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Review

A Literature Review on Cable Extraction Practices of South Korea: 1990–2020

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Abstract: Cable yarding technology remains the most effective operation in steep terrain harvesting systems; however, it has limitations and challenges. Using cable yarders (tractor-, truck-, and excavator-based) to extract tree lengths and whole trees has been common since the late 20th century in South Korea, and cable yarding operations were developed in the late 1800s in the United States and Europe. Machine potential and limitations must be understood to ensure the widespread use of technology, strong cooperation, and optimal selection of machinery size. We reviewed the literature on tower yarder performances from 1990–2021 to determine the alteration of yarders and its productivity pattern and obtained 23 papers; <2 publications per year discussed the determination of cable yarding productivity. We selected independent variables (e.g., silvicultural treatment, harvesting method, and cycle log volume) for cable yarding that would likely affect productivity. Data were analyzed to compare productivities under silvicultural treatment, the harvesting method, and yarding direction and identify the interaction mechanical power (i.e., lifting capacity and machine power), yarding distance, and slope. Cable yarder productivity rates generally depended on the silvicultural treatment, harvesting method, and yarding direction, particularly in clear-cut, tree-length, and uphill yarding operation activities. The lifting capacity, machine power, and slope had no significant correlation with yarders' productivity, particularly in thinning operations, whereas, in clear-cut productivity, it was influenced by these variables. The results contribute to improving operation activities for cable yarding systems and towards future research directions.

Keywords: steep slope; cable logging; cable yarding; productivity; performance

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1. Introduction

Various harvesting systems (e.g., ground-based, cable, and aerial harvesting systems) have been developed to achieve economic and environmental sustainability under complex variable conditions, such as geophysical conditions, industrial infrastructure, and labor availability [1–3]. Ground-based harvesting systems can be described as the dragging or forwarding of felled trees from the stump location to landing by a skidder or forwarder that travels over the ground [4]. As a technology, cable systems using a sledge yarder and a tower yarder require cables to haul or extract trees on steep terrain for landing, whereas, in aerial systems, logs are hoisted and derived above the ground by a helicopter or airship [5,6]. In addition, globally, mechanized timber harvesting has been developed and has been preferred over the last few decades owing to its productivity and cost efficiency benefits and because of its reduced road infrastructure and safety risks [2,7,8].

Thus, the proper utilization of forest machines and mechanized systems is strategic to guarantee a sustainable supply chain. Further, choosing the appropriate harvesting system is challenging when considering the economic and environmental dimensions of each system.

Current technologies in South Korea (hereafter, Korea) are primarily small-shovel for the cut-to-length method and tower yarder for tree-length and whole-tree operations in steep terrains [9,10]. Forests covered approximately 63% of the Korean Peninsula in 2019, of which approximately 80% were native and 20% were plantation forests [11]. The net stocked forest area is 6.2 million hectares (ha), with an annual timber harvest area of 0.02 million ha (5.0 million m^3 of timber harvested annually) [11]. More than 67% of the harvested stands were conifer-leading stands (*Pinus densiflora* and *Larix kaempferi*), and 33% were mixed broadleaf stands (*Quercus mongolica* and *Quercus serrata*). The mean stand density increased from 63.5 m^3 in 2000 to up to 161.4 m^3 in 2019 [11]. In 2020, the mean area covered by forest road was 3.7 m/ha, and the mean longitudinal slope of the road was at 1350-m intervals [11]. Forests have slopes of up to 100%, and approximately 70% of the total forested areas are steep terrain. According to Spinelli et al. [12], Ghaffariyan [13], and Stoilov et al. [14], for slopes of $\geq$40%, cable-based extraction technologies can offer good performance results compared to ground-based harvesting, because they have the advantage of minimizing road construction and environmental impact if operated in a high-product-yield stand. As a result, although cable harvesting systems are inherently costly and complicated, this technology is more suitable for steep forests.

The mechanization of extraction operations is especially difficult on steep slopes and in remote areas [15]. In steep country forests (i.e., the United States (USA), Europe, and New Zealand), an alternative technology for extracting trees is to use cable yarding technology, which has emerged as a common practice since the 19th century [6]. Various cable yarders have been designed in different countries of the world, particularly in the USA and Canada (created in 1915; focused on heavy cable machines), Europe (developed in 1939; based on light cable machines), and Australia (used from the mid-20th century; based on heavy cable machines). A cable-based yarding technology, using motor-manual felling and processing and extraction by cable yarders, has been used in steep terrain due to a higher market value and lower environmental impact than ground-based technologies [16,17]. Cable yarding machines have advanced highly sophisticated diesel-powered engines and electro-hybrids [6,17]. In addition, motorized slack-pulling carriages, self-propelled carriages, and grapple carriages with GPS and camera technology have been developed to improve productivity [6,18]. The majority of the cable yarding activities require skilled operators and choker setters to bring the trees for extraction from the stump to the roadside or landing. Furthermore, many cable yarding guidebooks have been published to educate operators about controlling extraction processes and improving performance efficiency and safety [1,6].

After the Korean War (1950–1953), Korea completed forest recovery, restoration, and rehabilitation for sustainable timber resources through the first and second national economic development plans (NEDPs) from 1962 to 1987 [19]. In the third NEDP (1988–1997), a transitional period in forest policy was introduced, and the main focus was altered from reforestation to establishing forest management infrastructure (i.e., mechanized harvesting and forest road [19]). At this time, Korea began importing cable yarders (Koller K-300, Koller Forsttechnik GMBH, Schwoich, Austria) and Timbermaster (A&B Services Ltd., Killin, Scotland) to harvest forests in the mid-1980s, and several machines and technologies were developed domestically in the 1990s for application in Korean forests [11]. In 2019, 311 tower yarders, including tractor-based (255 machines), truck-based (30 machines), and excavator-based (26 machines) yarders, were imported and designed by the government's leading planning of mechanized harvesting (Figure 1; [11]). These facilities are state-owned and have been used about 35% of the total harvest unit area [11]. Tractor-based yarders are increasingly becoming more popular than machines. These machines were tested as early as in the 2000s to assist in effective steep terrain timber harvesting and operational planning and decision-making (Table 1).

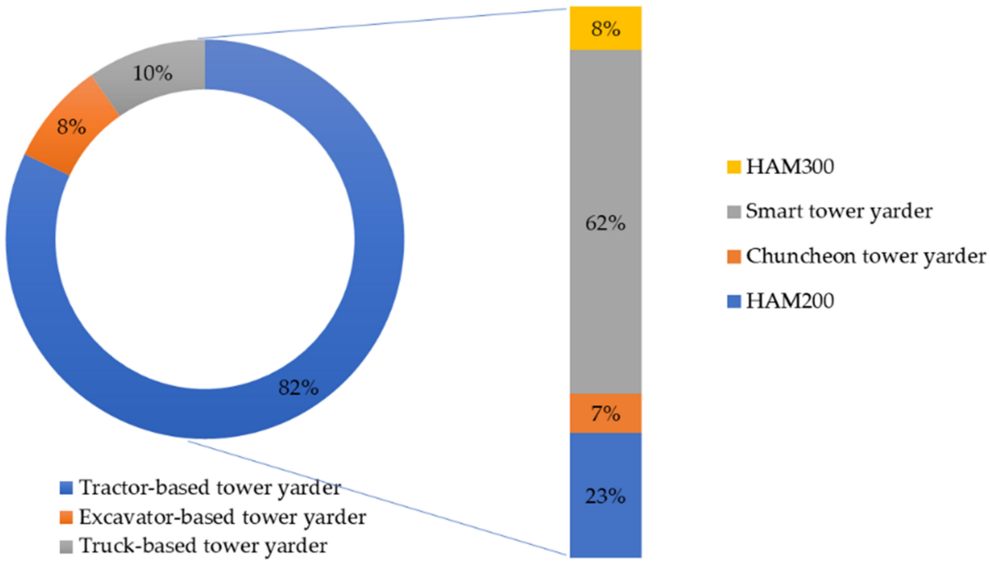

Figure 1. Distribution of the tower yarders in Korea, 2019.

Table 1. Summary of specific harvest information and productivity results from previous cable extraction activities studies.

Author	Equipment	Silvicultural Treatment		Harvesting Method			Yarding Direction	DBH [d] (cm)	Slope (%)	Work Team [e]	Cycle Log Volume (m^3)
		Clear-Cut	Thinning	CTL [a]	TL [b]	WT [c]					
[20]	K-300	×		×			Uphill	32	25	5	0.6
			×	×			Downhill	19	5	4	0.6
		×		×			Uphill	21	20	4	0.6
[21]	K-300		×			×	Uphill	19	32	2	0.2
			×			×	Downhill	19	20	2	0.2
[22]	HAM200		×			×	Uphill	27	37	3	0.3
[23]	RME-300T		×			×	Uphill	16	48	2	0.1
[24]	Chuncheon tower yarder		×		×		Uphill	26	60	4	0.7
			×		×		Downhill	26	52	4	0.5
[25]	TW-232		×		×		Uphill	26	40	3	0.6
[26]	Chuncheon tower yarder		×			×	Downhill	16	50	5	0.2
	RME-300T		×			×	Uphill	22	50	3	0.3
[27]	RME-300T		×			×	Uphill	14	n/a [f]	5	0.1
		×				×	Uphill	22	n/a	4	0.3
		×				×	Downhill	22	n/a	4	0.3
	TW-232	×				×	Downhill	20	n/a	5	1.0
		×			×		Downhill	20	n/a	4	0.8
		×				×	Downhill	20	n/a	4	0.4
[28]	RME-300T	×				×	Downhill	16	54	3	0.3
	TW-232	×				×	Downhill	16	54	3	0.3
[29]	K301	×			×		Downhill	32	74	3	0.2
	Smart tower yarder		×		×		Uphill	26	50	3	0.4
[30]	K301	×				×	Downhill	36	34	4	0.9
[31]	K301	×				×	Uphill	20	n/a [f]	3	0.5
		×				×	Downhill	34	n/a	3	0.5
		×			×		Uphill	19	n/a	3	0.6
	K300	×			×		Uphill	26	n/a	3	0.5
	TW-232	×				×	Downhill	20	n/a	3	0.3
[32]	RME-300T		×		×		Downhill	26	52	4	0.4
	Chuncheon tower yarder		×		×		Downhill	19	50	4	0.2
[33]	K301		×		×		Uphill	24	36	4	0.3

Table 1. *Cont.*

Author	Equipment	Silvicultural Treatment		Harvesting Method			Yarding Direction	DBH [d] (cm)	Slope (%)	Work Team [e]	Cycle Log Volume (m^3)
		Clear-Cut	Thinning	CTL [a]	TL [b]	WT [c]					
[34]	HAM300		×		×		Uphill	34	60	4	0.7
[35]	HAM300	×			×		Uphill	32	38	4	0.8
[36]	K301	×			×		Uphill	34	40	4	1.1
	HAM300	×			×		Uphill	34	40	4	1.2
[37]	HAM300	×			×		Uphill	34	39	4	0.9
[38]	SW-200	×				×	Downhill	22	40	2	0.5
[39]	HAM300	×			×		Uphill	34	40	3	0.6
		×			×		Downhill	34	42	3	0.6
[40]	Integrated yarder-processor	×				×	Uphill	22	36	2	1.2
[10]	K301	×			×		Uphill	36	n/a	4	1.0
	HAM300	×			×		Uphill	33	n/a	4	0.8
[41]	HAM200	×			×		Uphill	18	n/a	3	0.2
		×			×		Downhill	16	n/a	3	0.2

[a] Cut-to-length, [b] tree-length, [c] whole-tree, [d] mean diameter at breast height, [e] one yarder operator and remaining number of workers are choker setters, and [f] not available.

However, the level of mechanization in extraction activities is low [11]. The most widely used extraction method is the small excavator equipped with grapples (referred to as a small-shovel and used in 61% of extraction operations), and the remaining 19% were extracted by cable yarders [9,42]. Forest owners and forest contractors remain in doubt and are hesitant to own a yarder, primarily because of the high investment costs (i.e., purchase and operation costs) and, also, because using yarders requires more forest workers than small-shovel operation activities. In addition, the forest ownership structure is unique in that 67% is classified as private forest ownership, in which approximately 80% of the forests are owned in < 2 ha parcels [11]. As a result, understanding the cable yarding performance and the ability to identify appropriate machines may be fundamental for planning extraction activities and machine decision-making.

Many cable yarder models have been imported and developed in Korea since the industrialization of harvesting began. Therefore, the objectives of this review were to: (1) describe the alterations and developments of tower yarders from 1990 to 2021 and (2) summarize and share productivity data based on productive machine hours (PMH) and describe the pattern of tower yarder performance in various regions from 2000 to 2021.

2. Background on Cable Yarders

While cable logging systems became well known in the USA and Europe in 1970, the mechanized extraction of trees by a cable yarder in Korea commenced at the end of 1980 under the cut-to-length method in clear-cut and thinning treatments [20]. From 2000 to 2021, yarders have primarily operated and applied under tree-length or whole-tree methods in clear-cut and thinning treatments (Table 1). Tower yarders are divided into three main types: small, medium, and large [43]. Three main types were categorized and defined in the skyline system:

- Small mobile cable yarder: A 19–186-kW vehicle (include tractor, truck, and excavator) is required, and the tower height ranges from 4.5 to 10.0 m. The maximum load capacity is 5.8–24.5 kN. Power is provided by the power take-offs, and two or three guy lines are required.
- Medium mobile cable yarder: A 45–261-kW vehicle is required, and the tower height ranges from 7.5 to 20.0 m. Power is provided by the vehicle's engines, and three or six guy lines are required.
- Large mobile cable yarder: A 224–485-kW vehicle is required, and the tower height ranges from 15.0 to 37.0 m. Power is provided by the vehicle's engines, and three or eight guy lines are required.

To establish a comprehensive compilation of cable yarders in Korea, the machine picture and information described separately (Tables 2 and 3).

Table 2. Summary of small mobile cable yarders in Korea 1980–2021.

Yarder Type		Description
Small mobile cable yarder		
K-300		The first tower yarder was introduced and imported in the mid-1980s by the Korean German Forest Management Project organization. It is a yarder for uphill and downhill yarding, where the skyline, mainline, and haulback drums are attached to operate downhill. The 3-drum yarder is mounted on a small farm tractor (30–45 kW), the lifting capacity is 1.5 t, and it used together with a self-interlocking carriage (i.e., SKA 1) in standing skyline systems. The maximum tower height is 7.0 m, and the maximum yarding distance is 350 m.
Timbermaster		This yarder also first tower yarder and is a self-supporting frame and is mounted on a 45–60-kW farm tractor or trailer. The maximum tower height is 7.3 m, and the maximum yarding distance is 350 m.
HAM200		The HAM200 of the 1990s was developed by the National Forestry Cooperative Federation, Korea. The 2-drum (mainline and haulback) yarder for uphill yarding was mounted on various small farm tractors (37–60 kW) using mechanical gears that transmitted power from the engine to the yarder. The lifting capacity is 1.5 t, and it is equipped with a non-slack-pulling carriage in a standing skyline system. The maximum yarding distance is 200 m, and the tower height with extension reaches 4.2 m.
Chuncheon tower yarder		During the 2000s, various tractor-mounted tower yarders were developed by the Korea Forest Service. The yarder was assembled on various farm tractors (37–60 kW). This yarder had a 3-drum for uphill and downhill yarding, which is an upgraded version of HAM200. The lifting capacity is 1.0 t, and it is equipped with a non-slack-pulling carriage in a standing skyline system. The maximum yarding distance is 200 m, and the tower height, with extension, can range from 2.5 to 4.2 m.

Table 2. *Cont.*

Yarder Type		Description
Smart tower yarder		This yarder can operate for uphill and downhill yarding. The lifting capacity is 1.3 t, and it is equipped with a non-slack-pulling carriage in a standing and running skyline system. The maximum yarding distance and tower height are 200 m and 4.0 m, respectively.
RME300T		This yarder, which was designed by Oikawa Motors Co. Ltd., Japan, was imported and equipped on a six-wheel drive vehicle (67-kW). The yarder is a 3-drum, including the skyline, mainline, and haulback line for uphill and downhill yarding operations. The lifting capacity is 1.5 t, and it is equipped with a clamping carriage in standing and running skyline systems. The maximum yarding distance is 300 m, and the tower height, with extension, can reach 9.0 or 11.0 m.
TW-232		Excavator-based un-guyed tower yarder technologies were described in the USA in 1990 and required lower investment, fewer human resources and landing area requirements, and installation was more rapid than for other tower yarders [44,45]. Therefore, in Korea, two types of excavator-based tower yarders were imported and developed to operate in clear-cut and thinning treatments between the 2000s and the 2010s. TW-232, which was developed by Iwafuji Industrial Co. Ltd., Japan, is a swing yarder with a lifting capacity of 2.3 t, a 200-m yarding distance, and a 5-m tower height.
SW-200		SW-200, which is a 2-drum hydraulic interlocking power, was designed by the National Institute of Forest Science, Korea; it has a lifting capacity of 1.8 t, a 200-m yarding distance, and a 5-m tower height. Both yarders were used with a clamping carriage in a standing and running skyline system.
HAM300		The new type of HAM300 in the 2010s presented an advancement and allowed for uphill and downhill yarding using a hydraulic control system, since it was attached with a skyline drum. Commonly, this yarder is used together with a remote-control hydraulic slack-pulling carriage (HAM-C 1.0) in a standing skyline system to improve its performance and safety. The maximum yarding distance is 300 m, the tower height can extend up to 7.3 m, and the lifting capacity is 2.5 t.

Table 3. Summary of the medium and large mobile cable yarders in Korea 1980–2021.

Yarder Type		Description
Medium mobile cable yarder		
K-301		Koller has been the most successful and enduring manufacturer of truck-mounted tower yarders since the 2000s. K301 is a 4-drum yarder with a slack-pulling carriage (USKA 1.5) for uphill and downhill yarding. This yarder is mounted on an 84-kW diesel engine with two or three-axle trucks. The maximum yarding distance is 300 m, lifting capacity is 2.6 t, and tower height is 8.8 m.
Integrated truck-based yarder		An integrated truck-based yarder equipped with a four-drum winch and a grapple or processor was developed and tested by the National Institute of Forest Science, Korea during the 2010s. This yarder was integrated with other equipment that unified yarding, handling, and the processing functions tower yarder unified the handling and processing functions into the tower yarders. It was equipped on a 100-kW 6-wheel truck with a slack-pulling carriage (Sherpa u-1.5; lifting capacity of 2.7 t,), and it had a 200-m yarding distance and a 11.0-m tower height.
Large mobile cable yarder		There were no large mobile cable yarder machines operating in Korea.

3. Materials and Methods

In order to ascertain the performance data from cable yarding operations, a total of 23 references, such as 1 master dissertation, 18 scientific publications, and 4 technical, were retrieved and adopted to build database between 1990 and 2021. Based on the literature search, we extracted information on the two subtopics: productivity and independent variables (Tables 1 and 4). Explanatory variables were the silvicultural treatment, harvesting method, and yarding direction. To examine the explanatory variables effect, we tested for normality using the Shapiro–Wilk's method. Analysis of variance (ANOVA) was used to determine the differences between (1) clear-cut vs. thinning, (2) whole-tree vs. tree-length, and (3) uphill vs. downhill. Pearson's correlation test was led to investigate the relationship between productivity and (1) yarding distance, (2) slope, and (3) machine utilization rate. All statistical analyses were conducted though *R* software v4.0.2.

Table 4. Summary of the productivity (m^3/productive machine hours (PMH)/worker) from previous studies, 1990–2021.

Author	Equipment	Mean Yarding Distance (m)	Machine Utilization Rate (%)	Productivity (m^3/PMH/Worker)
[20]	K300	65-110	n/a [a]	0.8–1.3
[21]	K300	52-53	n/a	0.8–1.1
[22]	HAM200	40	68	2.1
[23]	RME-300T	60	65	0.5
[24]	Chuncheon tower yarder	47–66	65-68	3.0–3.3
[25]	TW-232	43	63	3.2
[26]	Chuncheon tower yarder	50	70	0.5
	RME-300T	70	74	1.2
[27]	RME-300T	43–131	61–72	0.5–1.1
	TW-232	49–89	62–86	0.5–1.1

Table 4. *Cont.*

Author	Equipment	Mean Yarding Distance (m)	Machine Utilization Rate (%)	Productivity (m^3/PMH/Worker)
[28]	RME-300T	60	72	1.1
	TW-232	60	81	1.8
[29]	K301	34	53	0.9
	Smart tower yarder	118	30	1.8
[30]	K301	68	75	3.2
[31]	K301	52–87	61–75	1.8–2.0
	K300	52–80	62–74	0.7–1.2
	TW-232	68	70	0.9
[32]	RME-300T	66	67	1.8
	Chuncheon tower yarder	101	77	0.5
[33]	K301	91	90	0.7
[34]	HAM300	47	59	2.3
[35]	HAM300	79	50	2.0
[36]	K301	97	n/a	3.2
	HAM300	85	n/a	2.9
[37]	HAM300	33–97	49–63	2.1–2.8
[38]	SW-200	69	80	3.8
[39]	HAM300	53–55	59–70	2.6–3.0
[40]	Integrated yarder-processor	30	n/a	5.9
[10]	K301	61–118	n/a	2.6–3.1
	HAM300	63–89	n/a	2.2–2.5
[41]	HAM200	50–100	n/a	0.6–0.8

[a] Not available.

4. Machine Productivity

Numerous studies in Korea have been published over the last 30 years regarding cable yarder productivity. Motor-manual felling followed by cable-based extraction with choker setters after processing on a forest roadside and landing has been the cable yarding system. Table 2 summarizes the range in productivity from 1990 to 2021. Productivity data were mostly collected from the time study method using a digital stopwatch in conifer-leading stands (*Pinus densiflora* and *Larix kaempferi*). This technique is the primary method used in timber production to estimate the machine time consumption and develop a productivity model based on independent variables (e.g., yarding distance, cycle log volume, and slope [3,46,47]). In addition, independent variables were manually measured. This technique was first introduced by Park [20] in Korea and has been commonly applied to understand the performance of individual harvesting machines and harvesting systems. Overall, the cable yarders were capable of productivity rates of 0.5–5.9 m^3/PMH/worker during the 21 years between 2000 and 2021 (Table 2). Machine productivity was estimated in m^3/PMH/worker to minimize the influence of the work team size, and there appeared to be a large variation. Large variations are arguably caused by differences in silvicultural treatments, machinery, operation conditions, and cycle log volume [18]. Therefore, in order to analyze the effects of independent variables on the productivity, we compared the published data with the exception of machine models under various site conditions. No productivity information was described by Timbermaster.

4.1. Effect of Silvicultural Treatments (Clear-Cut vs. Thinning) on Productivity

The productivity of machines varied depending on silvicultural treatments. The mean productivity rates of the thinning and clear-cut prescriptions were 1.6 and 2.0 m^3/PMH/worker, respectively (Figure 2). The mean yarding distances for thinning and clear-cut were 64 m (range, 40–118 m) and 72 m (range, 30–131 m), respectively. The mean productivity of the clear-cut was 25% higher than that of the thinning treatment for a higher cycle log volume, whereas there was no significant difference between the productivity distributions (ANOVA p-value = 0.4727). The cycle log volume conditions showed significant differences between the two silvicultural treatments (ANOVA p-value < 0.001), whereas there was no significant difference in yarding distance (ANOVA p-value = 0.2760) or harvesting method (ANOVA p-value = 0.2935). The productivity of machines generally increased by $\leq$30% within a cable-based clear-cut stand at the final harvest due to the handling and volume of trees [48,49]. Hartley and Han [50] reported that the trees left standing in thinning areas interfered with the choker setter movement and latera-cable-in process. Our analysis showed that cleat-cut can be 25% more productive than thinning. This is because of the cycle log volumes requiring large-diameter trees, which makes clear-cut more productive than thinning [48,50]. As a result, clear-cut cable yarding technology is more productive than thinning prescriptions.

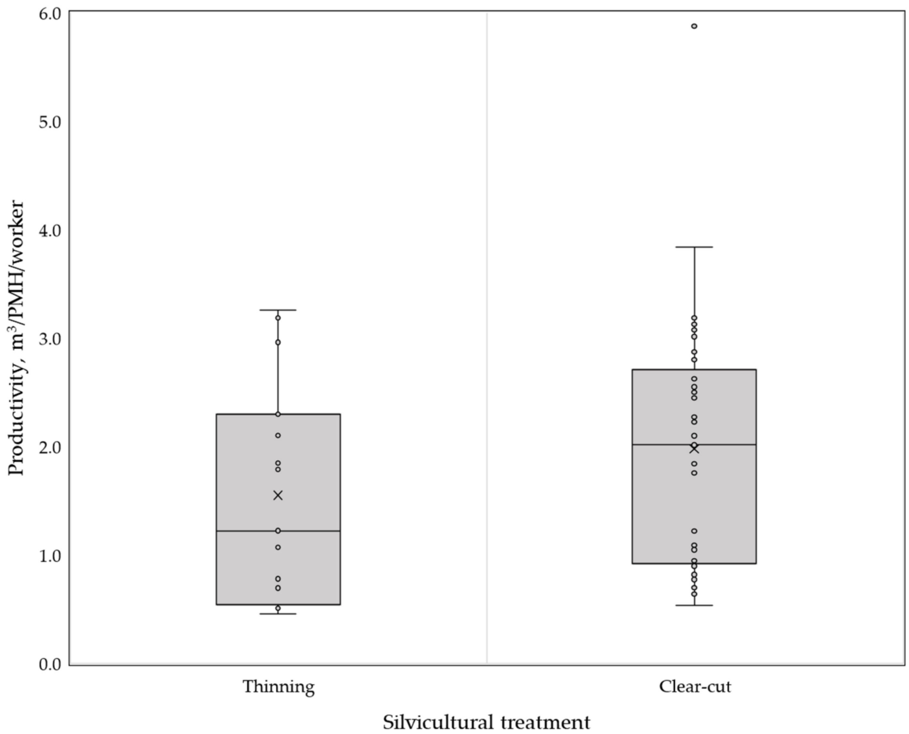

Figure 2. Changes in productivity evaluated for thinning and clear-cut treatments at mean yarding distances of 64 and 72 m, respectively. The circles are data points, and the × is the mean value.

4.2. Effect of Harvesting Method (Whole-Tree vs. Tree-Length) on Productivity

The productivity of tower yarders based on harvesting methods (tree-length thinning, whole-tree thinning, tree-length clear-cut, and whole-tree clear-cut) were 2.0, 0.7, 2.0, and 1.7 m^3/PMH/worker, respectively (Figure 3). Whole-tree thinning resulted in a significantly lower productivity than tree length (ANOVA p-value = 0.0137), and there was no difference in clear-cut (ANOVA p-value > 0.5). The cycle log volume was significantly higher in thinning than in the whole-tree harvesting method (ANOVA p-value < 0.001), whereas the yarding distance was not different. Han and Han [51] showed 60% higher cycle log volumes of 2.3 m^3/cycle in the tree-length and 1.4 m^3/cycle in the whole-tree harvesting methods. The cycle log volume was lower in the whole-tree harvesting method, because it required an additional volume of foliage, branches, and tree tops simultaneously during landing. Thus, the tree-length harvesting method may have a higher performance and cost efficiency than the whole-tree method if logging residues are not readily available.

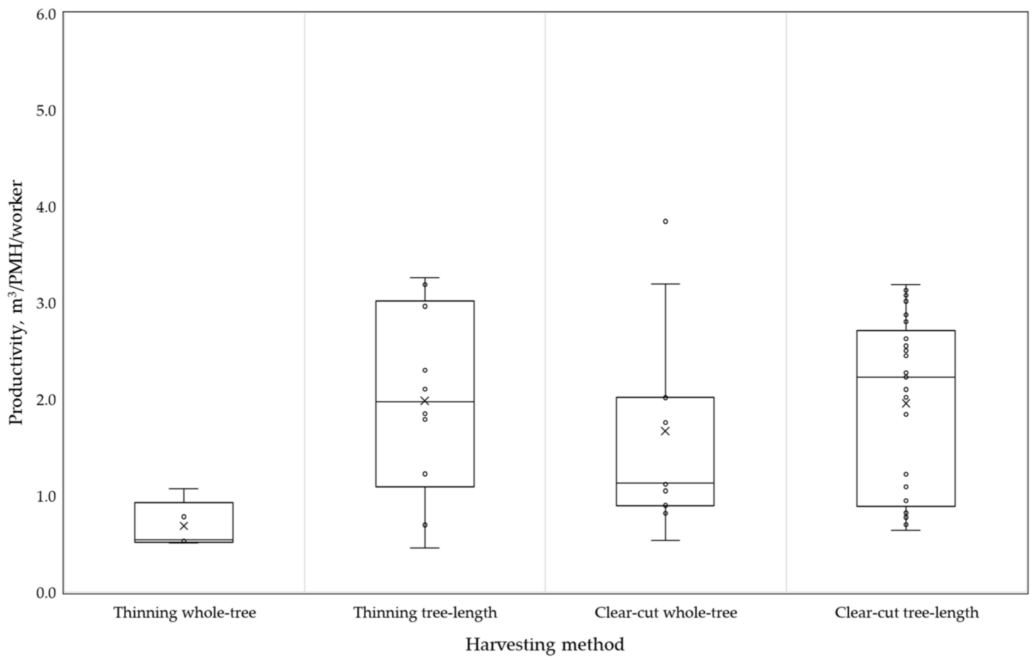

Figure 3. Changes in productivity evaluated for whole-tree and tree-length harvesting methods between two different silvicultural treatments: mean yarding distances of 54 and 69 m in thinning, and 70 and 72 m in clear-cut, respectively. The circles are data points, and the × is the mean value.

4.3. Effect of Yarding Directions (Uphill vs. Downhill) on Productivity

In the literature, we are able to collect operational data in two different yarding directions (i.e., uphill and downhill) for both silvicultural treatments, such as thinning and clear-cutting (Figure 4 and Table 1). Although there were no significant differences in yarding distance between the two yarding directions (ANOVA p-value = 0.2160), the productivity of the machines for uphill yarding increased from a 12% to 49% production rate compared to downhill yarding activities. The productivities were not significantly different in thinning (ANOVA p-value > 0.05), whereas there was a statistically significant difference between the yarding directions during the clear-cut operation (ANOVA p-value = 0.0132). In addition, the cycle log volume was significantly higher in uphill yarding, particularly in the clear-cut treatment, and the interactions of the yarding direction with the cycle log volume significantly affected the productivity (ANOVA p-value < 0.001). For example, the yarding direction may have affected the productivity for several reasons, such as the carriage movement and stops associated with the haulback line, and operator safety problems when the tower yarders HAM300 [39], K507 [52,53], and URUS MIII [54] were used. Thus, uphill yarding operation activities are more productive than downhill yarding activities.

4.4. Effect of Machinery on Productivity

The large variation was also obvious when the machinery model was compared (Figure 5). Although machinery variables make it difficult to compare productivity due to differences in the model year of the machinery [17,55], our results implied that a productivity increase in the clear-cut operations was attributed to a large lifting capacity (up to 2.7 t) and machine power (kW, up to 100 kW; Figures 6 and 7). These rates were significantly correlated with two different variables (Pearson's correlation, $p < 0.05$). This finding is consistent with those of previous studies such as Schweier et al. [56], Baek et al. [10], and Picchio et al. [57], who reported that higher load capacities of yarders enable better performances, because they can control larger cycle log volumes compared to the machinery with low lifting capacities. This could be related to the low piece volume reported by Ghaffariyan [58] and Berendt et al. [59], whose findings showed that increases in the harvesting productivity were associated with large log volumes, even though the extraction time per cycle increased. Consequently, the lifting capacities and machine powers of tower yarders affect their productivity. Further, proper decision-making regarding yarders may lead to increased productivities, because yarders with larger load capacities are not always more productive than those of lower lifting capacities.

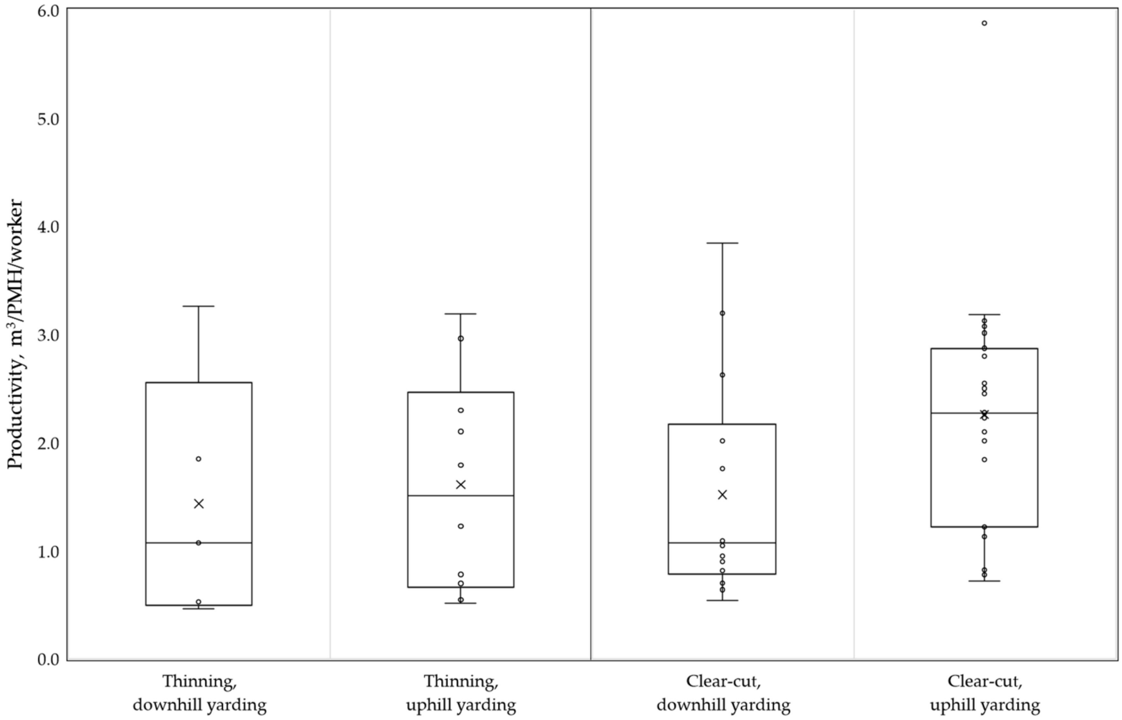

Figure 4. Changes in productivity evaluated for uphill and downhill yarding activities under different silvicultural treatments: average yarding distances of 64 and 72 m in thinning and 77 and 64 m in clear-cut, respectively. The circles are data points, and the × is the mean value.

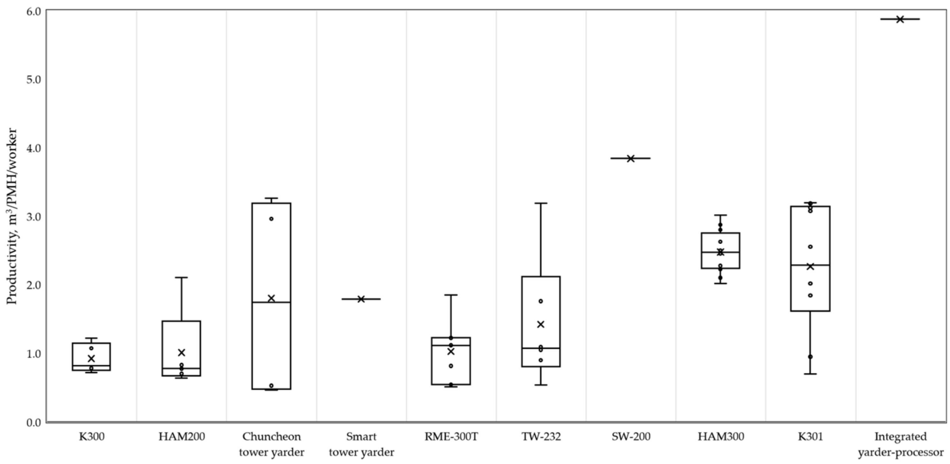

Figure 5. Summary of the variation in productivity among several tower yarders. The circles are data points, and the × is the mean value.

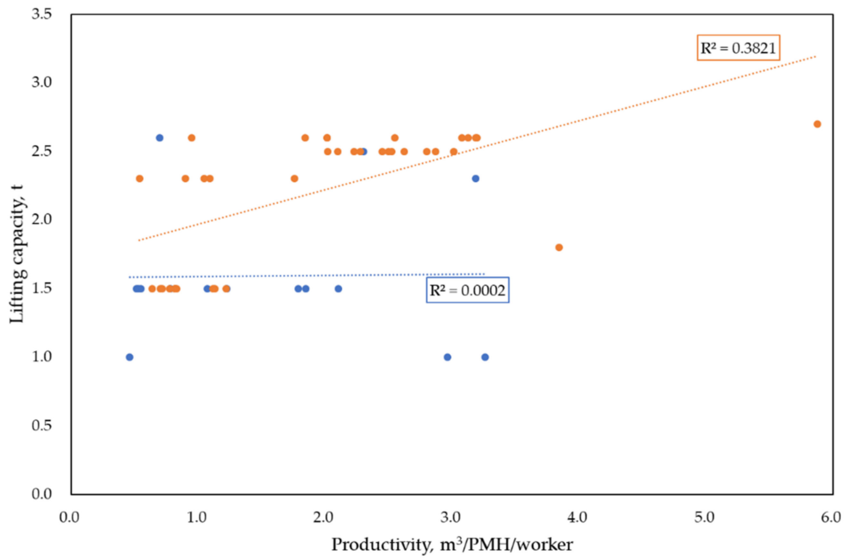

Figure 6. Productivity relationship with the lifting capacity. Productivity had a moderate correlation with two independent variables in clear-cut, whereas it had no correlation in the thinning operation.

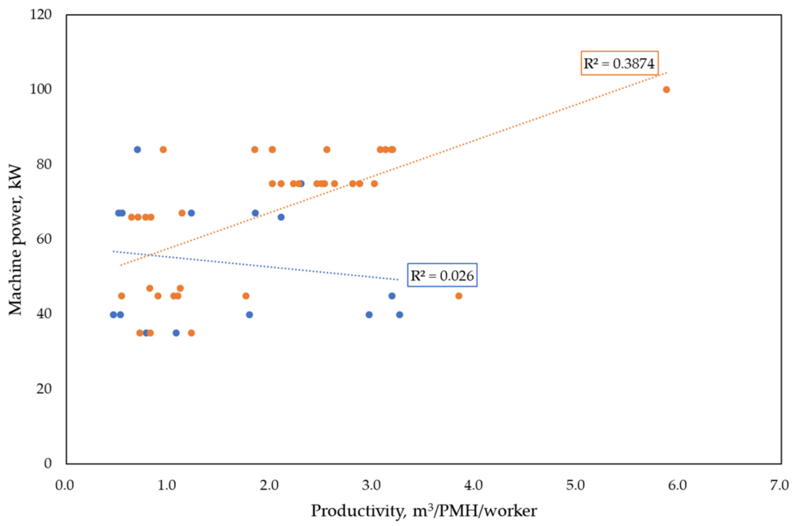

Figure 7. Productivity relationship with machine power. Productivity had a moderate correlation with two independent variables in clear-cut, whereas it had no correlation in the thinning operation.

Under thinning operations, the lifting capacity had no significant correlation or pattern with the productivity rates (Pearson's correlation $r = 0.0076$; Figure 6). In addition, the machine power had a weak-to-small negative correlation with productivity (Pearson's correlation $r = -0.1761$; Figure 7). The low productivity of more powerful machines may have caused the remaining trees within a stand. For example, trees left standing in thinning areas can obstruct extraction activities and operator visibility [50]. Thus, in terms of thinning extraction activities, there was no correlation between productivity, lifting capacity, and machine power.

4.5. Effect of Yarding Distance on Productivity

In our literature review, the yarding distance had a weak-to-moderate or small negative correlation in both silvicultural treatments (thinning and clear-cut): Pearson's correlations were $r = -0.2640$ and -0.1105, respectively (Figure 8). Our analysis results were consistent with those of previous studies, such as those by Ghaffariyan et al. [58] and Varch et al. [60], who reported that increasing the yarding distance will increase the extraction time consumption. Therefore, the time consumption per log volume (m^3) increased with increasing the yarding distance, which may lead to lower productivity. Accordingly, the extraction productivity tends to decrease with increasing the yarding distance.

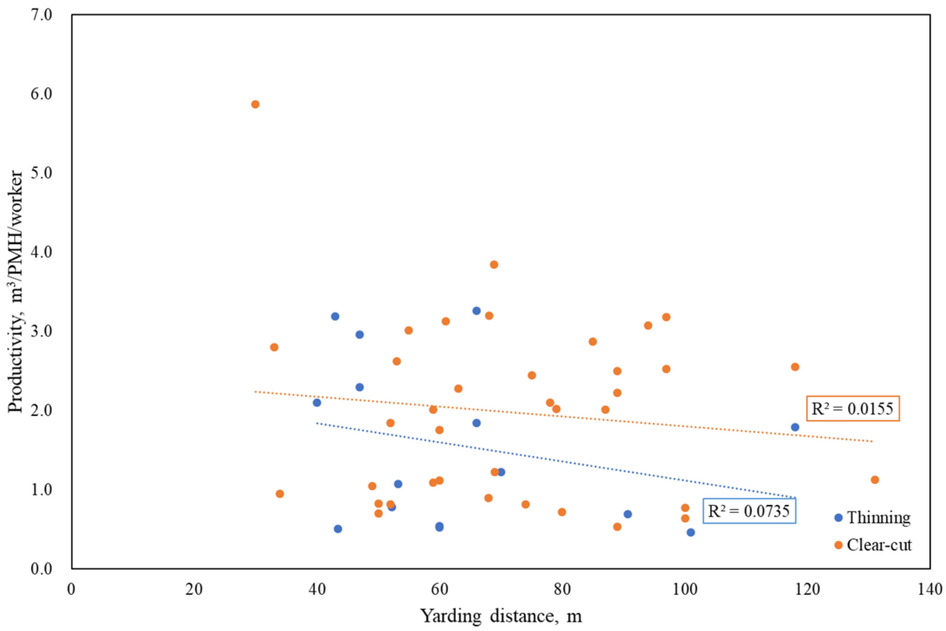

Figure 8. Productivity relationship with the yarding distance, and it had a weak-to-moderate (thinning operations) or small (clear-cut activities) negative correlation.

A wide range of yarding distances have been reported previously, ranging from 30 to 130 m (Figure 8 and Table 2). In our analysis, no source of data on productivity could be found for extractions exceeding 150 m in yarding distance.

4.6. Effect of Slope on Productivity

Although a broad range of slopes (36–60%) have been studied previously, the slope had no significant correlation with productivity in thinning operations (Pearson's correlation *p*-value = 0.3115). However, there was a weak-to-moderate correlation between productivity and slope variable (Pearson's correlation *r*-value = 0.3046; Figure 9). According to Ghaffariyan et al. [61], an increased slope can have a negative influence on cable yarding productivity. However, our results imply that the slope did not significantly impact the productivity during thinning operations. Furthermore, Spinelli et al. [62] reported that slope is not an available correction measurement and that yarding distance could be available on actual routes.

Our results imply that the slope had a significant correlation with the productivity rates for clear-cut operations (Pearson's correlation *p*-value < 0.001; Figure 9). Ghaffariyan et al. [61] reported that slope had a negative influence on the extraction time consumption and that it increased with increasing the yarding time per cycle. Furthermore, a steep slope operation may challenge the choker setter movement and present a high risk of accidents to workers. For these reasons, productivity decreases with the increasing slope.

4.7. Machine Utilization Rates

Machine utilization rates are defined as the proportion of productive to scheduled machine hours. As shown in Figure 10 and Table 4, previous studies have been conducted regarding machine utilization rates. These variables decreased with slight changes within the 20-year period from 2000 to 2020. For example, Spinelli et al. [12], Picchio et al. [56], and Varch et al. [60] found that machine utilization rates accounted for 77%–93% for uphill yarding, particularly in Europe. Our results, which showed an overall mean machine utilization rate of 66%, were considerably lower than that in previous studies. This may be influenced by operation skill and experience. Purfürst [63] and Hiesl and Benjamin [55] reported that the productivity levels differed between less-trained and experienced operators. In addition, operators attained the end of their learning curve after approximately 1000–1500 PMH of harvester operation. As a result, in Korea, cable-yarding workers lacked adequate training and experience, even though timber extraction by cable yarding was introduced in the mid-1980s.

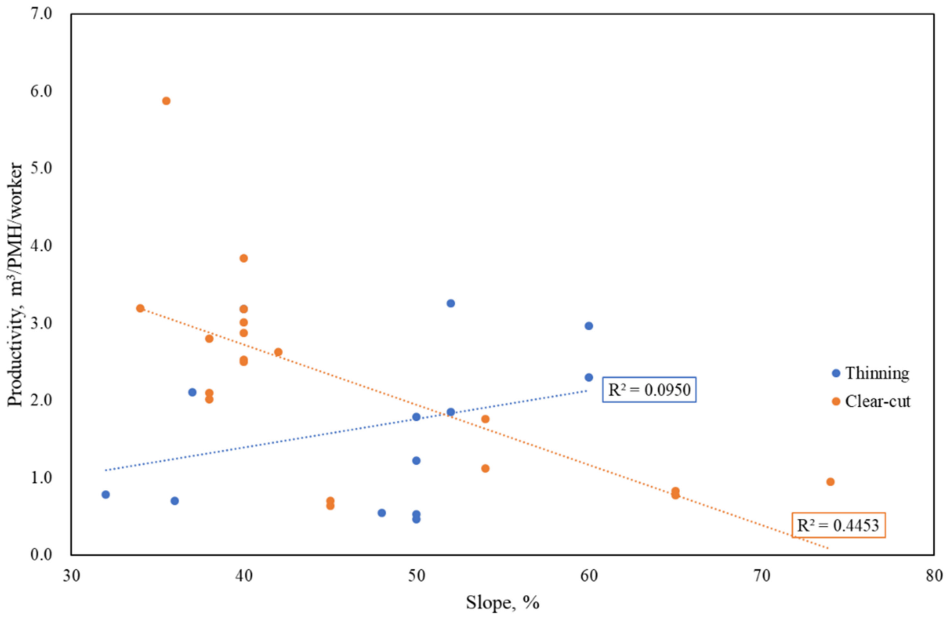

Figure 9. Productivity relationship with the slope. This rate had a weak-to-moderate correlation with slope in thinning operations, whereas it had a significant correlation in clear-cut operations.

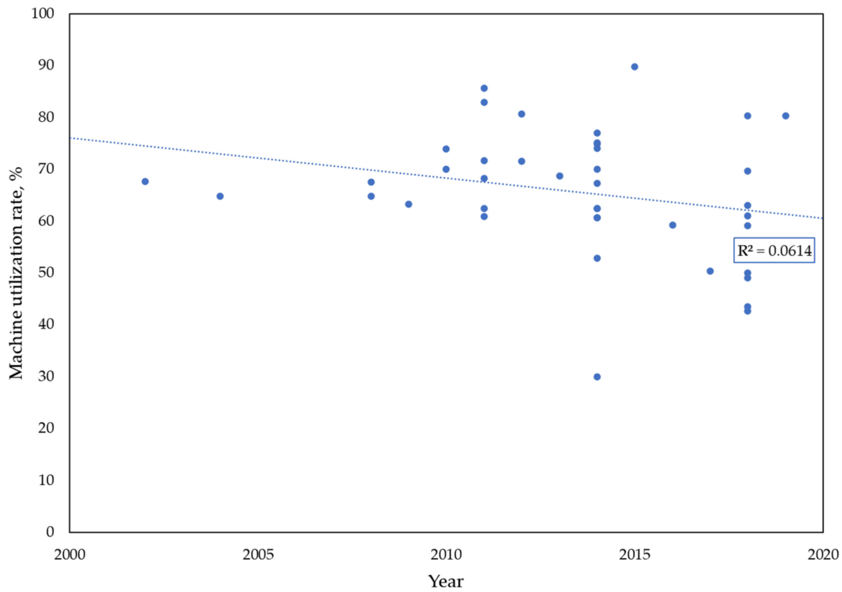

Figure 10. Changes in the machine utilization rate during the 20 years from 2000 to 2020, Korea.

5. Conclusions

5.1. Purpose of Review

The objectives of this review were:

- To inform on the types of tower yarder activities and the availability of machine productivity data over the last 30 years;
- To compare the productivity rates of nine different tower yarders in different silvicultural treatments (thinning and clear-cut); harvesting methods (cut-to-length, tree-length, and

whole-tree); and yarding direction (uphill and downhill) on a per-productive machine hour per worker basis over the last 20 years;
- To determine the effects of machine type, yarding distance, and slope on the productivity rates of tower yarders based on PMH/workers.

5.2. Summary of Findings

A literature investigation was performed to collate the available published productivity rate data for tower yarder operation activities. The data availability varied according to silvicultural treatments, harvesting methods, yarding conditions, and machine types. The available data on thinning operations were fewer than the clear-cut trial data. Tree-length and whole-tree harvesting data were available from many sources, whereas cut-to-length data were available from only a few sources. Data regarding the smart tower yarder, SW-200, and integrated yarder processor were available from only one dataset. Sometimes, data on the yarding distance and slope data were missing, and there were narrow-range sources.

The tower yarder productivity rates were primarily evaluated to be higher in clear-cut treatments, the tree-length harvesting method, and in the uphill yarding direction compared to other operation activities. Most independent variables influenced the productivity, except for the lifting capacity, machine power, and slope in thinning operations, as concluded from the current review of previous studies. In addition, the overall mean machine utilization rate was lower than that in previous studies, which was associated with a lack of personnel with adequate training and experience.

5.3. Data Gaps and Future Research

Previous studies have the potential to provide significant data regarding tower yarder operations, which can be used to optimize decision-making; however, there are information gaps that should be filled by future research. Therefore, future research, which may provide additional data of concern to optimize decision-making, should include the following:
- Trial tests for longer yarding distances (ranging from 150 to 500 m);
- Trial tests for the smart tower yarder, SW-200, and integrated yarder processor;
- Trial tests for the operator's effect on machine productivity;
- Trial tests for the choker setter size effects on machine productivity;
- Automated data recording systems within steep slopes;
- Time required for the operator's learning curve.

Author Contributions: Conceptualization, E.-J.L., K.-H.C., J.-H.O., S.-K.H. and S.-J.I.; methodology, E.-J.L., Y.-S.C., M.-J.C., K.-H.C. and J.-H.O.; validation, E.-J.L., Y.-S.C. and M.-J.C.; formal analysis, E.-J.L., Y.-S.C. and M.-J.C.; investigation, E.-J.L., Y.-S.C. and M.-J.C.; resources, E.-J.L., Y.-S.C. and M.-J.C.; data curation, E.-J.L., Y.-S.C., and M.-J.C.; writing—original draft preparation, E.-J.L., Y.-S.C. and M.-J.C.; writing—review and editing, E.-J.L., K.-H.C., J.-H.O., S.-K.H. and S.-J.I.; visualization, E.-J.L., K.-H.C., J.-H.O., S.-K.H. and S.-J.I.; supervision, E.-J.L.; project administration, K.-H.C.; and funding acquisition, K.-H.C. All authors have read and agreed to the published version of the manuscript.

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