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Assessing the Residual Stand Damage after Thinning with Different Levels of Mechanization

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Abstract: Thinning is a silvicultural process in which trees are both harvested selectively and systematically removed from a stand to enhance forest management and ecosystem dynamics. However, this practice is challenged by the mechanical damage to residual trees, and the nature of this damage, particularly on stand damage during mechanized row-thinning and manual selective thinning, in South Korea is unknown. Therefore, objectives of this study were to compare stand damage levels and wound characteristics between three different thinning operations: manual selective, manual row-, and mechanized row-thinning. After thinning, 12%, 15%, and 10% of the residual damaged trees were observed in manual selective, manual row-, and mechanized row-thinning, respectively. Both types of row-thinning predominantly demonstrated damages at the stem and butt region, whereas in manual selective thinning, the most of the damages occurred on the roots. Manual selective thinning exhibited a slightly larger average wound size (207 cm^2) compared to mechanized row- (181 cm^2) and manual row-thinning (165 cm^2). The wound sizes on the stem in mechanized row-thinning were significantly higher than manual selective ($p < 0.05$). These results may be helpful in understanding exposure to damage among different thinning types and in managing its occurrence in future practices.

Keywords: thinning operation; thinning type; mechanized operation; residual tree damage; mechanical damage

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1. Introduction

Forest management aimed to sustainably manage forest resources to meet both ecological and socioeconomic objectives. Silvicultural prescription efforts have improved economically productive forests, ecosystem protection, and social values [1,2]. Forest thinning operations such as selection and geometric thinning are crucial for reducing overstocked stands and restoring forest structure and ecosystem services [3,4]. In many cases, mechanized harvesting systems have been applied to thinning operations because they are effective technologies for improving productivity and work safety [4–6]. However, felling and extraction operations can adversely affect the remaining trees [4,7]. For example, Ursic et al. [4], Kizha et al. [7], and Han [8] reported that thinning operations are a crucial cause of declining standing tree growth and increased pests and diseases, resulting in lower wood quality. Thus, damage to residual trees is a critical consideration in the planning and implementation of thinning operations.

Residual stand damage can be defined as canopy, stem, and root damage to standing trees in a stand after thinning [8]. Previous studies have pointed out that 10%–32% of residual trees from a thinned site were damaged in a mechanized thinning [6,9,10]. Damage to 23% and 11% of residual trees due to skidding and winching operations, respectively, were reported by Borz et al. [10] and Hartsouth [11]. Most of the tree damages are observed close to the extraction trails [7,12]. The amount or level of damage to residual trees depends on several factors, including working conditions (tree species and density [2,13,14]), harvesting method (level of mechanization and thinning type [7]), harvesting system (cut-to-length and whole-tree [5,6]), and operator experience and skills [6,15]. In addition, damaged trees are concentrated close to felling, skidding, and forwarding trails at a height of less than 1 m, owing to machine movement, tree processing, and handling [6,16,17]. This damage is associated with fungal invasion because fungal decay begins to infect up to 1 m from the ground or near ground level [4,18]. If the size of the damaged area reached 100 cm^2, the scar could be recovered independently by the tree itself [4]. Therefore, minimizing residual stand damage for sustainable forest management is an important principle in thinning operations.

In South Korea (hereafter Korea), commonly used free thinning (also called selective thinning) systems indicate the use of manual felling and extraction using winches and small shovels [19]. Conifer (*Pinus koraiensis* and *Larix kaempferi*) stands cover approximately 40% of the forest area (6 million hectares (ha) [19]). This species produces high-value wood products, and 82% of the total conifer forest area is in an age class of more than 40 years [19]. As a result, the management of conifer forests is a critical issue.

In recent years, the mechanized row-thinning application, which uses a harvester and forwarder, has resulted in increased productivity and work safety [20]. For example, Hwang et al. [6] reported that although mechanized thinning is an effective tool to control overstocked stands and restore ecosystems, it can possibly expose the remaining damage to the stand. On the other hand, Cho et al. [21] studied the residual stand damage using two thinning applications: manual selective thinning with chainsaws and mechanized row thinning with grapple-saws. They found that the number of damaged trees and the extent of the damage were higher for the mechanized method than for the manual method because of the operator's experience. However, no published studies that determined row-thinning operations by harvesters and forwarders, and the subsequent evaluation of tree damage in Korea, were found.

Therefore, the main objective of this study was to observe residual stand damage in three different thinning operations: manual selective (chainsaw and winch), manual row (chainsaw and winch), and mechanized row (harvester and forwarder). Specific aims were to compare (1) tree-level damage (number of trees damaged and damage per tree) and (2) wound characteristics (type, size, and location).

2. Materials and Methods

2.1. Description of Study Sites

The data were collected from artificially forested areas in Central Gangwon-do, Korea (Figure 1). In the last decades, the air temperature in the study sites weather station has been varying from −4.8 °C in winter to 26.3 °C in summer. Two-thirds of annual precipitation occurs in summer from June to August, ranging between 38 and 745 mm, with an average of 219 mm.

The thinned units were harvested from October to November 2023. The site was an artificially regenerated 40-year-old Korean pine (*Pinus koraiensis*) stand for timber production and economic value. The stand characteristics are presented in Table 1. Before thinning, the unit was 3.3 hectares (ha; S1: 1.1 ha, S2: 0.9 ha, and S3: 1.3 ha) with steep terrain (ground slope ranging from 27 to 58%). The area consisted of 611 trees per hectare (ha), with Korean pine being the dominant species, followed by Japanese larch (*Larix kaempfer*). The trees were grown in rows in approximately a 1.4 m × 2.0 m grid at the time of the thinning. This area had an average diameter at breast height (DBH) of 26 cm, average height of 15 m, and soil texture of loam with a proportion of fine particles (<0.01 mm) ranging from 40 to 48%.

Prior to thinning, the area was divided into three regions to compare the amount and location of damage according to the harvesting method (Figure 1): manual selective (chainsaw and winch), mechanized row- (harvester and forwarder), and manual row-thinning (chainsaw and winch) types were named S1, S2, and S3, respectively. Two row thinning types with approximately 3 m row widths were practiced, and 5 m row widths were retained on either side of the cut strips. The harvesting technology in all units involved cutting the selected trees into 4–6 m logs. In both regions (S1 and S3), after motor-manual with a chainsaw felling and processing, the cut-to-length log was winched using a double-drum logging winch (DGV 2 × 55, Tajfun, Ferndale, WA, USA). A winch was mounted on the tractor to allow pulling and dragging the one or three logs uphill from the stump to the extraction tracks. Then, a small shovel was used to load logs close to roadside. The same operators and machines were used for the manual selection and manual row-thinning. The operator has more than 15 years of experience. A harvester (KDH-40; Konrad, Preitenegg, Austria) was used for felling and processing under the S2 conditions. Extraction was completed with a forwarder (LVS-720, Novotný, Zábřeh, Czech Republic). This technology was used to collect and load logs to transport along the track with an uphill forwarding direction. The harvester operator was insufficiently experienced in thinning with less than one month of training, while the forwarder operator was sufficiently experienced.

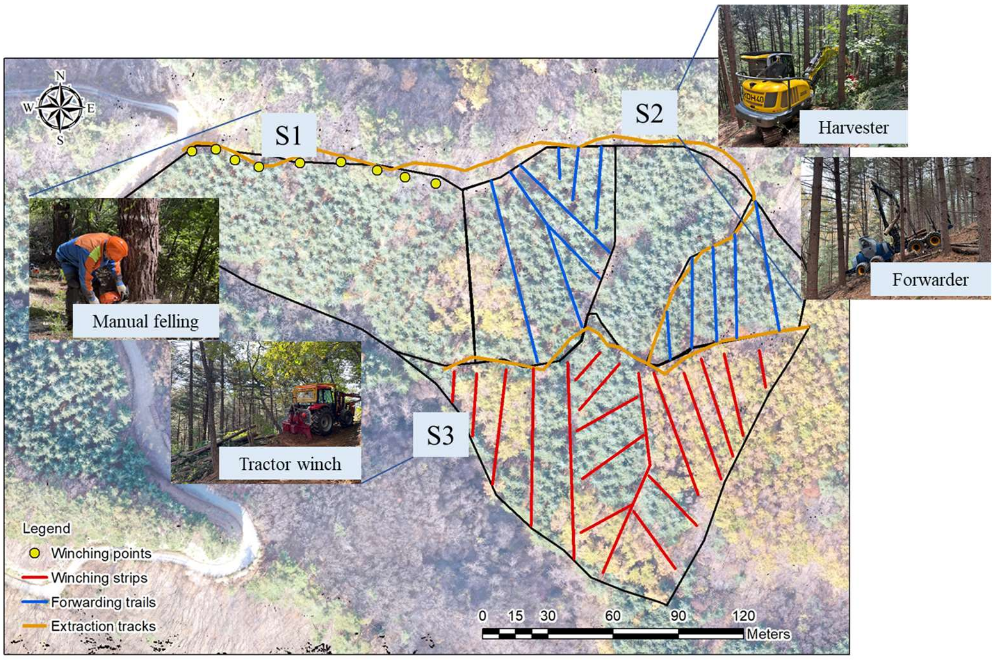

Figure 1. Map of study sites (S). S1: manual selective thinning; S2: manual row-thinning; S3: mechanized row-thinning. Background image by drone, yellow dots: winch yarding red lines: winch strips; blue lines: forwarder trails.

Table 1. Stand composition characteristics before thinning.

Area	DBH [1] (cm)	Height (m)	TPH [2]	BA [3] (m^2/ha)	KP [4] (%)	JL [5] (%)
S1	26.00	15.00	662.00	35.00	94.00	6.00
S2	26.00	15.00	557.00	32.00	95.00	5.00
S3	26.00	15.00	612.00	30.00	51.00	49.00

[1] Diameter at breast height, [2] trees per ha, [3] basal area, [4] Korean pine (*Pinus koraiensis*), [5] Japanese larch (*Larix kaempfer*).

After thinning, 32% of the trees in S1 were selected and thinned, leaving 195 trees per hectare (TPH), and the basal area (BA) was reduced to 9 m^2/ha (Table 2). In S2, 31% of the trees were cut and the residual stand had a BA of 23 m^2/ha. A total of 210 TPH were thinned in S3, comprising 29% of the total number of trees before thinning. There was considerable similarity between the units.

Table 2. Post-thinning stand component characteristics of DBH, height, trees per hectare, and basal area.

Area	DBH [1] (cm)	Height (m)	TPH [2]	BA [3] (m^2/ha)
S1	26.00	15.00	447.00	26.00
S2	26.00	15.00	398.00	23.00
S3	26.00	15.00	422.00	21.00

[1] Diameter at breast height, [2] trees per ha, [3] basal area.

2.2. Field Data Collection and Analysis

This study used a complete enumeration design to evaluate stand damage a month after thinning. This design is expensive and time-consuming compared to random and systematic sampling [22]. However, when all single units of the population are detected in small tracts, all samplings have a preference for determining the mean rather than inferencing with sampling [22].

In all regions, only damaged trees were observed after felling and extraction activities (Figure 2). The measurements included (1) the type (stem, butt, and root) of damage, (2) scar size (maximum width and length), (3) height of wound from ground level, (4) number of trees damaged per hectare, (5) number of damages per tree, (6) location and position of damaged trees, and (7) diameter at breast height (DBH). Stem damage was defined as 1.3 m above the ground [4,5]. Damage to the butt ranged from 0.3 to 1.3 m from the ground and root was further than 0.3 m from the edge of the stem [4,5]. The maximum width and length of each wound was measured with a ruler to an accuracy of 1 mm. The location and position of the wound was determined by measurement of the height between the center of the wound and the ground. Trees less than 6 cm at DBH were rejected from the damage measurements.

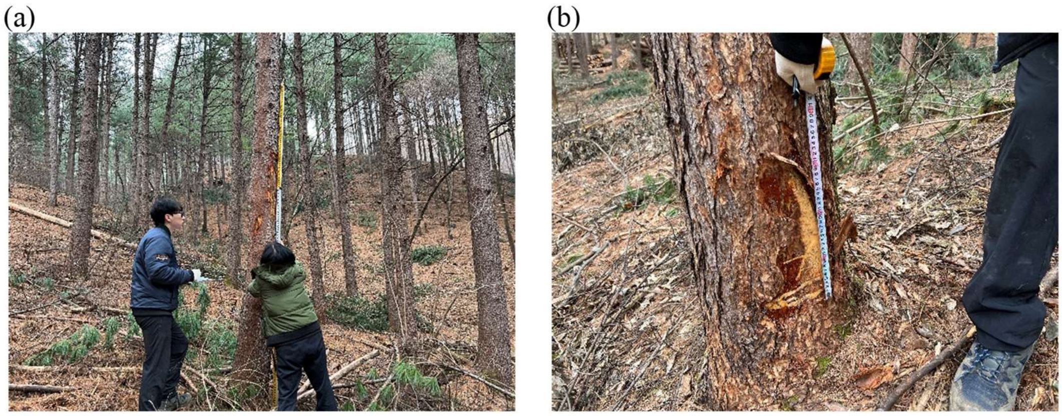

Figure 2. Measurement of injury on a tree: (**a**) injury height, and (**b**) injury dimension.

In addition, all injury sizes for the roots, butts, and stems were assigned a severity index of 1–6 to assess the level of wound severity: 1 = negligible injury, damaged area below 10 cm^2; 2 = very light, damaged area of 50 cm^2; 3 = light, damaged area of 100 cm^2; 4 = medium, damaged area of 200 cm^2; 5 = heavy, damaged area of 300 cm^2; and 6 = very heavy, damaged area above 300 cm^2 [23].

2.3. Statistical Analysis

The R statistical program (R Core Team, 2023) was used for the data analysis. Shapiro–Wilk test and equality of variance using Levene's test were used for normality. The data did not meet the assumptions of normality for one-way analysis of variance (ANOVA) test. Therefore, we used a nonparametric ANOVA. The Kruskal–Wallis H-test was used to determine the effect of thinning applications on the number of damages per tree, height of damage from ground, and wound size of damage on the tree. Additionally, the Bonferroni test was used as a post hoc test <0.05.

3. Results

In S1, selective thinning resulted in 12% of the residual trees being damaged, and the total number of damaged trees was 50 per ha (Table 3). These trees had an average DBH of 24 cm and an average of 2.1 injuries per tree. Figure 3 shows the results of the residual damage measurements owing to the thinning operation. The most common type of damage (36% of the total damage) was butt injury, with an area of approximately 796.00 cm^2 (mean, 144.00 cm^2). Approximately 34% of the damage intensity was measured in the root (average wound size of 376.00 cm^2) and 30% in the stem (average wound size of 108.00 cm^2). Most stand damage occurred at heights of 1.3 m above the ground line. In addition, the residual tree damage positions were mostly in the direction of the forest road at 36% of the total damage, and the remaining distribution was to the left (21%) or right (23%) of the standing trees.

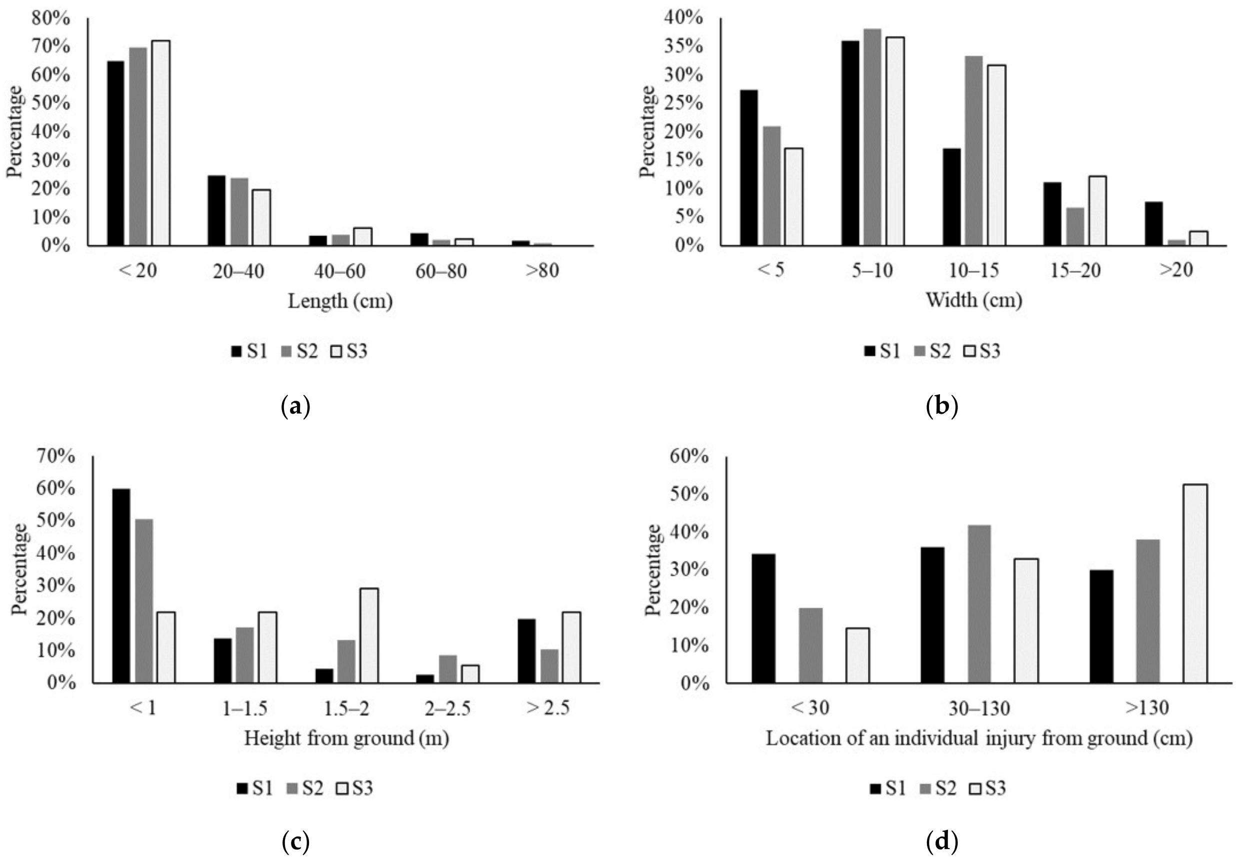

Figure 3. Injury distribution percentage as related to (**a**) length, (**b**) width, (**c**) height, and (**d**) location of individual injury for each unit. S1 (black): manual selective thinning; S2 (grey): mechanized row-thinning; S3 (white): manual row-thinning.

In S2, the data showed that mechanized row-thinning resulted in 10% of the residual trees being damaged, and 30 residual trees per ha were found to be wounded (Table 2). The trees had an average DBH and injuries per tree of 26.00 cm and 1.8, respectively. Most stand damage was recorded in the butt area (44%), with wound sizes ranging from 19 to 372 cm^2 (mean value of 129 cm^2; Figure 3). Stem injuries with an area of 15–611 cm^2 (average 150.00 cm^2 area) were recorded for 38% of the total damage. Approximately 18% of the injuries occurred on the root, with an area of up to 1020 cm^2 (mean value of 365 cm^2). In addition, the size of the root injury was statistically the highest compared to the other locations ($p < 0.01$). The damaged trees were arranged along the felling gaps and winching strips, accounting for 63% of the total damage.

Table 3. Summary of residual tree injuries in different thinning applications.

	Study Site			***p*-Value**
	S1	**S2**	**S3**	
Percentage of damaged trees (%)	12	10	15	-
Number of damaged trees per ha	50	30	72	-
Number of injuries per tree	2.1	1.8	1.5	<0.05
Percentage of injuries location (%)				
Root injury	34	18	13	-
Butt injury	36	44	32	-
Stem injury	30	38	55	-
Mean height from ground (m)	1.3	1.2	1.6	>0.05
Mean size of injury (cm^2)	207	181	165	>0.05
Levels of wound severity	5 (heavy)	4 (medium)	4 (medium)	-
Scar width (cm)	94	93	91	-

A total of 422 trees in S3 remained within 0.9 ha, of which 72 trees were damaged as a result of manual row thinning. Approximately 15% of the remaining trees were damaged (Table 2). The trees with scar wounds had an average DBH of 26.00 cm and 1.5 injuries per tree. The most frequent type of damage was injury to the stem, which comprised of 55% of the total damage (Figure 3). The average stem wound size was 152 cm^2 (range, 9–704 cm^2). Butt and root damages accounted for 32 and 13% of the total stand area, respectively. The average wound area was considerably smaller in the butts (199.00 cm^2) than in the roots (139.00 cm^2). The trees were primarily wounded with broken stems and butts, but were rarely rooted. However, there were no statistically significant differences in the average wound size among injury locations ($p > 0.05$). Within the total amount of damages, 68% of the damaged trees occurred within the forward trail.

To determine whether manual selective thinning causes more damage to the remaining trees that the other types, the number of injuries per tree, injury height from the ground, and wound size by region, such as the root, butt, and stem, were compared. There was a statistically significant difference in the number of injuries per tree between manual selective thinning and mechanized row thinning ($p < 0.05$), but manual selective thinning and row thinning did not differ. The injury height was significantly lower in the manually thinned units than in the mechanized row-thinned sites ($p < 0.05$). The thinning type had no significant effect on the length, width, or size of the damaged trees ($p > 0.05$).

We also analyzed whether the wound size by location, such as the root, butt, or stem, was associated with the thinning type (Table 4). The wound size on the root was significantly greater in S1 (376 cm^2) than in S3 (139 cm^2; $p < 0.05$), whereas there was no statistically significant difference between S1 and S2 (372 cm^2; Table 4). The Kruskal–Wallis H-test showed that there was a slight difference in the average sound size at the butt location, but the difference was not statistically significant ($p > 0.05$). The wound sizes on the stem in S2 (150 cm^2) and S3 (152 cm^2) were slightly different, whereas that in S1 (108 cm^2) was only statistically lower ($p < 0.05$). Thus, the range of wound sizes and location differences caused by the thinning types could be demonstrated.

Table 4. Mean scar size (cm^2) of root, butt, and stem in each unit.

Area	Root	Butt	Stem
S1	376 [a]	144 [a]	108 [a]
S2	372 [a]	129 [a]	150 [b]
S3	139 [b]	199 [a]	152 [b]
p-value	<0.05	0.8687	<0.05

Means with the same letter are not significantly different from each location.

4. Discussion

A field test to observe the conditions of the remaining trees was completed under three different thinning types: manual selective, manual row-, and fully mechanized row-thinning. Our results indicated that the frequency of injuries and the level of wound size were substantially lower in row-thinning operations than in selective thinning. The majority of wounds was located on the butt (0.3 to 1.3 m high) and stems (above 1.3 m), and position of injuries was more uniform along the edges of the extraction trails, where the trees were removed with a line. In contrast, during selective thinning, the most frequent damage and heights were lower than 1.3 m from the ground level, and the average wound size on the root was statistically greater than that of the other thinning types. This knowledge may provide potential alterations to residual-stand damage and support decisions for sustainable forest management.

The frequency and characteristics of the damage to residual trees varied considerably and may have been affected by the thinning methods and the type of equipment used. Our results provided that the damage frequency was lower for the mechanized row-thinning, compared to the manual thinning. Similar results were obtained by Magagnotti et al. [23]. Akay et al. [24], Cudzik et al. [5], Kizha et al. [7], and Suhartana et al. [25] reported that the most damage occurs during tree felling and extraction by machine traffic and log dragging and loading from the stump to the landing. Hwang et al. [6] found that residual stand damage was between 16.2% and 32.2%, and damaged trees were closed near forwarding trails with injuries near the ground where mechanical thinning operations were practiced. In contrast, the results of this study showed that the most common damage type was injury to the bole in the harvester-forwarder thinning unit, but the trees were rarely damaged in the roots area. These results are similar to those reported by Cudzik et al. [5], Kizha et al. [7], and Ursić et al. [4]. This can be explained by the equipment running over the course of the felling and extraction [2,7]. However, chainsaw winch or skidder systems produce a greater impact on the surface of the damage owing to the lack of skilled chainsaw operators in determining the felling direction [25] and the difficulty in manually controlling the winched logs along the surface of the machine [10]. Consequently, the injury location depends on the felling and extraction system.

In addition, wound size was associated with the thinning type. In mechanized operations, not only is the damage at higher heights greater, but the size of the damage at this location is also greater than that in selective thinning. During harvester head rotation, forwarder log loading, and machine traffic and turning, attributes of bole damage to residual standing trees can occur [7,16]. When cutting and forwarding a tree at the stump to landing, the harvester head and forwarder grapple travel downward on the tree and ground, causing the injury to be located higher than in manual operations [6]. Conversely, system chainsaw operations followed by winching had a greater impact on the surface, such as the root, and under 30 cm of damage than the bole and crown, owing to uncontrolled felling direction and cable work, which is required to drag the logs to the machine [10,25]. Therefore, the results of this study demonstrated a statistically greater root wound size in both manual thinning units. In addition, fungal infections may be expected and repaired independently by the tree itself because the root injury size is greater than 100 cm^2 [4]. Furthermore, these differences do not suggest that manual selective thinning caused greater damage to the residual stand than fully mechanized thinning, and detailed planning may be required to minimize damage in terms of the size of the injury and the locations of affected trees.

From the results, wounds produced as a result of row-thinning operations frequently occur and are concentrated along the winching strips and forwarding trails. In contrast, manual selective thinning had no pattern of injury to residual trees because it was difficult for the motor-manual felling to cross over other trees and winching of trees to drag and control without proper strip planning. Previous studies, such as those by Sist et al. [26] and Bodaghi et al. [27], reported that residual stand damage is one of the most important operational limitations and challenges in single-tree selection cutting. However, a wider extraction trial could provide more space for machine movement, felling trees, and log dragging, thereby minimizing residual stand damage [7]. As a result, proper extraction of winching strips and forwarding trial planning may decrease the damage to residual stands.

Previous studies explained that mechanized operations may cause less damage than motor-manual logging operations because machines can easily control and handle the direction of trees to avoid damage to standing trees [28–30]. We observed that the percentage of trees damaged by manual thinning was considerably higher than that damaged by mechanized row-thinning. This can be explained by the tree handling skill and direction control [24]. This was not available with motor-manual operations: manual felling has limitations in terms of directional control due to the random spatial distribution of trees, and it was very difficult to avoid damaging standing trees during extraction. Thus, the thinning that occurs during motor manual treatment increases the residual damage to the stand.

The study contained the following limitations, the first of which may be attributed to the data on the residual damage that were not collected prior to thinning. The study site was planted and precommercial-thinned during the same year. For this reason, we did not find it problematic to compare residual tree damage in different systems. In addition, the interval between felling and extraction was limited by the distance of the tree from the trail. Therefore, we could not detect the amount and severity of the damage attributed to each activity.

5. Conclusions

In conclusion, in Korea, this study was the first attempt to understand the effects of the harvester and forwarder system on residual stand damage in row-thinning activity and to compare the amount and intensity of damage between different thinning types. We found that a total of 10%, 15%, and 12% of trees were damaged in mechanized row-, manual thinning, and manual selective thinning, respectively. The findings of this study show that the thinning technologies have considerably different damage characteristics. The mechanized row-thinning operation reduces the frequency and severity of wound damage in comparison to manual selective thinning. In contrast, the average wound size on the roots was larger for manual selection and row thinning than for mechanized row thinning. Our results may help ameliorate the residual damage caused by thinning. In addition, this comparison demonstrates the need for effective planning (making sites more productive and health) based on thinning operation methods for sustainable forest management and to minimize negative effects. Furthermore, forest managers should consider the potential damage of each prescription, such as residual stands to minimize environmental footprints. Future research is required to evaluate ecological and environmental impacts along with economic losses in terms of future timber value, quality, and feasible tree growth reduction.

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