Comparison of harvesting productivity, cost, and residual stand damages between single-tree selection thinning and mechanized line thinning using a small-scale grapple-saw

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ABSTRACT
Considerable amounts of noncommercial materials generated from thinning treatments remain unattended on the site because the value of small-sized timber is lower than overall thinning operation costs in South Korea. In addition, thinning operations with conventional and mechanized harvesting systems often cause severe physical damage to residual trees. In this study, therefore, we compared and analyzed the harvesting productivity, cost, and residual stand damage between single-tree selection thinning (SST) and mechanized line thinning (MLT) systems on conifer plantation forests. For conventional SST, ground skidding (uphill/downhill) was performed using a tractor winch after manual felling and bucking. The MLT consisted of mechanized felling, downhill shovel logging, and processing with a small-scale grapple-saw for the fourth double row (MLT1) and the third row (MLT2) thinning section. The MLT system was more productive and cost-effective in performing thinning treatment and collecting thinning materials than SST. The MLT1 and MLT2 costs were 81.4% and 70.6% lower than the SST cost ($77.6/m³), respectively. The residual stand damages of the SST (3.4%) were lower than those of MLT1 (4.8%) and MLT2 (21.2%); however, there was no significant difference in residual stand damages between two thinning systems ($p > 0.05$). Therefore, forest managers should consider the use of MLT system to reduce thinning costs and efficiently produce thinning materials for their thinning operations. However, operators still need to be careful felling and extracting operations to reduce the residual stand damages for thinning treatments.

Introduction

Forest ecosystems offer various environmental benefits, such as maintaining water resources, reducing global warming, and enhancing biodiversity (Behjou 2014). Sustainable forest management is needed to maintain the various functions of forest ecosystems, promote the efficient production of forest resources, and reduce negative impacts on the forest environment (Higman et al. 2005; Klenner et al. 2009; Karlsson et al. 2013; Schweier et al. 2019). Thinning treatments in forest management can positively affect tree growth (Boncina et al. 2007) and increase the value of timber in a final harvesting operation (Emmingham and Elwood 2010; Nikooy et al. 2020). Furthermore, woody biomass collection from thinning operations can be used to generate electrical power (Karlsson et al. 2013), reduce forest fire hazard, prevent insect and disease outbreaks, and improve overall forest health (NIFoS, 2019).

A successful reforestation project after the Korean War in South Korea resulted in the increase of forest growing stocks from 23.1 m³/ha in 1981 to 161.4 m³/ha in 2019 (KFS 2020). However, ~74.5% of all forests are under forty-year-old plantations and growing under high density conditions (e.g. 1082 trees/ha) (Korea Statistical Information Service 2020). In overstocked dense stand with small-diameter trees, competition for light, water, and nutrients gradually intensifies as they grow, resulting in reduced tree growth and mortality. In addition, these stands generally increase the hazard of forest wildfires. Therefore, forest thinning programs can be implemented to produce high-quality and large trees at final harvesting operation, improve forest health, and reduce forest fire hazards. The Korea Forest Service designated 2.34 million ha of Commercial Forest Promotion Complexes nationwide as of 2018 (0.66 million ha for national forests and 1.68 million ha for private forests) to increase the domestic timber supply and obtain other forest management objectives such as activating the local economy and sustainable wood supply (KFS 2018).

For thinning treatments, ground-based harvesting system is cost-effective to treat the overstocked dense...
stand (Proto et al. 2018). The most common ground-based harvesting system has been accompanied by conventional mechanized harvesting system including chainsaw and farm tractors equipped with winches (Stankić et al. 2012; Borz et al. 2013; Proto et al. 2018; Jeong et al. 2019), although the harvesting productivity and its cost are strongly correlated with the mechanization level (Borz et al. 2013; Spinelli et al. 2014).

Over the last decade, numerous studies on ground-based harvesting system using fully mechanization (e.g. harvester, forwarder, and skidder) were conducted (Sirén and Aaltio 2003; Vitorelo et al. 2011; Spinelli et al. 2014; Mederski et al. 2018; Proto et al. 2018; She et al. 2018; Cabral et al. 2020; Miyajima et al. 2020). Thinning costs of conventional mechanized harvesting system (Kim and Park 2010; Cho et al. 2016; Jeong et al. 2019) tend to be higher (e.g. $50/m^3$, include felling, deliming, and extraction operation) than that of fully mechanized harvesting system (e.g. $16.6–18.8/m^3$) (Spinelli and Magagnotti 2010a; Mederski et al. 2018).

In thinning operations, there is very important for how to fell and extract small-diameter trees selected from thinning prescription because of their low market values compared to high thinning treatment costs (Sirén and Aaltio 2003; Kärhä et al. 2004; Spinelli and Magagnotti 2010a; Mederski et al. 2018; Proto et al. 2020). Several past studies were conducted to solve the high thinning treatment cost problems including the efficient production of noncommercial thinning material (Spinelli and Magagnotti 2010a; Karlsson et al. 2013; Shizuoka Prefecture 2020). The selection of appropriate thinning methods could be applicable as a solution for reducing thinning costs. The mechanized line thinning (MLT) system that is often applied to reduce thinning treatment costs and to enhance thinning materials’ production, has shown to be 20% more productive than the single-tree selection thinning (SST) system (Shizuoka Prefecture 2020). Furthermore, reduced machine moving time in systematic thinning operations (e.g. corridors, lines, rows and strip thinning) significantly improve harvesting productivity and increase wood production (Karlsson et al. 2013).

Machine selection could be the other solution for reducing thinning operation costs (Sirén and Aaltio 2003; Kärhä et al. 2004; Spinelli and Magagnotti 2010b; Mederski et al. 2018). This has led to the development of dedicated thinning harvesters which can achieve the same productivity as larger units, but at a lower operating cost (Kärhä et al. 2004; Spinelli and Magagnotti 2010b). Past studies reported that the use of small sized harvesters (60–118 hp, 30–37 cm of felling capacity) was more cost-effective than the use of medium/large sized harvesters (107–127 hp, 45–60 cm of felling capacity) for thinning operations (Iwaoka et al. 1999; Kärhä et al. 2004; Spinelli and Magagnotti 2010a; Kaleja and Zimelis 2019). These results were contributed by the difference of machine costs (purchase price, fuel consumption, etc.) according to different machine sizes. The use of small sized harvesters enabled the reduction of 16–20% in overall thinning operation costs compared to the use of medium/large sized harvests, while there had similar machine productivities (small sized harvester: 13–16 m³/PMH; Productive Machine Hour, medium/large sized harvester: 14–15 m³/PMH) regardless of different machine sizes (Iwaoka et al. 1999; Kärhä et al. 2004; Kaleja and Zimelis 2019). In these reasons, therefore, forest managers could be often considering the use of small sized machine for thinning treatments and it’s also depends on the terrain slope, soil disturbance and fertility. A small-scale grapple-saw (53 hp, 35 cm of felling capacity) is also often applied for thinning operation in South Korea. This machine was developed with a 5-ton excavator base and a grapple-saw head and mainly used for the production of small diameter trees or pulp woods. In addition, the number of 5-ton excavator was extensively used for felling, extracting, and loading in shovel logging in South Korea and machine costs was also relatively cheaper than other small harvesters (Lee et al. 2019). Therefore, the low-cost excavator-based grapple-saw could be more efficient than a high-cost small harvester for thinning operation.

Although the main goal of thinning activity is to enhance the growth of residual trees, severe stand damage, such as scarifying and gauging, of residual trees often occurs through contact with thinning machinery and falling trees. Therefore, in thinning operations, the residual stand damage needs to be minimized because the wound on the tree stem can cause various problems including insect reproduction, decay fungi infection, and a decline in wind resistance (Reisinger and Pope, 1991; Smith et al. 1994; Froese and Han 2006; Hokkaido Prefectural Research Organization, 2020). The frequency and degree of stand damage for residual trees are typically influenced by thinning density, prescription, and thinning method (Han et al. 2000; Behjou and Mollabashi 2012; Behjou 2014; Sirén et al. 2015; Tavankar et al. 2015; 2017; Grzywinski et al. 2019; Han et al. 2019; Picchio et al. 2019a, 2019b; Gifu Forest Research Institute, 2020; Picchio et al. 2020). Thinning systems and equipment applied for thinning treatments highly affect residual stand damage. Residual stand damage reported in a previous study was 5.5% lower in the MLT system (44.5% of residual trees) than in the SST system (50% of residual trees) because trees did not exist on the lines when using the MLT system (Gifu Forest Research Institute, 2020). In an SST system using cable yarding, 7.4% and 6.9% of residual trees in felling and yarding operations, respectively, were damaged (Han et al. 2019). However, economic analyses of thinning operation costs and the degree of residual stand damage for different thinning systems in South Korea were not performed, and only the thinning productivity, cost, and residual stand damage for the SST systems were evaluated (Han et al. 2008; Kim and Park 2010; Cho et al. 2016; Han et al. 2019).

Therefore, this study aimed to evaluate the economic feasibility and impacts on residual trees on the mechanized line thinning systems using a small-scale grapple-saw. The specific objectives of this study were to: (1) compare harvesting productivity and cost
including thinning treatments and thinning material collection, and (2) analyze residual stand damage characteristics between the SST system using manual felling and the MLT system using a small-scale grapple-saw.

Materials and methods

Study area

This study was conducted on the Manchurian fir (Abies holophylla) stand of the experimental forest of the National Institute of Forest Science (NIFoS, 37°45′01.85″ N and 127°11′42.47″ E) in Namyangju, Gyeonggi-do, South Korea. The total thinning treatment area was 0.82 ha, which was divided into the SST (0.45 ha) and the MLT (0.37 ha) systems. The study site parameters are outlined in Table 1, and the site location is shown in Figure 1.

Table 1. Description of the study site.

| Parameter | SST | MLT1 | MLT2 |
|-----------|-----|------|------|
| Location  | Mt. 99-31, Bupyeong-ri, Jinjeop-eup, Namyangju-si, Gyeonggi-do, South Korea (experimental forest of NIFoS) | (Fourth double row thinned) | (Third row thinned) |
| Latitude  | 37°45′01.85″ | 27.4 | 29.9 |
| Longitude | 37°45′01.85″ | 0.29 | 0.08 |
| Elevation above sea level (m) | 127°11′42.47″ | 1.224 | 1.475 |
| Forest type | Plantation | 489 | 491 |
| Species   | Abies holophylla | 40 | 33 |
| Thinning type | SST | 16/4–22 | 16/5–18 |
| Slope (%) (avg.) | 30.4 | 27.4 | 29.9 |
| Area (ha) | 0.45 | 0.29 | 0.08 |
| Tree volume (m³/tree) | 0.23 | 0.20 | 0.25 |
| Stand density (trees/ha) | 1,055 | 1,224 | 1,475 |
| Removal (trees/ha) | 404 | 489 | 491 |
| Rate of removal (%) | 38 | 40 | 33 |
| Height (m,avg./min.–max.) | 16/4–22 | 16/5–18 | 16/6–19 |
| DBH (cm,avg./min.–max.) | 18/4–36 | 18/5–28 | 20/8–29 |

Figure 1. Location of study site in South Korea.

Description of SST and MLT systems

A total of 255 m of designated skidding road was constructed on the study site for SST and MLT operations (Figure 2). The average skidding trails were 48.9 m, 68.5 m, and 53.2 m in SST, MLT1, and MLT2, respectively.

The SST system is one of the most used thinning systems in South Korea. In the SST system, manual felling using a chainsaw (MS261 STIHL, Waiblingen, Germany) was conducted using the directional felling method to reduce the overlapping of the fallen trees. Then, ground skidding of fallen whole-trees was performed using a tractor equipped with a winch (EGV 65 A TAJFUN, Planina pri Sevnici, Slovenia) and two workers (one operator and one choker setter).

In addition, processing was conducted using a 5-ton excavator-based wood grapple loader (DX55MT-5K DOOSAN Infracore, Incheon, South Korea) and two chainsaws with three workers; a loader operator held
one-side of a whole-tree and then lifted it up to help two chainsaw workers delimb and buck the tree (Table 2). In the MLT system, fourth double row thinning (MLT1) was mainly applied on the entire thinning stand; however, only one third row thinning (MLT2) was used in the end of the thinning stand. It was because the boundary of this study site was not sufficient to set the additional fourth double row of thinning line. The width of corridor lines in MLT1 and MLT2 were 5.4 m and 3.6 m, respectively. Thinning operations including felling, shovel logging, and processing were performed with a 5-ton excavator-based grapple-saw (GS350 OAK, Cheonan, South Korea, Table 2). In South Korea, small-diameter trees are usually supplied to pulp mills (KFS, 2020); therefore, a specific log length was not applied in this study. Hence, an excavator-based grapple-saw without a device measuring log length should be more cost-effective than other mechanized machines, such as a harvester, in thinning with short extraction distance (<70 m). The specifications of the equipment used for SST and MLT are listed in Table 3.

Data collection
Before thinning treatments, the diameter at breast height (DBH, cm) and height (m) were measured for all trees on the thinning stand, and only thinning trees were marked to evaluate thinning productivity and cost using the time and motion study method with a stopwatch (Han et al. 2008; Cho et al. 2015; Choi et al. 2018).

To calculate the machine cost, the machine purchase price, durable years, annual operation time, oil consumption, oil price, repair and maintenance cost,
interest rate, and labor cost were obtained. Furthermore, to compare and analyze the residual stand damages between SST and MLT systems, the type, shape, and position of the residual stand damages were classified as shown in Table 4 (Smith et al. 1994; Grzywniński et al. 2019; Han et al. 2019). The residual stand damages with a width > 10.16 cm were investigated (Behjou 2014). Han et al. (2000) reported that damages with a width of 10.16 cm were naturally cured for needle-leaf trees. In addition, the height (m), length (cm), and width (cm) were measured using a measuring rod and ruler. Residual stand damages occurring > 5 m was photographed (Smith et al. 1994; Han et al. 2019).

### Analysis

**Thinning productivity and cost**

The thinning system operation times were divided into delay-free cycle time and delay time to calculate the machine utilization (%). Delays were consisting of operational (e.g. waiting for wood to process, hang-up, and re-choking), mechanical (e.g. fueling, maintenance, and repairing machines), personal (e.g. breaks, and personal time) types (Vitorelo et al. 2011). The productivity (m³/SMH; Scheduled Machine Hour) was analyzed using the total cycle time including the delay and volume (m³/trees) (Cho et al. 2019).

The thinning cost ($/m³) was calculated using the machine cost ($/SMH) and productivity (m³/SMH), as shown in equation (1):

$$\text{Thinning cost } = \frac{\text{Machine cost } / \text{SMH }}{\text{Productivity } / \text{SMH}}$$  \hspace{1cm} (1)

The machine cost ($/SMH) was calculated using the depreciation, interest, repair and maintenance expenses, fuel price, and labor costs using the Kuratorium für Waldarbeit und Forsttechnik e.V. (KWF) method (Germany) as shown in Table 5 (Woo et al. 1997; Brinker et al. 2002; Cho et al. 2015; Choi et al. 2018; NIFoS, 2018). In this method, depreciation is calculated with considering the annual operating time of machines and also used by the straight-line approach. Furthermore, the harvesting costs for MLT1 and MLT2 systems were compared based on the SST system cost.

### Table 3. SST and MLT machine specifications.

| Machine                        | Model          | Specifications          |
|-------------------------------|----------------|-------------------------|
| Chainsaw                      | STIHL MS261    | Weight (kg): 5.3        |
|                               |                | Displacement (cc): 50.2 |
|                               |                | Guide bar length (cm): 40 |
|                               |                | Fuel tank capacity (ℓ): 0.5 |
|                               |                | Oil tank capacity (ℓ): 0.25 |
| Tractor equipped a winch      | TAJFUN EGV 65A | Weight (kg): 515        |
|                               |                | Size (L × W × H, cm): 168 × 69 × 231 |
|                               |                | Required tractor capacity (hp): 50–90 |
|                               |                | Pulling power (kN): 64.5 |
|                               |                | Brake power (kN): 80.1  |
| Base machine for wood grapple loader and grapple-saw | DOOSAN DX55MT-SK | Weight (kg): 6,010 |
|                               |                | Size (L × W × H, cm): 594 × 196 × 258 |
|                               |                | Engine power (hp): 52.9 |
|                               |                | Boom length (cm): 300    |
|                               |                | Arm length (cm): 160     |
|                               |                | Bucket capacity (m³): 0.18 |
|                               |                | Fuel tank capacity (ℓ): 115 |
|                               |                | Max. pressure (kgf/cm²): 240 |
|                               |                | Max. oil flow (l/min): 116 |
|                               |                | Max. felling capacity (cm): 35 |
|                               |                | Max. felling force (kN): 85 |
|                               |                | Max. pressure (kgf/cm²): 250 |
|                               |                | Required oil flow (l/min): 35–65 |
| Grapple-saw head              | GS350 OAK      | Weight (kg): 245        |
|                               |                | Max. felling capacity (cm): 35 |
|                               |                | Max. felling force (kN): 85 |
|                               |                | Max. pressure (kgf/cm²): 250 |

### Table 4. Classification of residual stand damage.

| Items | Descriptions | Type | Scar: removal of the bark and cambial layer (width: >10.16 cm) | Gouge: wood fibers removed from the scar |
|-------|--------------|------|---------------------------------------------------------------|-----------------------------------------|
| Shape | Square, narrow rectangular, wide rectangular, irregular |      |                                                               |                                         |
| Location | North: 315°– 45°, East: 45°– 135°, South: 135°– 225°, West: 225°– 315° |
| Height (m) | Height of scars from ground level |      |                                                               |                                         |
| Length and width (cm) | Scar length and width |

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Residual stand damage

To compare the residual stand damage characteristics of each thinning system, statistical analysis was performed with the height (m), length (cm), and width (cm) of residual stand damages using IBM SPSS Statistics 23.0 (IBM Inc., Armonk, New York, USA). Before analyzing the residual stand damage characteristics of thinning systems, a Shapiro-Wilk normality test was performed using the residual stand damage height, length, and width. The results showed that the residual stand damage height, length, and width of SST, MLT1, and MLT2 did not follow the normal distribution within 95% significance level, except for the height of SST (Froese and Han 2006; Spinelli et al. 2010; Behjou 2014; Han et al. 2019; Picchio et al. 2019a). Therefore, a Kruskal-Wallis test was performed to analyze the statistical differences in the residual stand damages of thinning systems.

The residual stand damage areas (cm²) of square, narrow rectangular, and wide rectangular areas were calculated by the length and width, and irregular shapes were calculated using Media Cybernetics Image-Pro Plus 6.2 (Media Cybernetics Inc., 1700 Rockville Pike, Suite 240, Rockville, USA). In addition, frequency analysis was performed for the residual stand damage shapes, positions, and heights (m) for thinning systems.

Results and discussion

Thinning productivity and cost

The productivity of the MLT system was greater than that of the SST system. These results were mainly contributed by the lower machine utilization of felling (76.5%) and extracting (47.0%) activities in the SST system.

In the felling operation, a lower SST system productivity (2.0 m³/SMH) was observed due to searching and directional felling among residual trees, compared to that of the MLT system (10.9–11.2 m³/SMH) (Table 6). In the SST system, the choking activity for the directional felling was applied to prevent fallen trees from being overlapped and hung-up with residual trees. However, this choking activity increased the felling cycle time with additional activities such as set-up and displacement of the choker setter, reducing felling productivity.

The greatest difference in the productivities of the SST and the MLT systems was found during extraction. The extracting productivity was 2.0 m³/SMH in the SST system and 6.1–18.5 m³/SMH in the MLT system (Table 6). The low productivity in the SST system was caused by longer operational delay including the moving, set-up, and displacement times of the tractor and pulleys, reducing hang-up problems among residual trees which was previously reported by Jeong et al. (2019). On the other hand, the MLT system had a high machine utilization rate (92.4%) because there were no residual trees on the corridors disturbing the shovel logging performance.

In our study, the SST system was processed using a conventional processing method, including an excavator-based wood grapple and chainsaw, while the mechanized grapple-saw was solely used in the MLT system. The productivity of mechanized processing (8.1–9.9 m³/SMH) was higher than that of the conventional processing (5.5 m³/SMH) (Table 6). The lower productivity of the SST system was a result of the conventional processing performances which were divided into two phases for a processing tree. First, a

Table 5. Cost factors and assumptions used for machine cost calculation using the KWF method.

| Cost factor | Unit | Tractor-winch | Tractor | Winch | Wood grapple loader | Excavator | Grapple-saw |
|-------------|------|---------------|--------|-------|---------------------|-----------|------------|
| Purchase price (P) | $/hr | 772 | 77,154 | 18,860 | 49,464 | 46,292 | 18,860 |
| Endurance period | yr | 1 | 10 | 12 | 8 | 8 | 8 |
| Economic life (H) | hr | 1,392 | 13,920 | 16,704 | 11,136 | 11,136 | 11,136 |
| Annual operating time | hr/year | 1,392 | 1,392 | 1,392 | 1,392 | 1,392 | 1,392 |
| Fuel consumption | /hr | 1.04 | 1.35 | – | 4.50 | 5.50 | – |
| Fuel price | $/l | 1.28 | 1.16 | – | 1.16 | 1.16 | – |
| Repair and maintenance | % | 60 | 80 | 80 | 80 | 80 | 90 |
| Coefficient of lubricant | % | 40 | 40 | 40 | 40 | 40 | 40 |
| Interest rate | %/year | 10 | 10 | 10 | 10 | 10 | 10 |
| Machine cost | $/hr | 0.03 | 0.78 | 0.16 | 0.62 | 0.58 | 0.25 |
| Total machine cost | $/hr | 32.03 | 60.28 | 36.08 | 36.08 | 40.47 | 40.47 |

1/74 day = 8 h = 1392 h (KFS, 2012).
2/Standard of labor cost: feller ($99.47), machine operator ($160.37), worker ($107.52) (Construction Association of Korea 2019).
3/Exchange rate of 2019: KRW 1166.5
4/Insurance, storage fee etc.
5/Gasoline: $1.28, diesel: $1.16 in July 2019, South Korea (Korea National Oil Corporation, 2020).
6/Depreciation was divided corresponding to the annual use of machines by KWF method, as followed: J = P/(J + D).

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processing tree was lifted using an excavator-based wood grapple; then, two chainsaws were used to limb and buck the tree.

The system productivities of MLT1 and MTL2 were compared to evaluate the influence of two different line thinning methods. The extracting productivity of MLT1 (18.5 m³/SMH) after applying the fourth double row thinning method was approximately 3.0 times higher than MLT2 (6.1 m³/SMH) after applying the third row thinning method (Table 6). During extraction, the influence of corridor width between the remaining rows on was previously demonstrated by Hokkaido Prefectural Research Organization (2020). The productivity in wide areas (20.3 m³/h) were approximately 1.5 times higher than that in narrow areas (13.9 m³/h) for the MLT system using a harvester. Therefore, it is important to secure enough working spaces to enhance the extracting productivity of the MLT system.

SST system cost was $77.6/m³. This result was more expensive than previous study ($51/m³) which was conducted with chainsaw and grapple skidder (Proto et al. 2020) (Table 6). Proto et al. (2020) reported that wood extraction cost with the grapple skidder was cheaper than farm tractor equipped with a winch. This indicate that it is important to select the machine in SST system for reducing cost.

MLT1 and MLT2 systems cost were $14.8/m³ and $22.8/m³, respectively (Table 6). The wide corridor of MLT1 reduced the thinning cost (35%) by offering a sufficient working space for felling and extracting operations compared to the narrow corridor of MLT2 (Table 6). MLT1 system cost was cheaper than that of the harvester-forwarder system ($18.6/m³) reported by Spinelli and Magagnotti (2010a). In our study, there was no need for bucking to specific lengths for pulp production so small-scale grapple-saw was more cost-effective than harvester. However, depend on the markets demanded precise log lengths, the harvester would be more preferable than the small-scale grapple-saw.

MLT1 and MLT2 systems cost showed 81.4% and 70.6%, respectively, lower than the SST system ($77.6/m³) (Figure 3). The MLT system is more cost-effective than the SST system because only one machine and operator were used for felling, extracting, and processing in the MLT system.

The influence of machine size on thinning cost was previously reported by Iwaoka et al. (1999). They determined that there was no significant difference in operation time (small harvester: 45.0 sec./cycle, large harvester: 41.5 sec./cycle) according to the size of machines and suggested that small-sized machines were more competitive in thinning operations due to the low machine cost. Our results revealed that the cost of felling and processing operations using a small-scale grapple-saw ($11.5/m³) was 53.8% cheaper than that of a small harvester (Vimek 404 T5, $24.9/m³) which was demonstrated by Mederski et al. (2018) as shown in Table 7. The productivity of a small-scale grapple-saw (6.0 m³/PMH at DBH 18 cm) was 1.4 times higher than a small harvester (4.3 m³/PMH at DBH 13 cm) because of piece-volume-law. We also found that the small-scale grapple-saw (price: $65,152), initially developed for harvesting of small-sized trees, was more cost-effective in the thinning operation compared to a small harvester, owing to its high price ($273,164) (Table 7).

### Residual stand damage

The result of the Kruskal-Wallis H test for the residual stand damages of thinning systems showed that all variables such as the residual stand damage height, length, and width had no statistically significant differences ($p > 0.05$) (Table 8). Therefore, the residual stand
damages of the SST system, the MLT1 and MLT2 systems did not have statistically significant differences. Thus, the damage characteristics of each thinning system were analyzed, including the residual stand damage rate, type, position, height, and area.

The residual stand damage rate (%) of MLT2 (21.2% of total residual trees) was higher than that of MLT1 (4.8% of total residual trees) because of a narrow operation space. Therefore, MLT requires a sufficient operation space. The residual stand damage rate (%) of MLT1 was similar to the result of a previous study on MLT (5.5% of total residual trees) in Japan, whereas that of SST (3.4% of total residual trees) was lower than that reported in a previous study (50.0% of total residual trees) (Table 8) (Gifu Forest Research Institute, 2020). The residual stand damage rate of SST was lower than that of MLT because the latter was the initial step and had low experience for thinning operation. On the other hand, SST system has been widely applied by the national units of forest craft workers in South Korea. In addition, shovel logging operation using small-scale grapple-saw in MTL caused higher residual stand damage due to frequent rotation and movement of machines and whole trees in narrow tree spaces compared to ground skidding operation using tractor attached winch in SST.

The damage area of residual stands was high in MLT1 (667.9 cm²/tree) and MLT2 (644.5 cm²/tree) (Table 9) because residual stand damages were generated in large areas due to the grapple arm during felling and bunching operations. Sirén et al. (2015) also reported that felling operation using a harvester generated residual stand damages mostly by the harvester boom. MLT2 requires long-term monitoring for residual stand growth because the gouge area was large at 413.7 cm²/tree (Table 9).

Most residual stand damages were scars, reflecting 68.7–90.9% of damages in SST, MLT1, and MLT2 systems. This was similar to those reported in previous studies: 67.2–89.6% by Froese and Han (2006), 89.8–95.0% by Behjou (2014), and 67.5–98.5% by Picchio et al. (2019a). The ratio of gouge damages was the highest in MLT2 at 31.3%, which was performed in narrow operation spaces (Figure 4(a)).

The residual stand damage positions of the SST system using a tractor winch were mostly north and west at 72.8%, and the damage positions of MLT1 and MLT2 using an excavator-based grapple-saw were mostly east and west at 66.7% and 62.6%, respectively.
Previous studies demonstrated that the closer to the skidding road and corridor, the more the residual stand damages occurred (Smith et al. 1994; Bembenek et al. 2013a, 2013b; Allman et al. 2016), which was similar to MLT systems in this study. Kellogg et al. (1986) reported the residual stand damage height ratio of $< 2.1$ m was 82%, and Froese and Han (2006) and Han et al. (2019) reported that the ratio of $< 3.0$ m was approximately 80%. In this study, the residual stand damage to trees with heights of $< 3$ m was 70.4–81.8% for the SST, MLT1, and MLT2 systems (Figure 4(c)). Therefore, we suggest operators must be cautious (e.g. limiting machine activity and crane zone) to minimize residual stand damages.

The shapes of residual stand damages were mostly square and narrow rectangles in 72.7–85.2% of trees for the SST, MLT1 and MLT2 systems (Figure 4(d)). In all the thinning systems, the proportion of wide rectangular area was $< 9.1\%$. Regarding the wide rectangular shape of residual stand damage, previous studies reported that the width of the residual stand damage was more important than the length. When the width was $> 10.16$ cm, it decayed the residual stand and reduced the volume (Wallis and Morrison 1975; Han et al. 2000). Hence, long-term monitoring of the residual stand growth is required in the future.

To minimize residual stand damages, detailed harvesting plans, including the use of existing skidding road; skidding road placement, considering the machine capacity and wide operation spaces (Han et al. 2000; Sirén et al. 2015; Tavankar et al. 2017; Picchio et al. 2020) and operator still need to be careful felling and extracting operations (Reisinger and Pope 1991; Smith et al. 1994).

### Conclusions

In South Korea, approximately 77% of trees were not collected in all forest thinning programs in 2018 because of the high costs involved. Thus, low-cost thinning systems need to be introduced in place of the conventional SST systems. Furthermore, after thinning operations, the growth and value of residual stands...
should be studied simultaneously. Therefore, this study compared the productivity and cost between SST and MLT systems and analyzed the residual stand damage characteristics after thinning operations.

When the MLT system was applied, the productivity improved compared to the conventional SST system, enabling low-cost thinning operation. The MLT system using a small-scale grapple-saw with a wide operation space was the most economical. We did not find statistically significant differences in the residual stand damages between the conventional SST and MLT systems. It is believed that to minimize the residual stand damage, comprehensive tree harvesting plans and operator still need to be careful felling and extracting operations. In our study, we suggest that forest managers should consider the use of MLT system to reduce thinning costs and efficiently produce thinning materials for their thinning operations. However, forest managers should also take account of the ecological effects (e.g., soil fertility, biodiversity, and etc.) for their thinning treatments.

**Disclosure statement**

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