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Performance Analysis of Log Extraction by a Small Shovel Operation in Steep Forests of South Korea

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Abstract: In South Korea, logs for low-value products, such as pulpwood and fuelwood, are primarily extracted from harvest sites and transported to roadside or landing areas using small shovels. Previous studies on log extraction, however, have focused on cable yarding operations with the goal of improving productivity on steep slopes and inaccessible sites, leaving small-shovel operations relatively unexamined. Therefore, the main objectives were to determine small-shovel extraction productivity and costs and to evaluate the impact of related variables on productivity. In addition, we developed a model to estimate productivity under various site conditions. The study took place in 30 case study areas; each area has trees with stems at a diameter at breast height ranging from 18 to 32 cm and a steep slope (greater than 15%). The areas ranged from 241 to 1129 trees per hectare, with conifer, deciduous, and mixed stands. Small-shovel drives ranged from 36 to 72 m per extraction cycle from stump to landing. The results indicated that the mean extraction productivity of small-shovel operations ranged between 2.44 to 9.85 m^3 per scheduled machine hour (including all delays). At the forest level, the estimated average stump-to-forest road log production costs were US \$4.37 to 17.66/m^3. Small-shovel productivity was significantly correlated with stem size (diameter at breast height and tree volume) and total travelled distance (TTD). However, a Pearson's correlation analysis indicated that stand density and slope did not have a significant effect on productivity. Our findings provide insights into how stem size and TTD influence small shovel performance and the predictive ability of productivity. Further, this information may be a valuable asset to forest planners and managers.

Keywords: shovel logging; follow-up study; cut-to-length extraction; productivity; cost; scheduled machine hour

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1. Introduction

Logging operations (a.k.a., primary transportation), in which logs are transported from stumps to a designated roadside or central landing area using various extraction methods, are an important part of the timber harvesting process, but they can be extremely expensive and more time-consuming in practice than felling and processing [1–4]. Many studies have examined the performance of extraction methods on sites with differing characteristics in order to establish the logistics of extraction activities, such as ground-based extraction (skidding and forwarding) [5–8] and cable yarding [8–10]. It can be concluded from these studies that logging practices should be economically determined while maintaining a deep understanding of both the potential and limitations of the chosen method.

Time-and-motion studies have been widely used to evaluate the performance of individual logging equipment as well as entire harvesting systems [11,12]. This type of study has been essential for predicting machine productivity and utilization rates in various scenarios under similar working conditions [13,14]. However, this approach is limited in terms of data availability due to the relatively short period of data collection and high costs of field work [14–16]. Additionally, a number of past studies have assessed performance using the follow-up method, which utilizes historic output records, such as productivity and costs. This can provide more accurate information on long-term performance than time-and-motion studies [17–19].

In the Republic of Korea (a.k.a., South Korea), forest land covers an area of 6.3 million hectares (64% of the total land area), and approximately 80% of all forested areas are on steep terrain with slopes greater than 40% [20]. In 2017, the stand density was 154.1 m^3/ha, with conifers being the dominant species, namely the Korean red pine (*Pinus densiflora*), Japanese larch (*Larix kaempferi* [Lamb.] Carrière), and pitch pine (*Pinus rigida* Mill). The volume of timber harvested has considerably increased in recent years: from 1.3 million m^3 in 2013 to 2.2 million m^3 in 2017 [20].

Two harvesting methods are commonly used in South Korea: cut-to-length small-shovel production (CTL-S) and tree-length cable-yarder production harvesting (TL-C). There are a number of past studies that investigate the TL-C method to describe, understand, and improve upon the efficiency of log production and associated operational decisions. Other studies focus on the productivity and operation efficiency of individual machines [21,22], comparing extraction performances among different cable-yarder technologies [23,24], and the effect of yarding direction (uphill vs. downhill) on productivity and cost [10,25] in order to support operational decisions. However, the use of the TL-C method for log hauling activities remains limited since this method requires not only a high skill level, but also an inherently high level of investment [26]. Thus, cable yarding systems have rarely been implemented on steep slopes and remote areas due to operation costs.

In South Korea, CTL-S is the preferred system, and it has replaced TL-C on steep slopes. After felling and processing trees with a chainsaw, 2–4 m logs are extracted using a small shovel, which is a small-sized hydraulic excavator (5.0 metric tons in weight with a 0.2 m^3 bucket) with a log grapple (i.e., a small shovel or wood grab; Figure 1). Generally, small-shovel (SS) extraction activities use gravitational energy to transport logs from the stump to the roadside/landing area. For example, on steep terrain, gravity can be useful in assisting with throwing, sliding, and rolling logs downhill [3,27]. Thus, the small shovel-based logging method could be increasingly applied in Korea's harvesting operations, but the productivity level and costs associated with extracting 2–4 m logs using SS activities remains unclear.

Figure 1. Log extraction using a small shovel-mounted steel-track excavator with a log grapple (1.3 m maximum jaw opening and 0.1 m closed jar gap); the boom length of the excavator is 5.1 m (Photo create: E. Lee).

Therefore, in this study, the overall objective was to determine the performance of SSs in various types of forest. In particular, this study sought to: (1) determine the productivity (m^3/SMH) and costs (US \$/m^3) of extracting logs through the follow-up method, (2) establish the influential variables in SS extraction productivity, and (3) develop regression models to predict SS productivity. Further, the results of this study will lead to better-informed SS technology decisions and more efficient production of timber products.

2. Materials and Methods

In collaboration with a group of logging companies and contractors under the Korea Wood Products Association (KWPA), we conducted a follow-up study of SS extraction activity, which is becoming the prevailing extraction technology. The study focused on the production of CTL clear-cut harvest units (CHUs) in the Central Northeast region of South Korea (Gangwon-do, Gyeonggi-do, Chungcheongbuk-do, and Gyeongsangbuk-do; Figure 2). The main characteristics of the CHUs are presented in Table 1. The units are located on relatively steep terrain (ranging from 13 to 64%, with an average slope of 49%); trees in these areas have a DBH (diameter at breast height) of up to 32 cm (minimum DBH, 18 cm). On average, the units have 560 trees per hectare (TPH), and the range is from 241 to 1129 TPH. The data set covered the dominant forest stand types: conifer, deciduous, and mixed. The total traveled distance (TTD; a.k.a., total driven distance) ranged from 36 to 72 m and average road density was 108 m/ha (ranged from 32 to 188 m/ha). We defined TTD for small-shovel operations as the distance the extractor travels, starting when the small shovel leaves the forest road or landing area and ending when it returns to the landing (Figure 3). The study areas were selected to cover a wide range of forest conditions; this was done to achieve an enhanced understanding of small shovel extraction performance across South Korea.

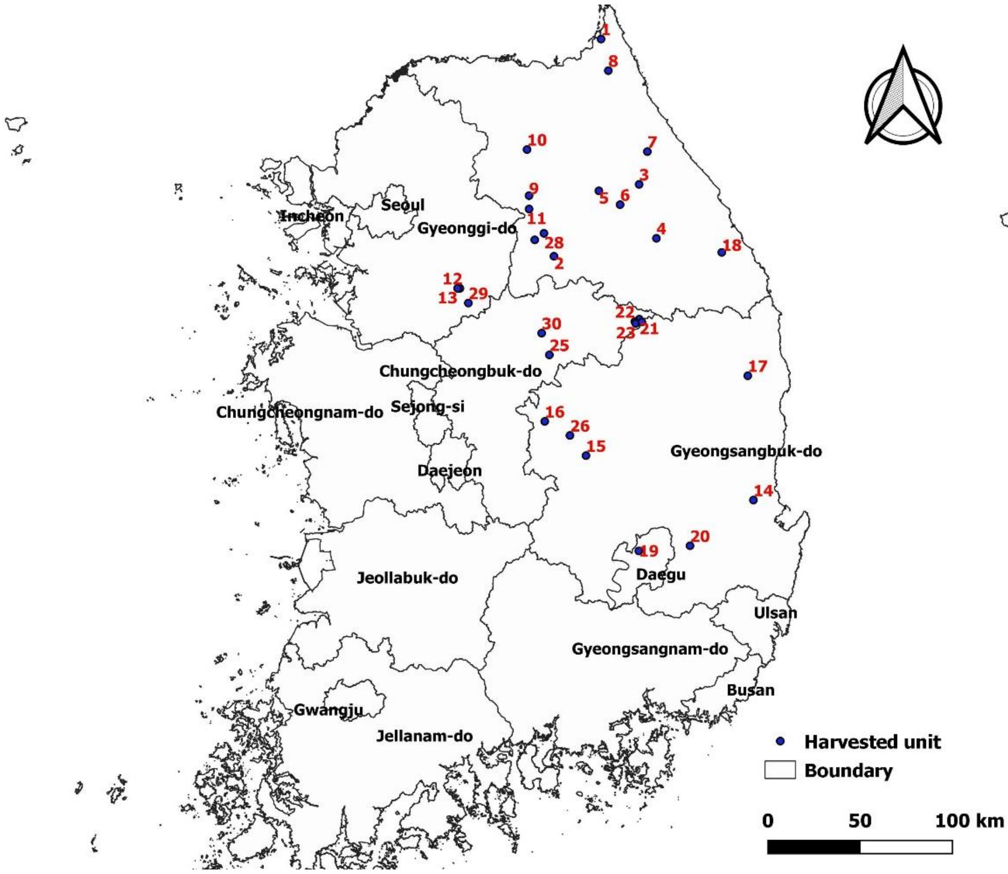

Figure 2. Map of study sites in South Korea showing the harvesting units.

Table 1. Summary of information collected for each unit: post-harvesting stand characteristics, average total travelled distance, and productivity.

Harvest Unit No.	Stand Type	Average DBH [a] (cm)	Average Volume (m^3)		Stand Density (Trees/ha)	Average Slope (%)	Average Total Travelled Distance (m)	Productivity (m^3/day)
			$tree^{-1}$	ha^{-1}				
1	Deciduous	22	0.26	112	435	64	58	50.9
2	Deciduous	22	0.26	119	466	60	60	58.4
3	Conifer	20	0.20	155	756	42	64	59.8
4	Conifer	22	0.24	271	1129	52	68	58.6
5	Conifer	24	0.34	148	436	42	44	44.1
6	Conifer	18	0.14	155	1,107	64	42	26.3
7	Conifer	24	0.30	188	627	32	69	75.5
8	Deciduous	32	0.56	157	278	64	55	52.7
9	Conifer	22	0.25	190	760	32	61	60.3
10	Deciduous	18	0.14	105	755	64	43	19.5
11	Mix	22	0.25	113	450	42	45	40.2
12	Mix	18	0.15	96	650	13	43	47.0
13	Mix	22	0.23	97	418	32	58	66.8
14	Mix	24	0.30	97	320	32	55	55.8
15	Deciduous	24	0.28	68	241	52	56	57.4
16	Deciduous	24	0.29	138	476	42	45	33.7
17	Deciduous	20	0.19	83	442	64	46	35.0
18	Deciduous	22	0.23	69	296	60	46	45.1
19	Conifer	18	0.16	118	716	42	53	26.1
20	Deciduous	24	0.28	72	255	42	42	37.7
21	Mix	18	0.18	161	909	40	45	42.4
22	Mix	32	0.60	169	282	64	72	78.8
23	Mix	32	0.56	162	287	60	65	71.8
24	Mix	20	0.19	121	626	52	36	33.8
25	Deciduous	18	0.16	134	819	64	61	50.9
26	Deciduous	24	0.27	124	459	52	39	43.3
27	Deciduous	18	0.15	62	408	52	41	22.8
28	Mix	24	0.27	154	580	64	44	43.4
29	Mix	22	0.22	77	344	22	45	48.9
30	Conifer	26	0.36	201	558	64	55	60.7

[a] DBH: Diameter at breast height.

CTL-S clear-cutting operations in each unit were performed using a semi-mechanized system that employs a chainsaw for felling, delimbing, and bucking trees into 2–4 m logs, which are mostly used as pulpwood. (An alternative to the use of the SS, especially on steep slopes, is manipulating all logs at the stump, as described by Lee et al. [10,28].) The SS operation utilized the gravity extraction technique, which involves throwing, rolling, and pushing logs, to move the logs to the roadside or landing area. When SS travels up and down, the machine moves along the slope direction. For each unit, timber harvesting had a similar target: (1) support sustainable forest management to ensure future availability and (2) benefit domestic timber industries by increasing the self-sufficiency rate.

Three years of historical data, from the period of 2015 to 2017, were manually collected from logging companies. The collected dataset includes a detailed description of harvest unit characteristics and the net production rate (m^3/day, based on an 8-hour work day) of log extraction by SS operation (Table 1). SS extraction productivity was determined by two processes: (1) the sorting of 2–4m logs when the SS commences travel into the felling site from the roadside/landing area and (2) the throwing and pushing of logs while the SS returns to the roadside/landing area.

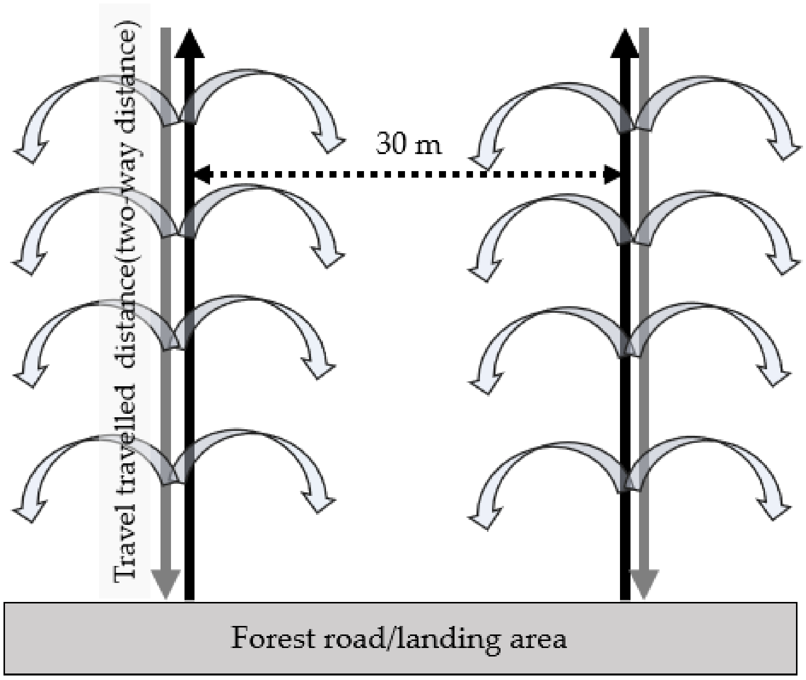

Figure 3. Vertical pattern for small shovel extraction activity cut-to-length to forest road/landing area and for operation in steeply sloped forests in South Korea.

In this study, the follow-up data collection method conducted did not involve a time-and-motion measuring device. This study relied solely on historical data from extraction operations performed by forest contractors. There was no information available on delay times, including mechanical, operational, or personal delays. Therefore, scheduled machine hours (SMH) were used to evaluate the productivity and cost of SS operations.

The costs for owning and operating SSs were calculated with the method developed by Miyata [29], which is a commonly accepted machine rate calculation technique. In addition to costs associated with machine ownership, operation, and labor, we included machine delays (mechanical, operational, and personal) and warm-up costs. This is necessary because the productivity data, which is divided into two categories: machine operation and idle time, is per SMH. The machine utilization rate, labor cost, and fuel consumption rate were collected from the KWPA (Table 2). The overhead, profit allowance, and transportation costs associated with SS were not obtained.

The SPSS package (IBM Co., New York, NY, USA, v. 22.0) was used for statistical analysis. Pearson's correlation test was conducted to clarify how the independent variables (DBH, slope, and TTD) affect SS productivity. Based on the value of the correlation coefficients, a predictive equation of productivity per SMH was developed using the ordinary least squares regression technique. Two-thirds of the follow-up data were randomly selected for model development, while the remaining one-third of the data was applied for validation of the proposed model. A two-sample t-test was used to compare the predicted and observed values and to describe any statistical differences for model verification.

Table 2. Cost components and estimated hourly cost to own and operate a small shovel.

Cost Component	Small Shovel
Purchase price (US $)	54,000.00
Salvage value (%)	20
Economic life (year)	7
Scheduled machine hour per year	1400
Interests (%)	10
Insurance (%)	3
Taxes (%)	2
Fuel consumption rate (liter/hour)	9.0
Fuel cost (US $/liter)	1.20
Lubrication (% of fuel cost)	40
Repair and maintenance (% of depreciation)	90
Labor (US $/hour)	17.00
Fringe benefit (% of labor)	22
Fixed cost (US $/hour)	8.21
Operating cost (US $/hour)	14.52
Labor cost (US $/hour)	20.35
Total operation cost (US $/hour)	45.87

3. Results

The study was designed to test the efficacy of SS extraction from stumps to roadside through 30 different case studies. Overall, the SS was capable of a productivity rate of 2.44 to 9.85 m^3/SMH at a cost of US $4.37 to 17.66/$m^3$ (Figure 4). There were large variations in productivity and cost evaluations across the harvest units.

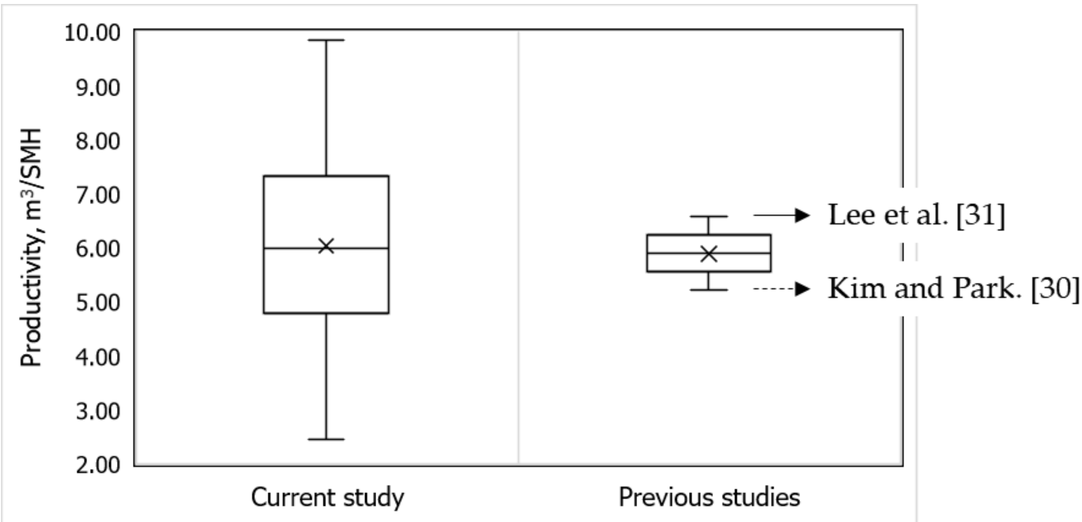

Figure 4. Box and whisker plots of productivity between the current study and previous studies: Kim and Park [30] and Lee et al. [31]; both studies evaluated the shovel logging productivity. The X indicates mean value.

Productivity may increase or decrease with variation in stem size, such as DBH and tree/log volume. Through Pearson's correlation test, we found that DBH and tree volume had a considerable impact on productivity ($p < 0.001$). Productivity and stem size, including DBH ($r = 0.6168$) and tree volume ($r = 0.6161$), were directly related (Figures 5 and 6).

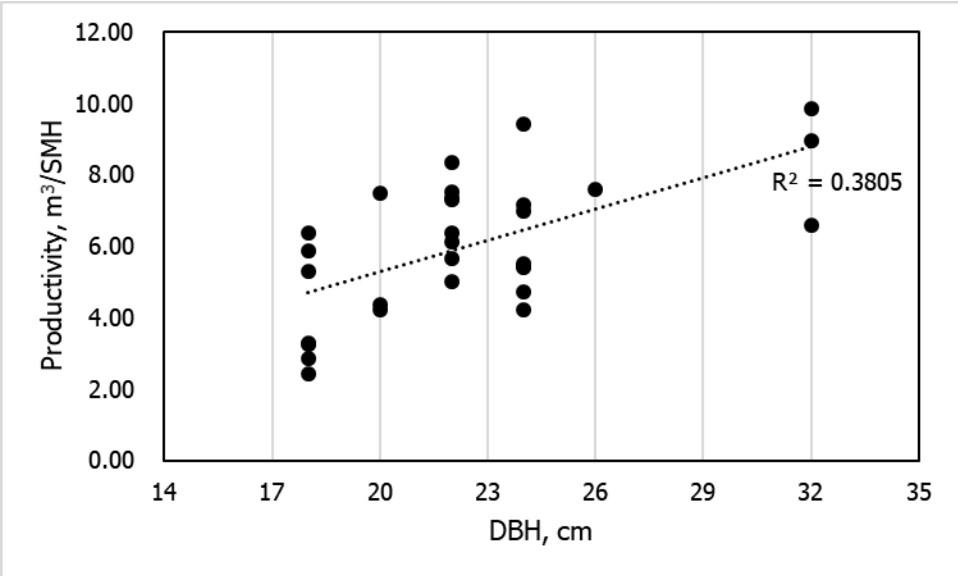

Figure 5. Productivity, which was calculated using follow-up data from 30 study areas, and its relationship with DBH (Diameter at Breast Height). Productivity had a moderate correlation with DBH.

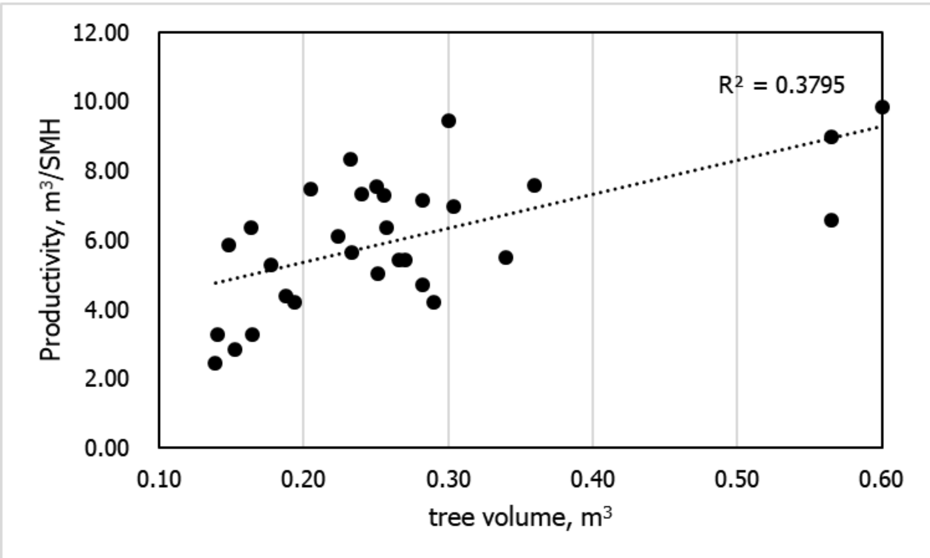

Figure 6. Productivity, which was calculated using follow-up data from 30 study areas, and its relationship with tree volume. Productivity had a moderate correlation with tree volume.

In most harvest units, a higher stand density is significantly associated with small stem size ($p < 0.001$; DBH of $r = -0.5830$ and tree volume of $r = -0.5322$). However, stand density had a weak to moderate negative correlation with SS productivity ($r = -0.2214$; Figure 7). As a result, SS productivity was inversely correlated with stand density.

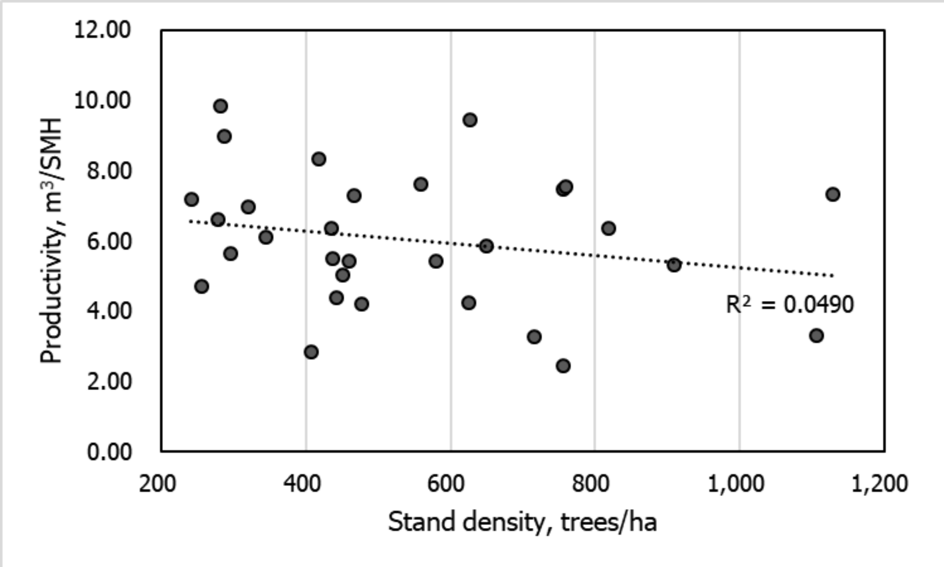

Figure 7. Productivity, which was calculated using follow-up data from 30 study areas, and its relationship with stand density. Productivity had no correlation with stand density.

This study implied that an increased TTD would be positively and significantly correlated with SS productivity ($p < 0.001$; $r = 0.8262$; Figure 8). On the other hand, slope had no significant correlation with productivity ($r = -0.1060$; Figure 9). Although our data is limited to divide into SS cycle elemental time, we found that the time spent throwing and rolling logs may be considerably longer than the travel time. Further, in terms of extraction activity, there was no common pattern across Korea for selecting SS operations in steeply-sloped forests.

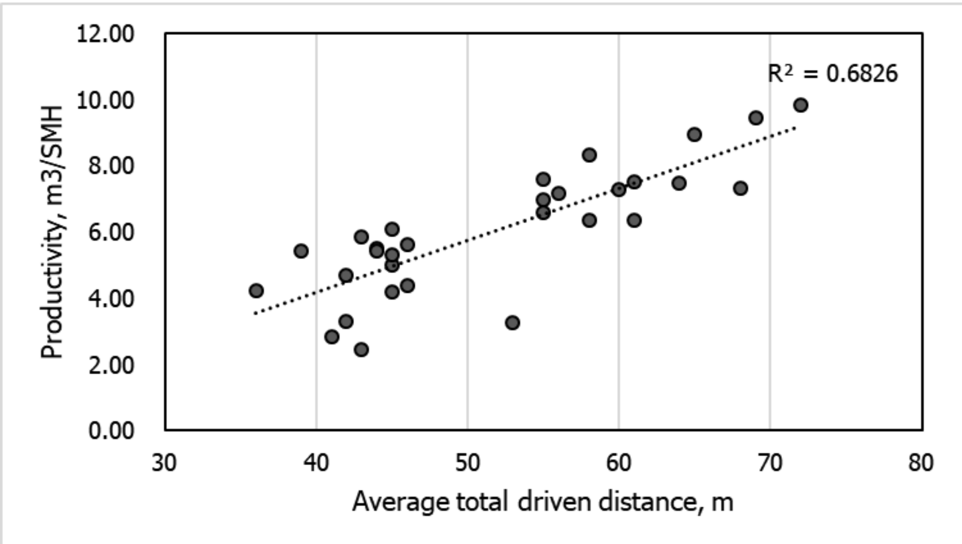

Figure 8. Productivity, which was calculated using follow-up data from 30 study areas, and its relationship with total travelled distance. Productivity had a strong correlation with average total travelled distance.

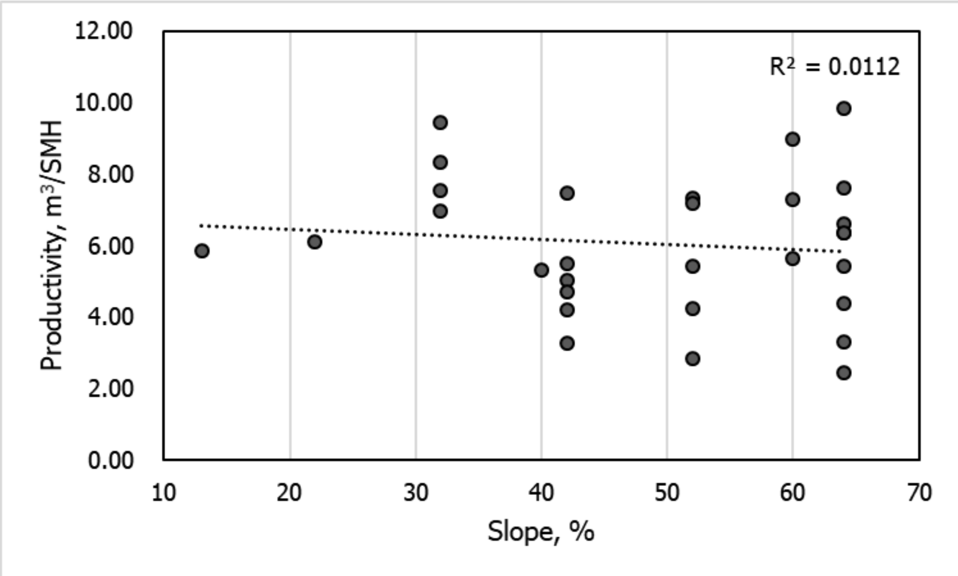

Figure 9. Productivity, which was calculated using follow-up data from 30 study areas, and its relationship with slope. Productivity had no correlation with slope.

The SS productivity regression equation was derived from the follow-up data to predict extraction productivity (Table 3). The independent variables ranged from 0.14 to 0.56 m^3 for tree volume and 36 to 69 m for TTD. This model was tested for assumptions of normality, independence, and equal variance to confirm the validity of the analysis. The TTD was significant ($p < 0.001$) as a variable, but tree volume was not a significant variable ($p = 0.0581$). A paired t-test was performed to validate the equation against the observed data. The results indicated that the predicted value was not significantly different from the observed value ($p > 0.05$). Thus, the obtained model may be quite accurate.

Table 3. Productivity regression model for small-shovel operations extracting 2–4 m logs. Productivity is in m^3/SMH (Scheduled Machine Hour). A paired t-test was used for model verification across observed data.

Average Productivity Estimator	**SE**	***t***	***p*-Value**	**Model adj. R^2**	**Model *p*-Value**	**t-Test (*p*-Value)**
= −2.1861	0.9966	−3.0810	0.0396	0.7517	<0.01	0.2935
+ 3.6873 × Average tree volume (m^3)	1.8400	2.2827	0.0581			
+ 0.1404 × Average total travelled distance (m)	0.0205	6.9908	<0.01			

The SS productivity model showed that productivity improved as tree volume and travelled distance increased; the average tree volume ranged from 0.15 to 0.50 m^3, and the mean TTD was between 40 and 70 m (Figure 10). The data indicated that when the volume of trees extracted increased from 0.15 m^3 to 0.50 m^3 (and the TTD ranged between 40 and 70 m), productivity increased by up to 30%. This result may be explained by the fact that efficiency improved with larger tree volumes and an increased number of logs at the stump area.

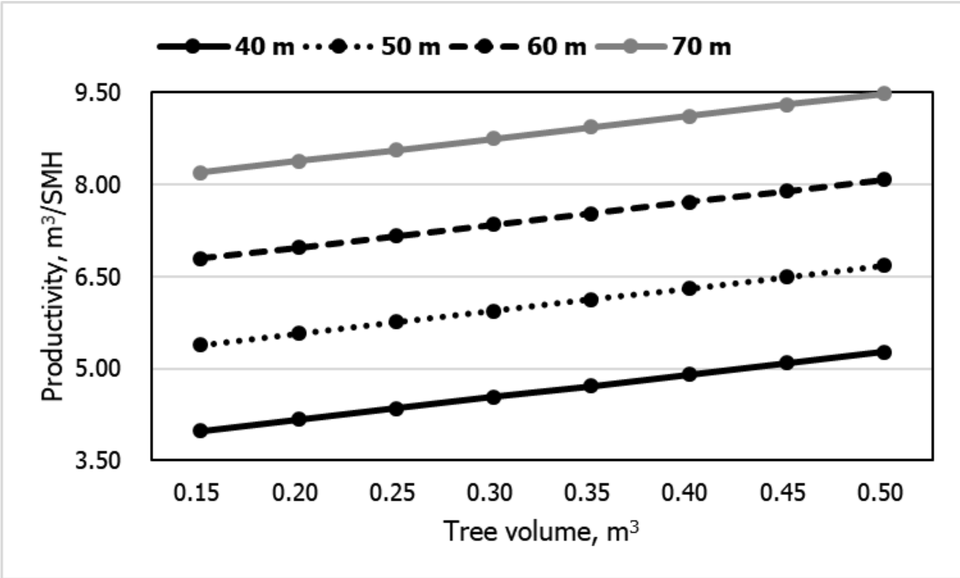

Figure 10. Productivity for the small-scale extraction operations in relation to tree volume (m^3) and total travelled distance (m).

4. Discussion

Small-shovel logging method has become widespread and has had increasing use across South Korea in steeply-sloped forests. With steep terrain extraction, the slope grade helps in hauling the logs downhill with the support of gravity from the felling area [28,32]. We conducted a follow-up study of the SS extraction method to evaluate the productivity and cost under various types of forests and established the influential variables in extraction productivity. In addition, we developed a regression model for the SS to estimate hourly productivity in SMH. The results show that the estimated stump-to-forest road log productivity was between 2.44 and 9.85 m^3/SMH at US $17.66 and 4.37, respectively. The stem size and TTD statistically have an influence on the productivity of SS extraction operation ($p < 0.001$), but the slope had no static correlation ($r = -0.1060$). Thus, the model showed that productivity improved as tree volume and TTD increased. Further, we examined a sensitivity analysis to evaluate the impact of the tree volume and TTD on the model. The result indicated that, when the volume of trees extracted increased from 0.15 to 0.50 m^3, with the TTD ranging between 40 and 70 m, productivity increased by up to 30%.

In our study, mean SS extraction productivity was 6.03 ± 1.90 m^3/SMH, which is very similar to the findings by Kim and Park [30] and Lee et al. [31], whose results were 5.21 and 6.57 m^3/SMH, respectively (Figure 4). These previous studies likely operated under similar conditions: an average DBH of 22 to 26 cm, tree volume of 0.24 to 0.27 m^3, and slope of 36 to 44%. Thus, the follow-up evaluation is deemed reasonable and acceptable in terms of accurately determining the productivity of the SS extraction process.

The productivity and costs of SSs varied when extracting 2–4 m logs in steep terrain due to a wide range of forest types. Numerous studies have pointed out that differences in productivity and cost of extraction activities were due to locally variable conditions, including the volume of extracted logs, stem size, extraction distance, and working conditions [33–35]. Our data significantly showed that stem size and TTD were important key factors in SS productivity prediction, while the slope was not statistically correlated.

Shovel logging productivity is affected by the number of swings and road spacing [36]. Although our data was limited to determine the effect of number of swings and road spacing, we tested how the DBH, slope, and TTD affect SS productivity using Pearson's correlation. We found that stem size had a statistical impact on productivity. Numerous studies have pointed out that stem size has been a primary factor in extraction productivity [11,34,37,38], because a larger log size increases the piece volume, payload, and productivity. Therefore, DBH and tree volume may be two of the main factors influencing SS productivity. Further, tree volume, instead of DBH, was selected in the regression model because this variable was evaluated as more stable and applicable [17,39,40]. Both the Berendt et al. [41] and Han et al. [42] studies found that the most commonly used variable is tree volume to estimate the productivity.

Another important variable that influences productivity was significantly related to extraction distance since the load travel time accounted for over one quarter of the variation in cycle time [43,44]. Thus, extraction productivity increases with a decrease in extraction distance [45–47]. However, our follow-up data provide only an average total travelled distance of SS across the harvest unit, while the extraction distance was not collected. We found that productivity and TTD were strongly correlated. These results are consistent with many published studies, such as Matthews et al., [48], Kumazawa et al., [49], and Berg et al., [50]. These studies posited that the driving unloading speed increases with an increase in driving distance. During extraction operation, operator's stress on long distances could lead to increase driving speed.

In addition, extraction productivity may be influenced by the number of logs [46,50]. This pattern could be explained by the fact that productivity increases with a decrease in the number of load stops and driven distances. The operation of SS in South Korea, unlike the excavator extraction method (a.k.a., shovel logging), uses gravity. During the operation, the throwing and rolling activity, which is done to transfer logs from the felling area down to the landing area, may be associated with a large number of logs and long TTD. Thus, the productivity of SS may depend on the number of throwing stops and TTDs.

Slope is shown to be a primary factor in productivity because it affects the accessibility of the harvesting machine [18,43,46,51,52]. However, this was also observed in Berendt et al. [41], Ghaffariyan et al. [53], and Walsh and Strandgard [54]. These studies found that the slope did not significantly impact loaded travel time during extraction activities. This study showed that slope had no statistically significant influence on SS productivity, since the time spent throwing and rolling logs may be considerably longer than the travel time. Further, in terms of extraction activity, there was no common pattern across Korea for selecting SS operations in steeply-sloped forests.

5. Conclusions

In conclusion, this study's findings showed that SS efficiency in extracting 2–4 m logs from stumps to roadside/landing areas varied across harvest units in mountain forests. The mean productivity was 6.03 ± 1.90 m^3/SMH, with a minimum of 2.44 m^3/SMH and maximum of 9.85 m^3/SMH. According to the cost deduction, the corresponding extraction costs were estimated to be from US $4.37 to 17.66/$m^3$. Productivity was significantly impacted by DBH, tree volume, and TTD, whereas stand density and slope were observed to be non-significant.

Assessing the productivity of forest operations is a challenging task due to rough and unstructured environmental conditions. In this study, an SS productivity prediction model was derived using follow-up data taken from 30 forest sites across South Korea. Two-thirds of the total dataset were used to build the model, while the remaining one-third of the data was used for validation. This model is expected to be used by harvest planners, forest managers, and decision makers to improve SS management and extraction operations. However, these results were limited to applications across South Korea. Further study is needed using a broader and more updated range of data with a tree volume greater than 0.6 m^3 to develop an applicable prediction model that can be used in other countries.

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Conflicts of Interest: The authors declare no conflict of interest.

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