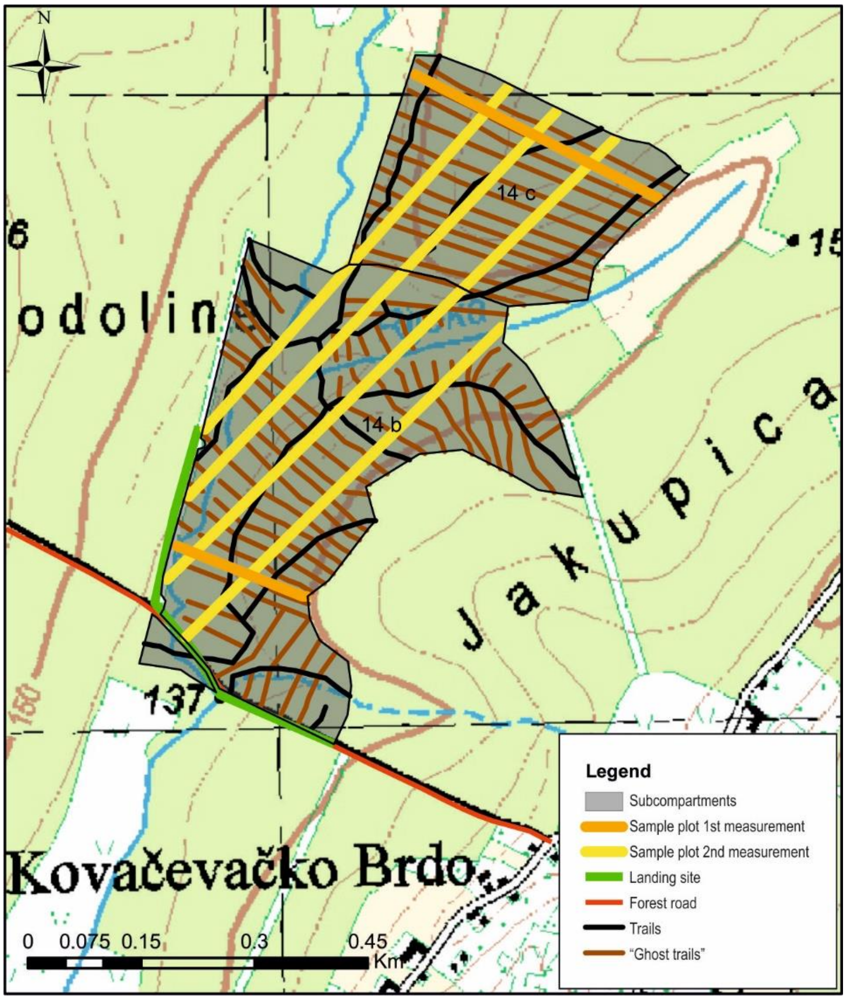

Figure 2. Sample plots.

Table 2. Data on trees marked for felling.

Subcompartment	**14b**		**14c**	
	Motor-manual felling and processing	Mechanised felling and processing	Motor-manual felling and processing	Mechanised felling and processing
Number of trees, N	1455	1782	423	559
Removal, m^3	741.81	731.24	407.02	446.3
Thinning intensity, % (m^3/ha)	13.92 (40.58)	13.72 (40.00)	11.06 (44.88)	12.13 (49.21)
Average DBH, cm		21.7		26.4
Average volume, m^3/tree	0.51	0.41	0.96	0.80

Table 3. Technical characteristics of the machines.

	Harvester Timberjack 1470D	**Forwarder Timberjack 1710D**
Length, mm	7700	10,900
Height, mm	3730	3900
Width, mm	3000	3050
Weight, kg	18,800	18,500–19,500
Payload, kg	-	17,000

Collecting the stand data, as well as determining, classifying and recording the damage to the trees, were performed following the content and structure of the recording sheets based on the concept proposed in previous research [5], but while taking into account the specifics of a fully mechanised timber harvesting system.

Field data collection was performed on two occasions, the first time during the timber harvesting and the second time after the harvesting work had been completed.

The first field survey was carried out twice in July 2017 in each subcompartment along one "ghost trail" (sample plots painted orange on the map, Figure 2). The first time was immediately after the work of the harvester and the second time immediately after the work of the forwarder, so that the recorded damages could be classified according to the cause concerning the means of work. During the measurement after the harvester operation, all damage was spray-painted to avoid recording one damage twice (Figure 3). In addition, tree species, diameter at breast height (*DBH*), type of damage, the position of damage on the tree, and the dimensions of damage were recorded for all damaged trees. The sample "ghost trail" length was 170 m in Subcompartment 14b and 340 m in Subcompartment 14c.

Figure 3. Damage recording (1: harvester-caused; 2: forwarder-caused).

The second field survey was conducted in March and April 2018 on four sample plots (transects) in Subcompartment 14b and three sample plots in Subcompartment 14c (sample plots painted yellow on the map, Figure 2). To achieve a representative survey result, a survey intensity of 10% was selected, which was, for example, prescribed for the forest management surveys on transect lines for stands above 2/3 of the rotation [46]. In Subcompartment 14b, the sample area was 1.83 ha, and in Subcompartment 14c, 0.91 ha. The total length of the sample plots in Subcompartment 14b was 1830 m, and in Subcompartment 14c, 828.1 m. The sample plots (transects) were placed at a distance of 50 m from each other to achieve the required sampling intensity for the width of the transects (10 m) and the subcompartment area. Considering that the processing and bunching, and thus the transport of the roundwood, took place mainly on "ghost trails", it was expected that the trees next to the "ghost trails" would be the most damaged; the transects were therefore placed in such a way as to vertically intersect the "ghost trails". Since the "ghost trails" in the stand were placed at an approximate angle of 135°, it was necessary to place the transects at an azimuth of 45°, thus enabling a representative coverage of the "ghost trails" and part of the stand between them. For all remaining trees after thinning, which were located on the transects, the second field survey had to determine and measure the following parameters: tree species, *DBH*, tree position, and—additionally for damaged trees—type of damage, tree damage position, and dimensions of damaged bark. The position of the tree was determined by its spatial position relative to the secondary transport infrastructure. According to their position, they were recorded as: (1) tree next to the "ghost trails" (trees that were in close proximity to the "ghost trails"); (2) tree next to the main forwarding trail (trees that were in the close proximity to the main forwarding trail); and (3) all other trees.

During both field surveys for damaged trees, it was necessary to determine the type of damage, defined as: (1) uprooted and/or broken tree, (2) broken branches on the tree, (3) squeezed bark or peeled tree bark. Squeezed bark meant surface damage to the outer dead part of the bark, and peeled bark meant a form of bark injury in which the cambium zone was visible. The method of determining the position of individual damage to the tree was performed following previous research, and is shown in Figure 4a [3,32]. As shown in Figure 4a, damage was classified as: (1) damage to the stem (if the damage was above 1.3 m from the ground); (2) damage to the butt end (if it was 0.3–1.3 m from the ground); (3) damage to the root collar (if located up to 0.3 m from the ground and at a distance of up to 0.2 m from the edge of the stem); and (4) root damage (if it was further than 0.2 m from the edge of the stem) [3]. The magnitude of the bark damage, i.e., the dimensions of the damage, was measured so that the shape of the damage would be approximated with a regular quadrilateral. Therefore, the length and width of each injury were measured (Figure 4).

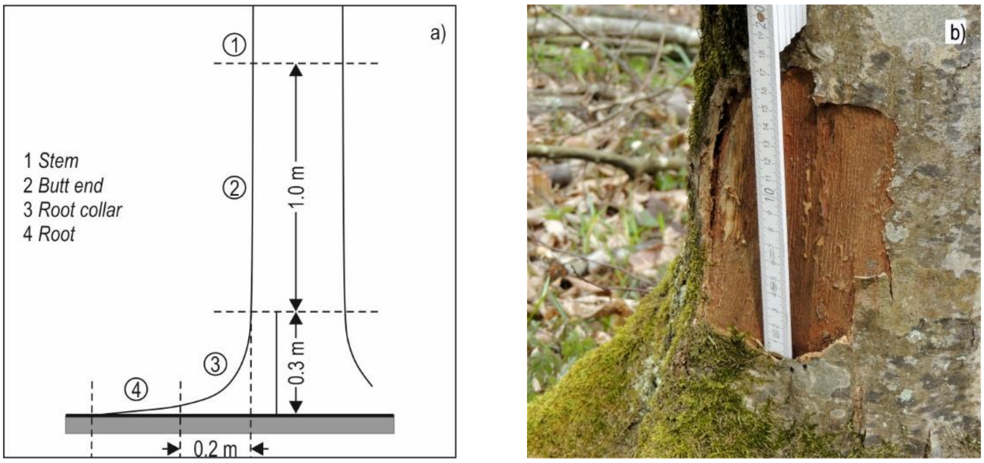

Figure 4. (**a**) Determining the position of an individual injury on a tree; (**b**) Measurement of injury dimensions.

The entry and computer processing of the collected data was performed using MS Excel and Statistica. In MS Excel, based on the collected data, the area of damaged bark was calculated for individual damage. The areas of peeled bark, as the most common form of damage, were summed at the level of each injury position on the tree and at the level of one tree. Statistical data processing referred to testing the size of peeled-bark injuries (individually and per tree) by *t*-test to investigate: (1) the impact of the subcompartment or the impact of stand factors (a) in the work of harvester and (b) in the work of forwarder; (2) the impact of the machine in the same stand conditions; and (3) the influence of stand conditions in the group work of harvester and forwarder. An analysis of the variance and a Scheffé post hoc test of the influence of the tree location on the total area of peeled-bark injury per tree and the position of the injury on the tree were performed.

3. Results

3.1. Results of the First Field Survey

According to the cause of the damage to the tree in Subcompartment 14b, the harvester and forwarder-caused damage to the same number of trees, and together damaged 60 trees. In contrast, the number of trees damaged by the harvester in Subcompartment 14c was higher by approximately 18% (37 trees were damaged by the harvester and 26 trees by the forwarder).

In Subcompartment 14c, 70 individual peeled-bark injuries were recorded following the work of the harvester, which primarily occurred on the butt end (56%), root collar (24%), and stem (20%). In Subcompartment 14b, 56 individual peeled-bark injuries were recorded, primarily on the root collar (57%), while other injuries were distributed on the butt end (32%) and stem (11%).

During the work of the forwarder, there was no significant deviation in the position of individual peeled-bark injuries between the subcompartments investigated. During the work of the forwarder in Subcompartment 14b, 58 peeled-bark injuries occurred, and the largest share of them was present on the root collar (55%), then on the butt end (33%), root (7%), and stem (5%). In Subcompartment 14c, during the work of the forwarder, 44 peeled-bark injuries occurred, and they were most common on the root collar (59%), then on the butt end (32%) and stem (9%).

T-test statistical parameters of the influence of stand conditions on the size of individual peeled-bark injuries and the sum of the injury area by the position on a tree are shown in Table A1 for the harvester operation and Table A2 for the forwarder operation. A statistically significant influence ($t = -2.43$, $p = 0.0190$) of stand conditions on the size of individual peeled-bark injuries on the root collar during the harvester operation (Table A1) was determined. According to the *t*-test results, stand conditions did not affect the size of the peeled-bark injury during the forwarder operation (Table A2).

In Subcompartment 14b, a statistically significant influence of the means of work on the size of the individual root collar peeled-bark injury ($t = -2.9909$, $p = 0.0040$) and on the sum of the peeled-bark injury area on the root collar ($t = -2.8467$, $p = 0.0068$) was determined. On average, the forwarder-caused a 146 cm^2 larger individual root collar bark injury (or 254 cm^2 summed at the tree level) (Table A3).

3.2. Results of the Second Field Survey

A total of 1090 trees were recorded on transects (sample plots) in both subcompartments, of which 387 had at least one form of damage. As the most common type of damage, peeled bark, was analysed in detail and presented in the research results. The second most common type of damage, but of much lower intensity, was squeezed bark, while other types of damage (uprooted and/or broken tree, broken branches) were almost non-existent. A total of 290 damaged trees was recorded in Subcompartment 14b. Of these, one tree was broken, one had broken branches and peeled bark, 21 had squeezed bark, of which 16, in addition, had a peeled-bark injury, and 267 had only peeled bark. A total of 97 damaged trees was recorded in Subcompartment 14c. Of these, one tree was broken, 25 had squeezed bark, of which 20 had a peeled-bark injury as well, and 71 had only peeled-bark injuries.

3.2.1. Squeezed-Bark Damage

A total of 29 squeezed-bark injuries were recorded on 21 trees in Subcompartment 14b, and 31 squeezed-bark injuries on 25 trees in Subcompartment 14c. Most of the damage in the form of squeezed bark in both subcompartments was up to 200 cm^2. In Subcompartment 14b, the area of the greatest damage was 1104 cm^2, and a maximum of three individual injuries were recorded on one tree. In Subcompartment 14c, the area of maximum damage was 695 cm^2, and a maximum of two individual injuries were recorded on one tree. According to previous research, fungal infection on trees with squeezed bark is generally not expected, and such damage is significantly less than in peeled-bark injury;therefore this damage has not been analysed in detail in this paper.

3.2.2. Peeled-Bark Injury

Peeled-bark injury was the most common of all damage types. In Subcompartment 14b, 859 trees were recorded, and 33% of the trees had peeled-bark injuries. A total of 231 trees were recorded in Subcompartment 14c, and 39% of the trees had peeled-bark injuries. Table 4 shows data per tree species.

Table 4. Share of damaged trees.

Subcompartment		Pedunculate and Sessile Oak	European Beech	European Hornbeam	Black Alder	Other	∑
14b	Undamaged, N	17	38	502	8	10	575
	Trees with peeled bark, N (%)	1 (5.6%)	5 (11.6%)	275 (33.1%)	2 (20%)	1 (9.1%)	284 (33 %)
	∑	18	43	777	10	11	859
14c	Undamaged, N	3	64	73	-	-	140
	Trees with peeled bark, N (%)	3 (50%)	34 (34.7%)	54 (42.5%)	-	-	91 (39 %)
	∑	6	98	127	-	-	231

3.2.3. Position of the Damaged Trees in the Stand

Considering the position of the tree in the stand relative to the transport infrastructure, in Subcompartment 14b, most of the total number of the damaged trees were located along the "ghost trails" (47%), 8% was located along the main forwarding trail, and the rest (45%) between the traffic infrastructure. In Subcompartment 14c, of the total number of damaged trees, 36% was situated along the harvester "ghost trails", 15% along the main forwarding trail, and the biggest share (52%) in the stand between the traffic infrastructure. However, more importantly, according to the location of the tree in the stand, in both subcompartments most of the undamaged trees were in the stand between the traffic infrastructure, with 78% in Subcompartment 14b and 73% in Subcompartment 14c.

3.2.4. Location of the Peeled-Bark Injury

According to the location of the peeled-bark injury on the tree, in Subcompartment 14b, the most common were root collar injuries (35%), followed by butt end (34%), stem (18%), and root injuries (13%). In Subcompartment 14c, injuries were equally present on the root collar (36%) and the butt end (36%), then on the root (16%) and the stem (12%). Up to a level of 1.3 m from the ground, in Subcompartment 14b there were 82% of all injuries, with 31% of them being greater than 100 cm^2. In Subcompartment 14c, 88% of the injuries were found to a level of 1.3 m from the ground, with 44% of them being larger than 100 cm^2.

3.2.5. Magnitude of the Peeled-Bark Injury

In Subcompartment 14b, injuries up to 100 cm^2 were most common on the butt end (38%) and the root collar (35%). Overall, in the structure of the injuries, those with an area up to 100 cm^2 prevailed (70%). Injuries with an area of 101–500 cm^2 were represented by 26% of the total number of injuries, and they were most common on the root collar (35%). In the category of serious damage, i.e., larger than 501 cm^2, there were only 34 injuries, or 4% of the total number of injuries, while the largest injury was present on the stem at a size of 4200 cm^2. On one tree, the sum of the areas of all injuries was 7499 cm^2, and a maximum of 14 injuries with an average size of 166.36 cm^2 were recorded.

In Subcompartment 14c, injuries up to 100 cm^2 were most common on the butt end (47%); in the overall structure of the injuries, these were the most frequent (56%). Injuries with an area of 101–500 cm^2 were represented by 38% of the total number of injuries, and they were most present at the root collar (41%). In the category of injuries larger than 501 cm^2, there were 13 injuries, which was 6% of all injuries in the subcompartment. The greatest damage was present on the stem with an area of 2250 cm^2, while on one tree, the sum of all injuries was 4101 cm^2. A maximum of 12 injuries were recorded on one tree.

The influence of stand factors on the size of individual injuries in the form of peeled bark, as well as the sum of areas of peeled bark when using group work of harvesters and forwarders, were tested by a *t*-test whose parameters are shown in Table A4. The statistical test revealed a statistically significant difference in the size of the injury on the root collar between the subcompartments examined, by injury (t = −3.4912, p = 0.0005) and by the sum of the areas of peeled bark per tree (t = −2.4414, p = 0.0154).

An analysis of variance and a Scheffé post hoc test revealed a statistically significant influence of the location of the tree in the stand in Subcompartment 14b on the sum of the size of the injury per tree (F = 4.8721, p = 0.0083). In Subcompartment 14b, the trees along the harvester "ghost trails" had a significantly larger area of peeled bark (434 cm^2) than the trees in the stand between the traffic infrastructure (215 cm^2). The trees along the main forwarding trail had an average 370 cm^2 area of peeled bark. In addition, a statistically significant difference in the size of the peeled bark on the butt end (F = 4.4440, p = 0.0133) and the root collar (F = 3.4585, p = 0.0338) was found when comparing the injuries on the trees along the harvester "ghost trails" with the injuries on the trees located in the stand between the forest road infrastructure (Table A5). In contrast to the situation in Subcompartment 14b, the analysis of variance showed no statistically significant influence of the location of the tree in the stand on the sum of the size of the injury per tree (F = 0.6789, p = 0.5100). In Subcompartment 14c, the trees along the main forwarding trail had a 644 cm^2 area of peeled bark, 394 cm^2 along the harvester "ghost trails", and 408 cm^2 for all other remaining trees in the stand. However, the results of the analysis of variance showed that there was a statistically significant effect of tree location on the size of peeled bark on the butt end (F = 7.8601, p = 0.0014) on trees located along the main forwarding trail in comparison with all other remaining trees (Table A5).

The number of injuries, the mean value of the injury area, the minimum and maximum injury area, and the standard deviation of the injury area are shown in Table 5 for individual injuries and summed on tree level by subcompartments and locations on the tree.

Table 5. Peeled bark magnitude on different locations on the tree.

	Valid N	Mean	Minimum	Maximum	Std. Dev.
14bS	141	132.5	2	4200	375.9
14bS∑	81	230.7	5	4200	513.1
14bB	269	96.2	2	1150	161.0
14bB∑	155	166.9	2	1238	226.8
14bRc	276	107.6	2	1296	157.5
14bRc∑	167	177.8	6	1428	245.6
14bR	107	171.7	6	858	157.2
14bR∑	69	266.2	9	1941	312.5
14cS	26	205.5	6	2250	430.7
14cS∑	15	356.1	6	2250	570.1
14cB	75	133.3	3	2050	279.2
14cB∑	42	238.0	3	2738	450.9
14cRc	77	182.1	4	920	192.1
14cRc∑	50	280.4	6	1462	306.5
14cR	34	219.3	10	750	184.6
14cR∑	27	276.2	12	750	205.7

S—stem, B—butt end, Rc—root colar, R—root. ∑—sum of the peeled bark area per tree in different locations on a tree.

4. Discussion

The most common type of damage to standing trees using a fully mechanised harvester-forwarder system in the subcompartments studied was peeled bark, followed by squeezed bark, but with a significantly lower intensity. In contrast, other forms of damage (uprooted and/or broken tree and broken branches) were almost absent. Similar results of the absence of crown damage were reported in the research on mechanised thinning of young coniferous stands [26].

The share of trees with peeled bark, expressed as a percentage of the number of remaining trees after finishing harvesting operations, was 33% in Subcompartment 14b and 39% in Subcompartment 14c. When compared with previous research on residual stand damage in mechanised thinning, the results are similar to those reported for young coniferous stands (29.1–36.1% and 25% damaged trees) [25,26] and for late thinnings of a mixed conifer stand (37.4% of the remaining trees damaged) [29], but higher than 21.5% damaged trees in uneven-aged Norway spruce dominated stands [28] as well as 20.47% and 23.36% damaged trees in shelterwood-system regeneration felling of sessile oakdominated stands [30]. Previous research shows a wide range in the intensity of damage to the remaining trees in timber harvesting operations for the thinning of hardwoods (3–50%) [23]. Interestingly, the results of this research are comparable to residual stand damage levels reported in the research on motor-manual felling and processing and mule (38.0% and 45.6% of damaged trees) and tractor (39.6% and 32.8% of damaged trees) extraction in the "Short Wood System" applied in the thinning from below of 20% volume in an even-aged beech high forest [47].

With regard to the cause of peeled-bark injury, the harvester in Subcompartment 14c damaged 18% more trees than the forwarder, while in Subcompartment 14b the harvester caused as much damage as the forwarder. This is opposed to the research results on the thinning of young Douglas-fir stands, where the harvester damaged more than twice as many residual trees than the forwarder [15]; it is also opposed to results from uneven-aged Norway spruce dominated stands, where 88.4% of the damage was caused by an harvester and only 11.6% by a forwarder [28]. However, it was to the results reported for mechanised thinning in young coniferous stands [25]. In Subcompartment 14c, more trees were damaged during the harvester operation. This was most likely due to larger tree sizes, which made the handling of timber more difficult, especially since the hardwood assortments that were processed are ones for which specific harvester heads are still being developed [20]. Several research reports stress the fact that the most trunk damage occurred because of operations of selective thinning while pulling the felled trees for later processing on the "ghost trails" [25], the influence of off-trail felling and processing of large-diameter trees on the damage levels [15], and damage related to felling and moving stems while delimbing and processing [7]. Similar explanations can be applied when comparing the research results regarding the means of work and the location of the peeled-bark injury on the tree in Subcompartment 14c. Here, larger trees were felled and processed, and the harvester primarily damaged the butt end (56% of the total number of injuries) with a statistically higher root collar damage in Subcompartment 14c than in Subcompartment 14b, and the forwarder primarily damaged the root collar (59% of the total number of injuries). Moreover, significantly greater damage on the root collar (individual and sum of damage per tree) was found after forwarder work compared to the harvester in Subcompartment 14b. High shares of forwarder-caused damage to the root system (in relation to harvester-caused damage) were also reported for the thinning of young Douglas-fir stands [15] and in research on mechanised harvesting of uneven-aged Norway spruce dominated stands, where all root damage was attributed to forwarder work [28]. Significant differences in the individual and sum per tree of root collar damage were found between the subcompartments, with greater damage in Subcompartment 14c. The results of this and previous research show that the greater number of damaged trees was influenced more by the dimensions of the assortments produced [9] than by the intensity of the felling [9,10].

Different studies have yielded different classifications of injury severity, but all indicate the two most important parameters for assessing the severity of damage: injury depth and injury size [9,10,31,34,48]. The results of this research show a smaller number of trees with injuries in the category of serious damage (>500 cm^2)—4% of all damaged trees in Subcompartment 14b and 6% of all damaged trees in Subcompartment 14c—in comparison with previous studies, where the prevalence of injuries in the category of serious damage was between 17–40% in the use of partially mechanised harvesting systems [31,34].

Considering the size of the peeled bark, in both subcompartments the most common injuries were up to 100 cm^2 (70% in Subcompartment 14b and 56% in Subcompartment 14c), which are considered not to have major consequences for the stand [32,34,35].

Further reduction of the residual stand damage can be expected by changing the season of harvesting from the sap period (summertime, as in this research), when the probability of contact damage is reported to be 1.5 times higher than in other seasons and the damage area to be double compared to wintertime [7]. In addition, minimising damage could be achieved by the correct selection of harvesting machines and the improvement of working techniques [25]. In the case of this research, this would suggest a smaller harvester and forwarder, as well as further professional training in broadleaf stand thinning for harvester and forwarder operators who have previous experience mainly in harvesting coniferous plantations.

5. Conclusions

Factors influencing the amount and intensity of damage to standing trees during harvesting operations are numerous and intertwined. They should be identified during the organisation of a felling site, and their impact should be minimised. Therefore, during the planning phase of timber harvesting operations, sufficient attention should be paid to the choice of timber harvesting methods and systems to reduce overall damage to the stand (standing trees and forest soil). A special approach is required for stands in which a certain system is applied for the first time. One example is the proper design of "ghost trails", which can be a challenge in late thinnings and can affect the level of damage compared with the stands that were designated for mechanised thinning from early thinnings onward and for which appropriate forest infrastructure for mechanised harvesting is already established. Certainly, it is necessary to have a well-trained operator, who, as one of the variables that can be influenced, can reduce the damage to the stand.

The results of the research point to the fact that the factors influencing the occurrence of damage to the standing trees cannot be unambiguously determined, and that they involve a combination of various factors, such as stand characteristics, structure of trees marked for felling, tree dimensions, dimensions of machines used, operator work techniques and skills, etc. The reported values in the category of serious damage together with the prevailing share of peeled-bark injuries below 100 cm^2 should limit damage-related economic losses in the stand, keeping in mind that most of the damage occurred on the European hornbeam trees (more evident in Subcompartment 14b following the growing stock composition). However, prior to application of the harvesting system researched to oak-dominated stands or to mixed stands with a high share of tree species that produce high-value timber assortments, appropriate residual-stand damage-mitigation strategies should be applied.

As the fully mechanised harvesting system that has been researched occupies an increasing share in timber production with the expected growth trend, it would be desirable to standardize methods for determining and reporting damage to stands, with a special emphasis on the maximum allowable degree of damage to broadleaf stands. This would lead to a reference value for assessing the quality of the work performed and for planning further management.

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Appendix A. Statistical Analyses Results

Table A1. Injury magnitude (harvester-caused) vs. stand factor *t*-test results.

	Mean Group 1	Mean Group 2	t-Value	df	*p*	Valid N Group 1	Valid N Group 2	Std.Dev. Group 1	Std.Dev. Group 2	F-Ratio Variances	*p* Variances
14bSH vs. 14cSH	91.50	97.00	−0.11	18	0.9114	6	14	103.58	98.36	1.11	0.8043
14bSH∑vs. 14c SH∑	109.80	194.00	−0.77	10	0.4613	5	7	105.83	226.38	4.58	0.1627
14bBH vs. 14cBH	103.56	120.59	−0.39	55	0.6979	18	39	175.36	142.19	1.52	0.2786
14bBH∑ vs. 14cBH∑	169.45	188.28	−0.29	34	0.7736	11	25	206.14	167.10	1.52	0.3840
14bRcH vs. 14cRcH	76.97	165.71	−2.43	47	0.0190	32	17	74.66	180.78	5.86	0.0000
14bRcH∑ vs. 14c RcH∑	102.63	201.21	−1.81	36	0.0791	24	14	93.13	239.90	6.64	0.0001
14bRH vs. 14cRH	0.00	0.00		−2		0	0	0.00	0.00		
14bRH∑ vs. 14cRH∑	0.00	0.00		−2		0	0	0.00	0.00		

S—stem, B—butt end, Rc—root colar, R—root, H—harvester. ∑—sum of the peeled-bark area per tree in different locations on a tree. Statistically significant differences ($p < 0.05$) marked in red.

Table A2. Injury magnitude (forwarder-caused) vs. stand factor *t*-test results.

	Mean Group 1	Mean Group 2	t-Value	df	*p*	Valid N Group 1	Valid N Group 2	Std.Dev. Group 1	Std.Dev. Group 2	F-Ratio Variances	*p* Variances
14bSF vs. 14cSF	185.00	185.25	−0.0027	5	0.9979	3	4	153.05	94.01	2.65	0.4345
14bSF∑ vs. 14c SF∑	277.50	247.00	0.2221	3	0.8385	2	3	95.46	171.40	3.22	0.7328
14bBF vs. 14cBF	151.32	261.71	−0.8183	31	0.4194	19	14	152.64	563.52	13.63	0.0000
14bBF∑ vs. 14cBF∑	205.36	366.40	−0.7692	22	0.4500	14	10	151.13	769.45	25.92	0.0000
14bRcF vs. 14cRcF	223.06	193.42	0.4882	56	0.6273	32	26	266.04	175.16	2.31	0.0353

Table A2. *Cont.*

	Mean Group 1	Mean Group 2	t-Value	df	*p*	Valid N Group 1	Valid N Group 2	Std.Dev. Group 1	Std.Dev. Group 2	F-Ratio Variances	*p* Variances
14bRcF∑vs. 14cRcF∑	356.90	295.82	0.5189	35	0.6071	20	17	426.51	249.88	2.91	0.0353
14bRFvs. 14cRF	275.25	0.00		2		4	0	127.11	0.00	0	1.0000
14bRF∑ vs. 14cRF∑	275.25	0.00		2		4	0	127.11	0.00	0	1.0000

S—stem, B—butt end, Rc—root colar, R—root, F—forwarder. ∑—sum of the peeled-bark area per tree in different locations on a tree.

Table A3. Injury magnitude vs. means of work (in the same stand) *t*-test results.

	Mean Group 1	Mean Group 2	t-Value	df	*p*	Valid N Group 1	Valid N Group 2	Std.Dev. Group 1	Std.Dev. Group 2	F-Ratio Variances	*p* Variances
14bSH vs. 14bSF	91.50	185.00	−1.1036	7	0.3063	6	3	103.58	153.05	2.1834	0.4164
14bSH∑ vs. 14bSF∑	109.80	277.50	−1.9304	5	0.1114	5	2	105.83	95.46	1.2290	1.0000
14bBH vs. 14bBF	103.56	151.32	−0.8850	35	0.3822	18	19	175.36	152.64	1.3199	0.5642
14bBH∑ vs. 14bBF∑	169.45	205.36	−0.5030	23	0.6198	11	14	206.14	151.13	1.8605	0.2924
14bRcH vs. 14bRcF	76.97	223.06	−2.9909	62	0.0040	32	32	74.66	266.04	12.6958	0.0000
14bRcH∑ vs. 14bRcF∑	102.63	356.90	−2.8467	42	0.0068	24	20	93.13	426.51	20.9721	0.0000
14bRH vs. 14bRF	0.00	275.25		2		0	4	0.00	127.11	0.0000	1.0000
14bRH∑ vs. 14bRF∑	0.00	275.25		2		0	4	0.00	127.11	0.0000	1.0000
14cSH vs. 14cSF	97.00	185.25	−1.5955	16	0.1302	14	4	98.36	94.01	1.0947	1.0000
14cSH∑ vs. 14cSF∑	194.00	247.00	−0.3590	8	0.7289	7	3	226.38	171.40	1.7443	0.8164
14cBH vs. 14cBF	120.59	261.71	−1.4619	51	0.1499	39	14	142.19	563.52	15.7077	0.0000
14cBH∑ vs. 14cBF∑	188.28	366.40	−1.1166	33	0.2722	25	10	167.10	769.45	21.2033	0.0000
14cRcH vs. 14cRcF	165.71	193.42	−0.5010	41	0.6191	17	26	180.78	175.16	1.0652	0.8639
14cRcH∑ vs. 14cRcF∑	201.21	295.82	−1.0680	29	0.2943	14	17	239.90	249.88	1.0849	0.8941
14cRH vs. 14cRF	0.00	0.00		−2		0	0	0.00	0.00		
14cRH∑ vs. 14cRF∑	0.00	0.00		−2		0	0	0.00	0.00		

S—stem, B—butt end, Rc—root collar, R—root, H—harvester, F—forwarder. ∑—sum of the peeled-bark area per tree in different locations on a tree. Statistically significant differences ($p < 0.05$) marked in red.

Table A4. Injury magnitude vs. stand factors *t*-test results.

	Mean Group 1	Mean Group 2	t-Value	df	*p*	Valid N Group 1	Valid N Group 2	Std.Dev. Group 1	Std.Dev. Group 2	F-Ratio Variances	*p* Variances
14bS vs. 14cS	132.52	205.46	−0.8883	165	0.3757	141	26	375.89	430.72	1.3130	0.3259
14bS∑ vs. 14cS∑	230.69	356.13	−0.8549	94	0.3948	81	15	513.15	570.08	1.2342	0.5362
14bB vs. 14cB	96.17	133.29	−1.4744	342	0.1413	269	75	161.00	279.23	3.0078	0.0000
14bB∑ vs. 14cB∑	166.90	238.02	−1.4160	195	0.1584	155	42	226.80	450.94	3.9532	0.0000
14bRc vs. 14cRc	107.57	182.09	−3.4912	351	0.0005	276	77	157.50	192.12	1.4879	0.0227
14bRc∑ vs. 14cRc∑	177.78	280.42	−2.4414	215	0.0154	167	50	245.65	306.52	1.5570	0.0417
14bR vs. 14cR	266.25	276.19	−0.1526	94	0.8791	69	27	312.52	205.73	2.3076	0.0199
14bR∑ vs. 14cR∑	266.25	276.19	−0.1526	94	0.8791	69	27	312.52	205.73	2.3076	0.0199

S—stem, B—butt end, Rc—root collar, R—root. ∑—sum of the peeled-bark area per tree in different locations on a tree. Statistically significant differences ($p < 0.05$) marked in red.

Table A5. Analysis of the variance of the influence of the tree location on the total size of the injury (peeled bark) per tree.

	SS Effect	df Effect	MS Effect	SS Error	df Error	MS Error	F	*p*
14bS	669854	2	334927	20350732	77	264295.2	1.2672	0.2874
14bB	437602	2	218801	7483819	152	49235.6	4.4440	0.0133
14bRc	405392	2	202696	9611604	164	58607.3	3.4585	0.0338
14bR	88734	2	44367	6552689	66	99283.2	0.4469	0.6415
14b∑	3142156	2	1571078	88999703	276	322462.7	4.8721	0.0083
14cS	232730	2	116365	4317072	12	359756.0	0.3235	0.7298
14cB	2395113	2	1197556	5941986	39	152358.6	7.8601	0.0014
14cRc	740	2	370	4603150	47	97939.4	0.0038	0.9962
14cR	130389	2	65195	970057	24	40419.0	1.6130	0.2202
14c∑	563651	2	281825	34040275	82	415125.3	0.6789	0.5100

S—stem, B—butt end, Rc—root collar, R—root, ∑—sum of the peeled-bark area per tree. Statistically significant differences ($p < 0.05$) marked in red.

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