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Comparison of Cut-to-Length Harvesting Methods in Tree Plantations in Brazil

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Abstract: The aim of this research was to determine the most productive tree-cutting methods, and the factors influencing them, in flat and sloping terrains in tree plantations in Brazil. The study utilized drone-captured video material from harvesting operations in *eucalyptus* and *pine* plantations. In both terrains, two cutting methods were compared, differing in the felling to the side method used: either at the edge or inside of the harvesting front. In addition, on flat terrain, the efficiency of forward felling was studied in relation to the aforementioned cutting methods. In sloping terrain, the machines were also equipped with a winch assistance system. The time study data of the harvesting work were processed using a video analysis tool developed for the research. The output data of the cut trees were collected with the automatic measuring system of the harvester. Statistical tests were used to determine the most productive cutting methods by analyzing differences in productivity. With an average tree size of 0.3 m^3, cutting productivity was 45 m^3/E_0h in *pine* cuttings and 55 m^3/E_0h in *eucalyptus* cuttings. The average cutting productivity on flat terrain was about 11 m^3/E_0h higher than on sloping terrain, mainly due to the time spent attaching the winch assistance system, which was a necessary phase of the work on sloping terrain. The research results suggest that it would be most productive to use sideways felling inside the harvesting front method. However, the need for further research is evident, if we want to precisely identify the factors and work phases in the tree-cutting cycle affecting differences in the productivity of the harvesting chain in tree plantations.

Keywords: time study; productivity study; cut-to-length method; harvester; forwarder; *Eucalyptus*

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1. Introduction

1.1. Background

In the fully mechanized cut-to-length (CTL) harvesting method, stems are bucked into logs in the forest, facilitating the development of relatively lightweight forest machines and appropriate tree-cutting methods for these machines [1]. The machines used in CTL include a combination of either tracked or wheeled harvesters and tracked or wheeled forwarders [2–4]. Modern wheeled harvesters, manufactured by Ponsse in Vieremä and John Deere in Joensuu in Finland, use cranes with a reach of approximately 10 m [5–7]. This reach allows for selective thinning, preserving the best trees for future growth, thereby enhancing the overall value of trees and forests. This approach ensures that both trees and forests increase in value, and high-quality timber can be obtained during later thinnings or final felling. Additionally, the CTL method is gaining social acceptance as a harvesting method for nature conservation management in sustainable forestry, due to its smaller ecological footprint, profitability in harvesting small stands, and the benefits of selective thinning [8–10].

The CTL method facilitates wood procurement operations in tree plantations in several beneficial ways compared to the tree-length method [1,11]. Firstly, wood harvesting using

CTL is more profitable because fewer machines are required at the harvesting site [12]. Typically, a machine fleet consists of a harvester and a forwarder, where the harvester fells, delimbs, measures and cuts trees for wood assortment according to market needs. After the cutting, a forwarder performs the forest hauling of the separately stacked timber assortments from the forest to a roadside storage area. Secondly, the CTL method requires a small roadside storage area, because the bucking has already been performed in the forest, and there is no need for a special machine for this work phase. Typically, timber transport takes place rather soon after the logs have been hauled by the forwarder to the roadside [13]. This possibility keeps the storage area at a manageable size. Timber trucks can be equipped with cranes for loading and unloading the logs, to perform long-distance transport to terminals, railway stations or production plants. Thirdly, because the stems have already been cut optimally in the forest, the sawmill can sort the logs into separate batches according to their diameters before the sawing process even begins [14]. These kinds of batches can be sawn at a higher line speed, because all the logs being fed into the saw are in the same diameter class, meaning that the saw's settings do not have to be changed for each log separately.

Because the trees are delimbed and cut to logs in the forest, the mass of leaves, needles, branches and the crown—all of which contain large amounts of nitrogen, phosphorus and potassium—remain in the forest [5]. This saves site nutrient reservoirs and ensures a nutrient supply for the remaining stand or planted seedlings and reduces the need for fertilization. At ecologically fragile harvesting locations, CLT facilitates that the harvester also lays down a carpet made from branches and the tops of the delimbed stems over which the forwarder drives, thereby protecting the soil from compaction. When it comes to damage to the environment such as tire tracks or broken trees, the CTL method also exerts significantly less environmental impact than the tree-length method [15–17]. Therefore, CTL is seen as an environmentally friendly method [5].

1.2. Timber-Harvesting Productivity Studies on Eucalyptus Plantations

In South America, the tree-length method as a harvesting method is gradually being replaced by the CTL method. In recent years, the CTL method has also become the most important of the mechanized harvesting methods used in Brazil [18]. The competition of land use is high between *eucalyptus* cultivation areas and agriculture in Brazil. For this reason, a significant portion of tree plantations have been established on steep slope terrains. The impact of slope has been considered in several productivity studies of *eucalyptus* plantation harvesting [2,4,19–21]. These studies have found that a slope has little effect on logging productivity, and the impact on productivity only appears on particularly steep slopes. In these conditions, the productivity of tracked harvesters designed for logging remains more stable, compared to cutting machines built directly on the base of an excavator [21].

In previous productivity assessments of *eucalyptus* plantation wood harvesting, the emphasis has been on the characteristics of the harvesting machine and particularly on the impact of the harvesting conditions. These studies have compared the costs and productivity of the tree-length and CTL methods on *eucalyptus* plantations [22,23]. Despite a slightly lower productivity, the CTL method has been found to be a competitive method in terms of cost, especially if logging residues are to be left on the site [22,23]. On the other hand, logging residues as whole wood or small logs may be harvested for energy wood, which is an economically valuable fuel, compensating for a low productivity.

The tree species of *eucalyptus* plantations has also been a focus of productivity studies. Within the *Eucalyptus* genus (*Eucalyptus* spp.), nine species are utilized in commercial plantations. It has been observed that the species has a statistically significant effect on harvesting productivity [21]. When the impact of the stem form of *eucalyptus* on harvesting productivity was studied, productivity was lower on trees with thick branches and on trees with a curved or crooked stem, compared to good-quality trees [24].

Eucalyptus plantations can be regenerated either by planting or naturally using stumps, allowing one or more stems to sprout from the same stump. The highest harvesting productivity levels have been achieved with planted single-stem trees, and the harvesting of naturally regenerated single-stem trees has been found to be the next most productive [23]. On the other hand, a skilled harvester operator can handle single- and double-stemmed *eucalyptus* trees with the same productivity; the productivity difference has been observed only among less skilled operators [25]. As the planting spacing increases in *eucalyptus* plantations, harvesting productivity also rises [20]. Similarly, pre-harvest chainsaw felling [2] and initial thinning enhance the harvesting productivity of *eucalyptus* on its final felling.

The productivity of *eucalyptus* plantation harvesting has been extensively studied in the native regions of *eucalyptus* in Australia [23,26], as well as, notably, in South Africa [21,23,25] and Brazil [18,20,27,28]. Studies have also been conducted in California [22] and the Iberian Peninsula [2]. However, the productivity of *pine* plantations has more seldom been a focus of previous studies [25,29]. In Table 1, average productivity figures comparable to this study have been compiled from some previous studies, where the average volume of tree size, however, varies considerably.

Table 1. Productivity studies of CTL method from tree plantations. EH = excavator-based harvester, WH = wheeled harvester.

Authors of Study	Year	Harvester Model	Species	Country	Tree Size (m^3)	Productivity (m^3/h)
Spinelli et al. [2]	2002	EH	*Eucalyptus* spp.	Spain, Portugal	0.11–0.26	5–14
Norihiro et al. [21]	2018	EH	*Eucalyptus* spp.	South Africa	0.12–0.38	13.8–27.5
Ramantswana et al. [24]	2013	EH	*Eucalyptus* spp.	South Africa	0.21	16.1
McEwan et al. [25]	2016	EH	*Eucalyptus* spp.	South Africa	0.47	24.8
Ackerman et al. [29]	2017	EH	*Pinus* spp.	South Africa	1.05	54.13
Martins et al. [28]	2009	WH	*Eucalyptus* spp.	Brazil	0.25	17
Seixas and Batista [18]	2014	WH	*Eucalyptus* spp.	Brazil	0.29	19.1

Eucalyptus trees are typically debarked during the processing of the stem, immediately after the felling phase in the tree-cutting cycle, as the bark adheres tightly to the stem when it dries. The degree of debarking has been found to impact harvesting productivity [22]. In most of the presented studies, stems were likely debarked, which naturally increased the time required for harvesting.

1.3. Harvesting on Sloping Terrain Forests

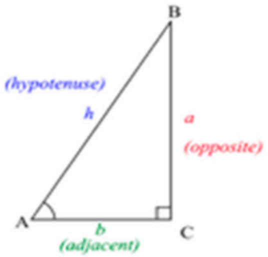
In planning harvesting operations on sloping terrain forests, the harvesting conditions, such the topsoil type, weather, and steepness of the slope, must be considered in advance. The steepness of the slope can be expressed in degrees and in percentage terms (Figure 1). In steep slopes, the concepts of the average and operational slope are also used. To obtain the operational slope, the angle on-site is monitored by the operator at the beginning and during the operation. Depending on the terrain, the maximum usable slope for harvesting can be up to 30–35 degrees, corresponding to about 58–70 percent (Figure 1).

Machine operators can operate on steep slopes with traction-assisted harvesting machines, which consist of wheeled harvesters and forwarders, including a winch, seat levelling system, reversing camera, tracks in all bogies, steel cable, inclinometer, etc. [30–32]. There are two basic groups of winches used: winches mounted on a machine (described within the article) and T-winches that are not used in the study. When traction assistance is used, it is possible to work with the same CTL harvesting chain as on flat terrain, although anchoring times have a negative effect on the productivity of harvesting (Figure 2). In sloping terrain, traction assistance is also necessary for safety reasons during both cutting and forwarding [33,34]. The use of winch-based traction assistance causes additional work phases such as attaching and removing the anchoring, but during the actual cutting work or loading work, the operator can work regardless of the use of the winch, as the system automatically adjusts the speed of the winch in relation to the driving speed of the forest machine.

slope in %

$$= \frac{opposite(a)}{adjacent(b)} \times 100$$

$$= \tan(A) \times 100$$



degrees	%
45	100 %
40	84 %
35	70 %
30	58 %
25	47 %
20	36 %
15	27 %

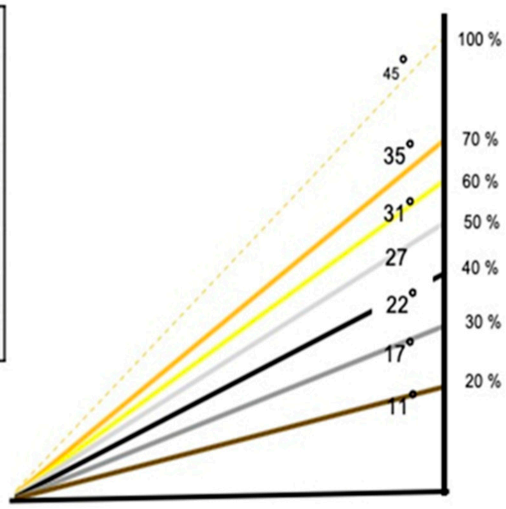


Figure 1. The slope is expressed in degrees and in percentages.

Figure 2. Ponsse Ergo harvester with Ponsse Syncrowinch winch assistance has been anchored to the stump.

Typically, work with winch assistance-mounted machines is carried out in a downhill direction. The limiting factor in this case is the operative length of the winch cable (330–340 m). The winch assistance weighs about 1900 kg, and it is installed in front of the engine of the harvester and on the rear frame of the forwarder. The winch is attached on the top of the slope to a stump, a tree or another machine. The cable is 14.5 mm thick and allows a tensile strength of 20 tons. With winch assistance, a pulling power of 0–7 tons can be achieved in cutting machines and a pulling power of 0–10 tons in forwarders [35].

If the slope is steep, the risk of loss of traction increases and consequently the risk of getting stuck also increases. Therefore, changes in the harvesting conditions, like weather, must be taken account of more carefully in advance. In addition, the logs may slide downhill if they are left parallel to the slope. Therefore, there is a need to stack logs in a perpendicular direction on sloping terrain. It is also possible that the stacks may need to be supported in some way.

From the forwarding point of view, the load space is typically on the uphill side, where there is no risk of logs sliding away from the load space. There is also a risk of reversing the forwarder onto too steep terrain when the load space is on the downhill side, and it is not possible to use the traction assistance system. However, a decision about the forwarding direction should be made by following the local circumstances, not by "automatically" selecting the traditional way of a downhill direction.

In addition to understanding technical issues, the harvesting staff must be well educated for work with the winch system. In this respect, the planning of the anchoring zone should be performed in advance and finalized on the harvesting site, where the difference between the average and absolute (operational) slope is important to note for a determination of the maximum degree of slope. The maximum slope in the case of traction assistance is always the operational slope. In addition, the selection of the anchor stump is fundamental to the safety of the operation and should be carried out in accordance with all recommended technical criteria. In addition, to establish a safe working method, both the operator and the planning staff must be familiar with the local conditions and tree species [34].

In addition to environmental characteristics, the efficiency of harvesting is influenced by the manner in which the trees are felled around the harvester's workplace. The operator plays a crucial role in determining the direction in which the trees are felled in relation to the strip road, the positioning of the harvester in relation to the trees to be felled, the size of the piles made from the trees, and the angle at which the piles are placed in relation to the strip road for forwarding. These variables, referred to as the cutting method, have been empirically shown to impact both the productivity and the quality of the harvesting operation [36]. Despite extensive research on the productivity of *eucalyptus* plantation timber harvesting and documentation of the employed cutting method, the detailed cutting method has not been systematically adopted as a classifying variable in the dataset. A notable challenge in such studies is finding machine operators capable of working with different cutting methods with consistent efficiency.

1.4. Aims of Study

The main aim of this research was to find out the most productive CTL cutting method for flat and sloping terrain on *eucalyptus* or *pine* plantations. In both terrains, two sideways cutting methods were compared: sideways felling at the edge of the harvesting front and sideways felling inside the harvesting front. In addition to sideways cutting methods, one forward cutting method was studied on flat terrain: forward felling in the middle of the harvesting front. Comparisons of the alternative CTL methods were made using statistical tests. The possible effects of influencing factors are considered in the Discussion section, to find out how they may affect the results of the most productive CTL methods.

2. Material and Methods

2.1. Study Area and Material

The material was collected in 2022 from three tree plantations. The plantations were in the state of Paraná in southern Brazil, near the border of Argentina and Paraguay (Figure 3).

The work study focused on two forest machines (Table 2). In this way, it was possible to minimize the impact of forest machine characteristics on productivity. The harvester was a Ponsse Ergo wheeled harvester. The forwarder, the Ponsse Elephant King, was suited for forest hauling, with its 20-tonne load-carrying capacity. The forest machines were equipped with the Ponsse Syncrowinch winch system [35]. Both machines were powered by the same type of efficient diesel engine, and the machines were also equipped with tracks.

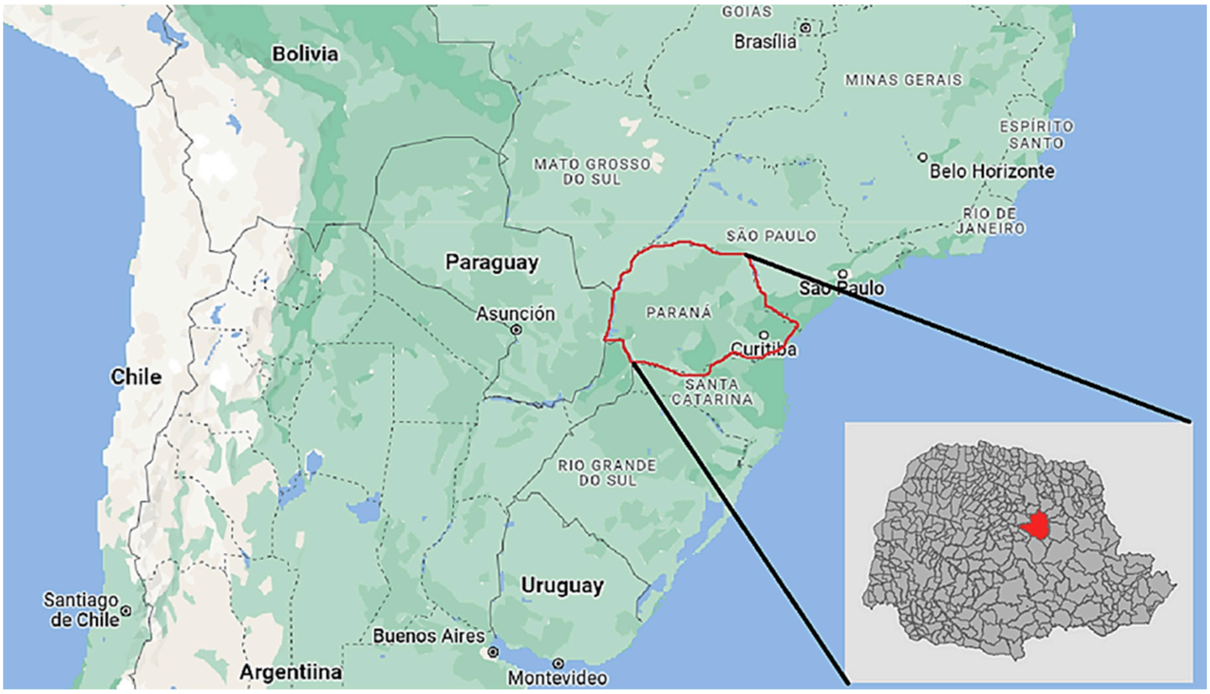


Figure 3. Stands located in the state of Parana in southern Brazil.

Table 2. Technical characteristics of the forest machines in the study.

Characteristic	Ponsse Ergo H7 C5 Harvester	Ponsse Elephant King Forwarder
Operating mass (with accessories), kg	24,650	23,900
Engine power, kW	205	205
Traction force, KN	195	240
Engine torque, rpm	1100	1100
Boom reach, m	9.5	10.0
Wheels, "	26.5 "	26.5 "
Tracks	Yes	Yes
Year of manufacturing	2016	2016
Operating hours, h	22,235	20,459

" = an inch i.e., 2.5 cm.

Selecting the combination of harvester head, harvester and forwarder requires that the features of the machines be compatible with the features of the forest and trees. The most important selection criteria are average tree size (m^3/ha) and stocking in the plantation (trees/ha) to be harvested [28]. *Eucalyptus* forest is an example that has a high stocking. Further, the average tree size is typically 0.2–0.3 m^3, allowing use of smaller harvester heads from the category of harvester heads (Table 1). In this case, the harvester was equipped with the H7 Euca harvester head developed specifically for the processing of *eucalyptus* trees.

There were four forest stands for the comparison of CTL methods (Table 3). The main characteristics varying between the stands were the degree of slope and tree species. The terrain was categorized into two classes: flat and sloping. In the stands representing sloping terrain harvesting methods, the average slope was 10%–15% higher than in the flat terrain harvesting methods. When looking at the slope, the operative slope of the machine's working point must be distinguished from the average slope of the forest stand (Figure 1). Further, due to the gradually steepening shape of the slopes, sloping terrain harvesting methods were partly worked on operative slopes significantly higher than the average slope. Therefore, the cutting methods needed harvesting-assisting equipment on the sloping terrain, which affected the time consumption, productivity, performance and profitability of the human–machine systems.

Table 3. Characteristics of four stands for comparison of CTL harvesting methods. DBH = diameter at breast height.

Characteristic	1	2	3	4
The main tree species	*Eucalyptus saligna*	*Pinus taeda*	*Eucalyptus saligna*	*Pinus taeda*
Slope of terrain, %	17.5	22.5	7.5	7.5
Number of trees, trees/ha	1650	1350	1650	1350
DBH, mm	184	205	178	210
*) Tree's stem length, m	21.3	13.3	22.1	15.1
Tree's stem volume, m^3	0.416	0.315	0.386	0.366
Samples	4	4	6	3

*) Length was measured by harvester as sum of lengths of cut logs.

The type of tree species varied between the stands. The main tree species in *pine* plantations was loblolly *pine* (*Pinus taeda*), and in *eucalyptus* plantations, it was Sydney's *eucalyptus* (*Eucalyptus saligna*). The tree species differed considerably in their stem shape. The *eucalyptus* trees' working part of stem was very uniform in thickness. While the average tree diameter at the breast height (205–210 mm) in *pine* plantations was slightly larger than in *eucalyptus* plantations (178–184 mm), the average stem lengths of *eucalyptus* plantations (21.3–22.1 m) were significantly higher than the average stem lengths of *pine* plantations (13.3–15.1 m). The pines were also smaller than the *eucalyptus* trees in their average volume per tree (m^3). In addition, the thick branches of *pine* trees extended lower, as compared to *eucalyptus* stems.

The spatial distribution of trees in the stands was even, since the trees were planted in rows. The tree-planting density in *eucalyptus* plantations was 1650 trees/ha, while in *pine* plantations, it was a little lower, 1350 trees/ha. The density of stands at the moment of cutting corresponded to the planting density, because these short-rotation forests were not thinned during the growing rotation. Therefore, the mean distance of the trees was high, and this characteristic may be effective as the influencing factor.

2.2. Cutting and Forwarding Methods in Harvesting

Figure 4 describes three different cutting methods that were used on flat terrain. In this respect, two sideways (A and B) and one forward-felling (C) cutting methods were compared to each other. On the sloping terrain, two cutting methods (D and E) applied sideways felling (methods A and B), but with winch assistance for the harvester and forwarder.

A total of 17 harvesting samples were prepared as the datasets of the four stands on flat and sloping terrain (Table 3). Each operator processed 100 trees per sample. Table 4 consists of the average size of the trees (m^3) in the samples of harvesting methods on flat terrain.

The study layout of cutting and forwarding methods is presented in Table 5. Table 5 also depicts the abbreviations of the forwarding methods after the respective cutting method. There, A means sideways felling at the edge of the harvesting front, B is sideways felling inside the harvesting front and C is forward felling in the middle of the harvesting front. D means sideways felling at the edge of the harvesting front with traction assistance, and E is sideways felling inside the harvesting front with traction assistance. AL means forwarding after sideways felling at the edge of the harvesting front, BL is forwarding after sideways felling inside the harvesting front, CL is forwarding after forward felling in the middle of the harvesting front, DL is forwarding after sideways felling at the edge of the harvesting front with traction assistance and EL is forwarding after sideways felling inside the harvesting front with traction assistance.

Figure 4. Two sideways (A,B) and one forward-felling (C) cutting method on flat terrain.

Table 4. The average size of trees (m^3) in samples of cutting methods on flat terrain: A = sideways felling at the edge of harvesting front, B = sideways felling inside the harvesting front, C = forward felling in the middle of the harvesting front, E = *Eucalyptus*, P = *Pine*, 1 = Operator 1, 2 = Operator 2.

Tree Species/ Operator	A	B	C
		m^3	
E1	0.414	0.319	0.436
E2	0.413	0.418	0.432
P2	0.290	0.287	0.351

Table 5. Study layout of cutting and forwarding methods. A = sideways felling at edge of the wood harvesting front, B = sideways felling inside the wood harvesting front, C = forward felling in the middle of the wood harvesting front. D = sideways felling at edge of the wood harvesting front with traction assistance, E = sideways felling inside the wood harvesting front with traction assistance. AL = Forest hauling after sideways felling at edge of the wood harvesting front, BL = Forest hauling after sideways felling inside the wood harvesting front, CL = Forest hauling after forward felling in the middle of the wood harvesting front, DL = Forest hauling after sideways felling at edge of the wood harvesting front with traction assistance, EL = Forest hauling after sideways felling inside the wood harvesting front with traction assistance.

Terrain	Tree Species	Cutting Method			Forwarding Method			Traction Assistance
Flat	*Eucalyptus*	A	B	C	AL	BL	CL	No
Flat	*Pine*	A	B	C	AL	BL	CL	No
Slope	*Eucalyptus*	D	E	-	DL	EL		Yes
Slope	*Pine*	D	E	-	DL	EL		Yes

In addition, to be an efficient harvesting method, machine operators must be educated in using the harvesting methods, and they must be able to work fluently with the models [36].

In this study, one study operator represented a local forest industry company, and one operator represented a Finnish forest machine manufacturer. The harvester operator of a forest industry company had worked as a forest machine operator for seven years. The Finnish forest machine manufacturer's test operator was the same for both the harvester and forwarder. He had worked as a forest machine operator for nine years, and then for eight years as an operator trainer for a forest machine manufacturer. This test operator had a total of 17 years of work experience. The operators used the same machines, and the new speed of the boom was adjusted to a constant for both operators.

2.3. Data Analysis

A work study was applied in the analysis of harvesting methods [37], in which work was observed visually using video material. The time study material of the harvesting work was processed using a video analysis tool developed for the research. The output data of cut trees were collected with the automatic measuring system of the harvester. In the beginning of the analysis, time distributions of work phases of the cutting cycles were calculated for the cutting methods. The cutting cycle on flat terrain included the following work phases: driving to work point, grapple to tree, felling, moving of tree, processing and auxiliary time. In addition to these work phases, anchoring, removal of anchoring and driving were included in the cutting cycle on sloping terrain.

Then, the time consumption analysis of the work phases was evaluated more precisely with the help of statistical analysis [38]. First, the normal distribution of samples from the time study data was examined with the Kolmogorov–Smirnov test (K-S). It was found that the distribution of variables of some samples differed statistically from the normal distribution. Therefore, it was decided to use nonparametric tests in the statistical analysis. Statistical differences between the samples were examined with the Kruskal–Wallis test (K-W) and the Mann–Whitney U-test (M-W).

After the time consumption analysis of the cutting methods, a productivity analysis was implemented using the same analysis methods. Cutting productivity was examined by average calculations and statistical tests at the forest stand level, using the cutting cycle times. Since the number of working breaks (interruptions) in the data varied, the comparison of cutting methods was performed using effective hour productivity (m^3/E_0h). The average differences were considered significant (*p*-value) at the level of 0.05.

A further effort was made to identify the differences between harvesting methods by testing the time consumption of the loading cycle of the forwarder. The same tests were used in the analysis (K-W and M-W), because it was found that the distributions of variables of the samples differed statistically from the normal distribution. For example, on sloping terrain, the loading cycle times of the forwarder were tested in DL (K-S, $p = 0.004$) and in EL (K-S, $p = 0.012$).

3. Results

3.1. Time Consumption of Cutting Cycles

In the data for flat terrain (Figure 5), the average time consumption of grabbing a tree (23%–24%) in cutting *eucalyptus* would seem to be slightly lower compared to the cutting of *pine* (25%–31%). On the other hand, the share of the processing time seemed to be higher in *eucalyptus* cutting (41%–46%) compared to *pine* cutting (28%–38%). In addition, the time distributions of the work phases of the cutting cycles were also slightly different between the cutting methods (1%–4%).

The time consumption was also analyzed on sloping terrain in groups formed by the cutting methods and tree species (Figure 6). The effect of tree species on the time consumption of the work phases would seem to decrease when moving from flat terrain to sloping terrain. Omitting the *pine* stands' processing phase, this difference was caused by the increased total time consumption of the cutting cycle because of the anchoring phases. Further, only a minor difference was observed in the processing time, when it was compared between *eucalyptus* (30%–36%) and *pine* (35%–36%). In addition, the time consumption of moving the grabble to the tree (20%–23%) in *eucalyptus* is very similar compared to *pine*, as are all the time distributions of the cutting cycles between the cutting methods.

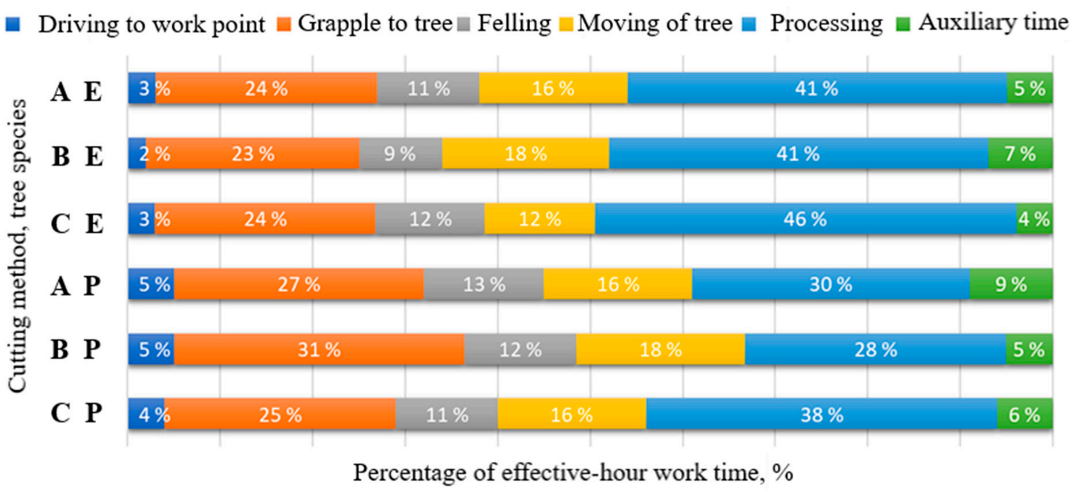


Figure 5. Effect of cutting method and tree species on percentages of time consumption (m^3/E_0h) on flat terrain. A = sideways felling at edge of harvesting front, B = sideways felling inside harvesting front, C = forward felling in middle of harvesting front, E = *Eucalyptus*, P = *Pine*.

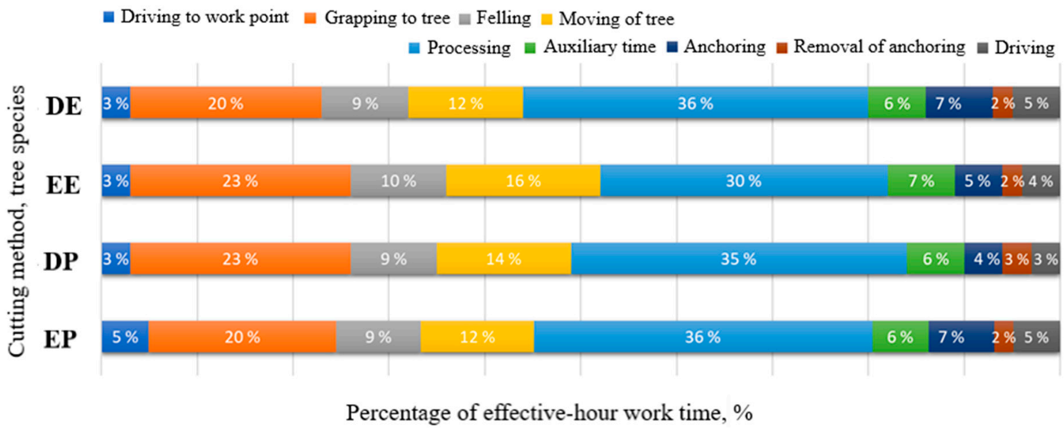


Figure 6. Effect of cutting method and tree species on time consumption (m^3/E_0h) on sloping terrain. DE = sideways felling at edge of harvesting front with traction assistance in *Eucalyptus* forest, EE = sideways felling inside harvesting front with traction assistance in *Eucalyptus* forest, DP = sideways felling at edge of harvesting front with traction assistance in *Pine* forest, EP = sideways felling inside harvesting front with traction assistance in *Pine* forest.

3.2. Time Consumption Analysis of Loading Cycle of Forwarder

There was a statistically significant difference in total time consumption in the loading cycles (K-W, $p < 0.000$). In a pairwise comparison, the loading cycle methods AL and CL (M-W, $p = 0.023$) and the methods BL and CL (M-W, $p < 0.000$) caused statistically significant differences in the time consumption of the loading cycles. On the other hand, no statistically significant difference was observed between the loading cycles in the methods AL and BL. In addition, a statistically significant difference was observed in the average time consumption of the loading cycles between flat and sloping terrain (M-W, $p = 0.006$). On the other hand, the average time consumption of the loading cycles did not differ statistically significantly between *eucalyptus* and *pine* loading. Furthermore, in contrast to the cutting cycles, a statistically significant difference between the operators was observed in the loading cycles (M-W, $p < 0.000$).

Table 6 presents average time consumption values of the loading cycles, which are presented separately for flat and sloping terrains. A statistically significant difference in the time consumption of the loading cycles of *pine* was observed in the data of Operator 2 (K-W, $p < 0.000$) on flat terrain, where the loading time of the CL method was 25.4%–13.4% lower than the loading times of other methods (Table 6). On the other hand, a statistical difference between methods DL and EL was observed in sloping terrain (M-W, $p = 0.013$), even though the position of the stacks along the logging trail was similar between the methods.

Table 6. The average time consumption of the loading cycle (s = second) and testing of statistical differences (p) between loading regarding factors on flat and sloping terrains. AL = forest hauling after sideways felling at edge of harvesting front, BL = forest hauling after sideways felling inside harvesting front, CL = forest hauling after forward felling in middle of harvesting front, DL = forest hauling after sideways felling at edge of harvesting front with traction assistance, EL = forest hauling after sideways felling inside harvesting front with traction assistance, E = *Eucalyptus*, P = *Pine*, 1 = Operator 1, 2 = Operator 2, K-W = Kruskal–Wallis test, M-W = Mann–Whitney U-test.

Species, Operator	Flat Terrain				Sloping Terrain		
	AL, s	BL, s	CL, s	K-W, p	DL, s	EL, s	M-W, p
E1	18.6	17.9	17.7	0.638	18.2	20.8	0.013 *
E2	21.8	22.9	22.9	0.550	26.0	26.4	0.883
P1	17.6	18.7	16.4	0.147	-	18.4	-
P2	22.4	26.0	19.4	0.000 *	-	22.7	-

* = Statistical difference at significance level 0.05.

3.3. Effective Hour Productivity of Cutting Methods on Flat Terrain

The productivity of the cutting methods was considered in respect to tree species and operators. When the average productivity of the cutting methods was compared between tree species, the cutting of *eucalyptus* was more productive (20%–35%) compared to the cutting of *pine*. The productivity differences caused by the operators were, on the other hand, significantly smaller (5%–9%) regarding the cutting methods.

A more precise analysis shows that sideways felling at the edge of the harvesting front (method A) was the least productive method in the samples of flat terrain for all tree species and operators (Figure 7). Sideways felling inside the harvesting front (method B) and forward felling in the middle of the harvesting front (method C) were found to be statistically significantly more productive than method A on flat terrain. On the other hand, the mutual difference between methods B and C was not very clear, especially in *eucalyptus* stands. In *eucalyptus* stands, method C was 7%–8% more productive than method A. Method B was correspondingly 5%–8% more productive than method A. In *pine* stands, the methods differed clearly. Method C had the highest productivity, and method A had the lowest productivity. Method C was found to be up to 14% more productive than method A. Method B was 9% more productive than method A.

3.4. Effective Hour Productivity of Cutting Methods with Traction Assistance

In the sloping terrain stands, the average productivity differences between tree species did not differ as clearly as in the flat terrain stands, when the results were calculated by the cutting method. *Eucalyptus* cutting was 0%–5% more productive compared to *pine* cutting, due to the cutting method and the operator. The differences caused by the operators were larger (2%–16%) when the results were calculated by the cutting method.

Whereas, on flat terrain, a clear difference in the effective hour productivity was observed between two different sideways cutting methods (method A vs. method B, which was more productive), on sloping terrain, the differences in cutting methods D and E were not completely unambiguous (Figure 8). Cutting method E was clearly more productive than method D in the data for the cutting work of Operator 1. In the *eucalyptus* stands, the productivity difference in favor of method E was 16%, and in *pine* stands, it was 8%. However, similar differences were not observed in the cutting work of Operator 2. In the *eucalyptus* stands, only a small difference (2%) between methods D and E was observed in the data for Operator 2. In the *pine* stands, the effective hour productivity of the methods seemed to be equal in the cutting work.

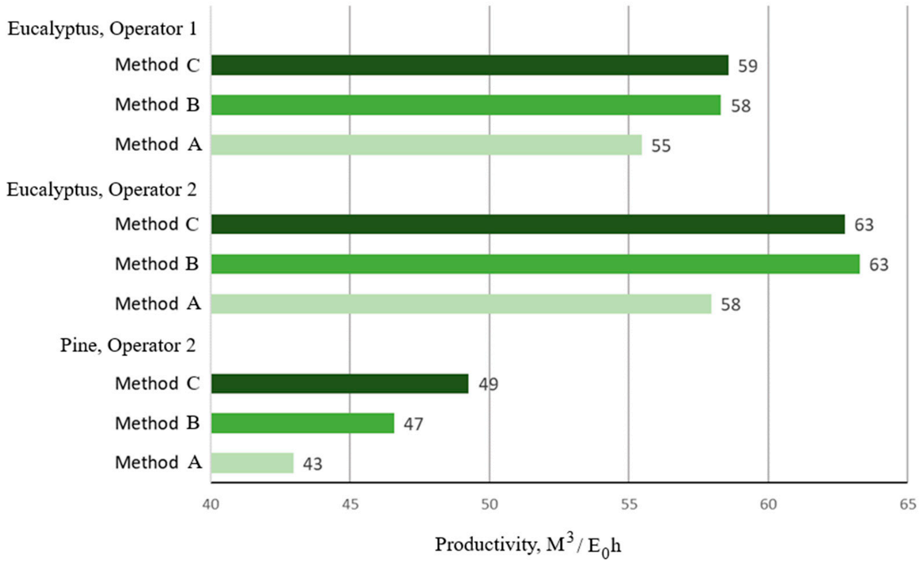


Figure 7. Average effective hour productivity of cutting methods in stands on flat terrain. Method A = sideways felling at edge of harvesting front. Method B = sideways felling inside harvesting front. Method C = forward felling in middle of harvesting front.

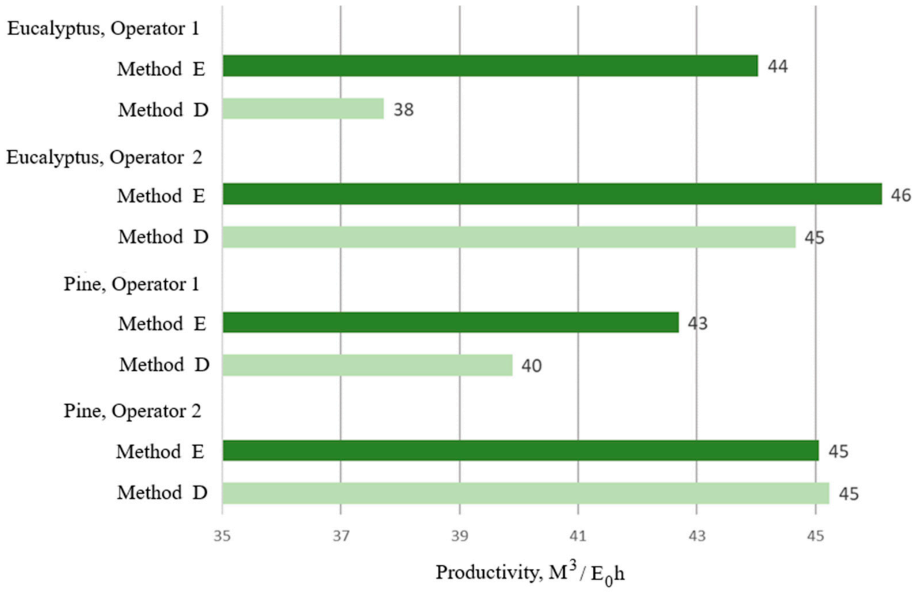


Figure 8. Effective hour productivity of cutting methods D and E on sloping terrain. Method D = sideways felling at edge of harvesting front with traction assistance. Method E = sideways felling inside harvesting front with traction assistance.

3.5. Productivity Analysis of Cutting Cycles by Statistical Tests

When analyzing the productivity of cutting cycles in the entire material, a statistically significant difference between the cutting methods was observed (K-W, $p = 0.005$). In a pairwise comparison, methods A and B (M-W, $p = 0.033$) and methods A and C (M-W, $p = 0.002$) differed statistically from each other. On the other hand, no statistical difference was observed between methods B and C. In the entire material, the effect of variables on productivity was also analyzed. It was observed that the productivity of cutting cycles differed statistically significantly in a pairwise comparison between the *eucalyptus* and *pine* study stands (M-W, $p < 0.000$) and flat and sloping terrain (M-W, $p < 0.000$). On the other hand, no statistically significant difference was observed between harvester operators (M-W, $p = 0.257$).

An average productivity calculation of the cutting methods on flat and sloping terrain is presented in Table 7. The average productivity of method A was generally lower than methods B and C in the datasets of both operators. Further, the productivity of the cutting methods was higher on flat terrain in *eucalyptus* forests; however, the situation was opposite—i.e., the productivity of cutting methods was higher—on sloping terrain in *pine* forests. Table 7 also shows that the average productivity did not differ statistically significantly between different cutting methods on flat stands. On the other hand, a statistically significant difference between cutting methods D and E was observed in both *eucalyptus* and *pine* stands on sloping terrain (M-W, $p = 0.030$). This statistical difference was observed in the data of Operator 1, where method E was 7.0–7.7 m^3/E_0h more productive than method D, depending on the tree species.

Table 7. Average productivities (m^3/E_0h) of cutting methods and statistical differences (p) between them: A = sideways felling at edge of harvesting front, B = sideways felling inside harvesting front, C = forward felling in middle of harvesting front, D = sideways felling at edge of harvesting front with traction assistance, E = sideways felling inside harvesting front with traction assistance, E = *Eucalyptus*, P = *Pine*, 1 = Operator 1, 2 = Operator 2, K-W = Kruskal–Wallis test, M-W = Mann–Whitney U-test. Standard deviation is in parentheses.

Species, Operator	Flat Terrain				Sloping Terrain		
	A	B	C	K-W	D	E	M-W
		m^3/E_0h		p	m^3/E_0h		p
E1	58.1(24)	64.8(27)	62.1(24)	0.149	46.1(25)	53.8(27)	0.030 *
E2	66.3(26)	64.0(28)	63.9(27)	0.716	57.9(27)	56.0(23)	0.615
P1	-	-	-	-	51.7(19)	58.7(23)	0.030 *
P2	49.3(23)	53.6(25)	53.8(23)	0.730	55.1(24)	57.7(25)	0.325

* = Statistical difference at significance level 0.05.

4. Discussion

4.1. Productivity Comparison of Cut-to-Length Harvesting Methods

There has been quite a little research on the harvesting methods of tree plantations with CTL wheel machines. In addition, the stands were very dense at the final cutting, including a high relative volume as cubic meters of a single trunk, which caused difficulties in productivity comparisons to studies in respect to Nordic harvesting conditions. Table 1 describes the previous productivity studies for tree plantations. Since comparative information seems to be rather scarce, we proceed in the examination of the results via the harvesting conditions of tree plantations.

When the productivity of this study is compared with previous results, it is noticed that the productivity is on a considerably higher level. If the average size of the stem is about 0.3 m^3, then the cutting productivity has been about 20 m^3/E_0h in previous studies, while in this study, it was 45 m^3/E_0h in *pine* cuttings and 55 m^3/E_0h in *eucalyptus* cuttings. The power of the harvesters in comparison may have an effect on the results [39]. The engine power of track-based harvesters is generally lower compared to the power of the harvester used in this study (205 kW). For example, in the material of Strandgard et al. [26], the power of the harvesters varied between 104 and 224 kW. On the other hand, Seixas and Batista's [18] study found no significant difference in the productivity of wheeled harvesters and tracked harvesters when they worked in similar conditions. In Nordic studies, another significant factor causing differences is the operators' experience [36]. The test operators of this study can be considered very experienced, with 17 and 34 years of work experience, while in the material of Strandgard et al. [26], the operators' experience varied between 1 and 20 years of work.

Regarding cutting methods, the time distributions of the work phases provided weakly unambiguous information about the impact of the cutting method on the efficiency of wood-harvesting methods. Further, tree species did not affect the time distribution differences. The tree density of the stands indirectly affected this study, because the trees of the forest stands grew in denser positions compared to the cited reference materials.

4.2. Productivity Comparison between Flat and Sloping Terrains

A previous study has already confirmed the notion that winch-assisted wood harvesting is significantly more productive than traditional slope harvesting methods (such as manual felling and short-distance transportation using cable cars) [34]. However, the productivity values for winch-assisted harvesting have been considered indicative. Therefore, the importance of further research on the topic has been emphasized, in order to achieve a sufficient understanding of the profitability of winch-assisted harvesting in varying conditions. This research contributes to the presented further research needs and increases the understanding of the productivity of the winch-assisted CTL method for harvesting in tree plantations.

When cutting methods on sloping terrain with winch assistance were compared to cutting methods on flat terrain where winch assistance was not used, productivity was found to decrease by an average of 11.26 m^3/E_0h when winch assistance was used. In previous studies comparing harvesting productivity without winch assistance and with winch assistance, winch assistance was clearly found to decrease productivity [40]. The use of winch assistance was found to decrease productivity by up to 36 m^3/E_0h [41]. Based on previous studies, the use of winch assistance is justified mainly in conditions where mechanized wood harvesting would not otherwise be possible or if soil impacts want to be avoided [17,34]. On the other hand, winch assistance has been found to increase the work efficiency of the forest machine, so that the driving speed and the load of the forwarder can be increased [32]. This should be taken into account in future studies when thinking about the impact of the additional work phases of anchoring on productivity.

Winch assistance has been shown in a previous study to enable a safe and efficient alternative to conventional methods for wood harvesting on steep slopes [34]. The results achieved in this study support and complement the previous rather limited research data on the time consumption and productivity of winch-assisted wood harvesting. Based on the results, it can be concluded that winch assistance enables the use of forest machines developed for the CTL method on steep terrain. With the harvesting productivity remaining at a good level thanks to winch support, forestry can be practiced even more efficiently in areas where harvesting costs were previously thought to be too high. In addition, winch assistance was found to offer useful opportunities for managing the environmental impact of harvesting on sloped areas that are prone to erosion. This study did not focus on the safety aspects of harvesting work, but the improvement in work safety is obvious if winch assistance can be used to replace manual harvesting work [34].

The most significant work phases that reduce the productivity of winch-assisted harvesting are related to the attachment of the winch assist [34]. Additional work phases that increase the effective working time for harvesting have been reported in previous studies to take 10%–23% of the effective working time [30–32]. In this study, the average share of the additional work phases from the effective working time was 12% for the cutting methods and 16% for forwarding. The results correspond to the percentage of time required for anchoring the winch support in previous studies, but it is important to note that the percentage of additional work phases depends strongly on the effective work time of the entire work cycle and its distribution to the work phases. For example, in forwarding, the length of the driving distance and the number of stacks processed in cutting are variables that cause a variation in the distribution of the effective working time between studies.

The forest machines were equipped with the Ponsse Syncrowinch winch system [35]. When anchoring the winch and removing the anchoring are considered, the work phases mentioned above took significantly less time in this study than in previous studies, an average of 4.4 min. In previous studies, the average winch attachment times varied between 21.6 and 23.3 min [30–32]. The longer time of the additional work phases may be explained by the different winch systems used in other studies, because the work phases required for anchoring and removal are probably not completely comparable to the method used in this study.

In this study, information was collected only on the average slope of the harvesting stands. However, the operative inclination of the stands varied between different working points of the machines, but no research data were collected of this variation. The operational slope of the working point probably has some effect on harvesting productivity, even when winch assistance is in use, but the previous research does not give an unequivocal answer to that issue [30,34].

4.3. Validity of Data and Methods

According to Harstela [42], when collecting representative time research data, one should try to control the conditions by choosing research sites with the most uniform quality possible. As a research environment, tree plantations are of a uniform quality compared to, for example, Nordic forests. Despite this, the average size of the stem was found to vary significantly between different cutting methods (Table 4), which may reduce the reliability of the results at the study stand level. It may be a matter of chance, which is impossible to influence by the selection of research samples. It should be noted that the outliers in the data may also significantly disturb statistical comparisons [3]. One option would have been to remove outliers from the data. However, a better option was to collect a sufficiently large dataset so that the impact of abnormal findings is reduced. Therefore, the material of this study was large enough to compare productivity variations at the stand level. On the other hand, when the harvesting conditions are rather uniform, the number of outliers should be minimal.

In the actual comparative time study, for increased validity, there should be at least three operators, each of whom should work with all the studied methods in all study environments. Contrary to the original plan of the study, however, the number of test operators had to be reduced from three operators to two. The productivity difference between the operators examined in the study was 2.21 m^3/h in favor of Operator 2. This difference may be considered as a greater influence on productivity than was assumed when preparing the study layout. In other words, operator-specific choices and habits during harvesting may have an impact on the results of the study [36]. On the other hand, the variability caused by the equipment was minimized by using the same machines and adjusting the speed of the boom to a constant for both operators. In addition, it should be noticed that harvesting conditions and tree size may also affect the productivity difference between operators.

The influence of the operators on the variation in the study material could hardly be fully controlled. The simplest method to control the operator effect would be to use average operators [42]. The test operators in the study were used to working with the old method and were very good at that. Even if the operators learned the new methods quickly, it is very possible that getting used to the old method still influenced the results [3]. When choosing the operators, it was assumed that they had a similar motivation and attitude towards new wood-harvesting methods and the research situation. In the end, however, the evaluation of motivation is uncertain, which makes the selection of test operators a very challenging task. Test operators are also generally more motivated and enthusiastic at the beginning of the research, when work productivity is higher. For this reason, the advice has been that the results of the first two research days were recommended to be removed from the data. However, there were not enough financial resources for removing data in this study. Instead of removing the data, by giving the study operators enough training time on the cutting methods of the study, the remove of the material can be avoided.

A manual time study like this, in which work is observed visually using video footage, has become a common method of time studies in wood-harvesting studies, although an automatic time study has become more common recently [43–45]. With an automatic time study, the division of work phases could not have been carried out to the extent required. Particularly, measuring special work phases, such as the time consumption of winch anchoring, required the collection of video material for the study.

It should be noted that, in a manual time study, the measurement accuracy is always limited, because it is based on the observation made by the work researcher [43]. However, the characteristics of the time study tool used in the study made it possible to separate the work phases with sufficient accuracy from the video. It was also possible to quickly correct observation errors made by the researcher. However, in a manual time study, the effect of the researcher's skills and experience on the results cannot be completely eliminated [46,47]. In particular, the three-dimensional visualization of distances and movements from video material was a challenge. The movements of the grapple device in the lateral direction could be detected accurately, but it was more difficult to observe the movements of the grapple device in the depth direction because the video material was shot from above.

The time distributions of the work phases provided weakly unambiguous information about the impact of the cutting method on the efficiency of harvesting methods, especially for a comparison in flat terrain and sloping terrain conditions. Therefore, productivity analysis by statistical methods was necessary. The quantitative statistical methods used in the study have already been successfully applied in many previous studies (e.g., [36,43]). Even if the research methods are established, statistical testing is almost always accompanied by uncertainty. When evaluating the reliability of the results, it must be noted that the study used a significance level of at least 5% ($p < 0.05$) in the interpretation of statistical tests and the finding of differences.

4.4. Future Studies

The case studies of harvesting methods consisted of both the cutting of trees and the loading of logs to the load space. However, both methods could be analyzed more precisely. The reason for that was that the time study data of cutting was more precise than the data of loading of logs to the load space. In other words, the results of the cutting were at the stand and tree level, while the results of the forwarding were at the loading cycle level. When looking at the average loading times of the forwarder between the time study units, a clear line in favor of cutting methods A or B was not observed, despite some statistical differences. This analysis could be expanded to tree level (spatial stack level) for a more precise consideration of flat and sloping terrain. Further, a productivity analysis of forwarder–operator systems could be implemented if precise work phase data is to be collected from work cycles of interest.

Although the study only measured quantitative outputs, the outputs are always qualitative as well, which could be considered more precisely in the future. Since the logs of the study stands ended up as raw material for the fiber industry, the importance of product quality was not really emphasized in the research setting. In addition, the effect of harvesting on the quality of the environment could be emphasized, as some of the research sites were in erosion-sensitive slope areas. Although the quality of the environment was not actually measured in the study, indirect interpretations of the impact of the harvesting operation on the soil can be made from the video recordings. The machines and work methods used in the study were not found to cause significant wear and tear on the soil, which supports the use of a harvesting chain equipped with winch assistance and tracks in harvesting on slopes.

5. Conclusions

The layout and material of the study can be considered good for reaching the main goal of the study. In the study's harvesting conditions, sideways felling inside the harvesting front was the best suited and the most productive (63 m^3/E_0h) for harvesting on both flat and sloping terrain. It was found that winch assistance has a negative effect on harvesting productivity (11 m^3/E_0h). Despite this drawback, the winch assistance system examined in the study enabled a sufficiently productive cutting even on steep slopes (45 m^3/E_0h), while at the same time being an environmentally sustainable solution for harvesting on erosion-sensitive slopes. As a method that increases work safety, it also has a positive effect on the perspective of the social sustainability of working life. The significant variation of the average size of trees (m^3) between the time study units partly reduced the validity of the research material or at least made it difficult to draw conclusions. Therefore, in further studies, it would be useful to model productivity as a function of tree size and make more precise comparisons in respect to harvesting conditions.

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