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ORIGINAL PAPER

An enhanced method for improving the efficiency of harvesting tree plantations on flat and sloping terrain using a cutting-cycle productivity model

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Abstract This study aimed to model and identify the most productive cutting methods of tree plantations by comparing a forward felling technique (C) with sideways techniques outside (A and D) or inside cutting edge (B and E). Drone video material of each tree was analyzed by comparing time distribution of work phases. The relation between this input data and harvester production data was analyzed by regression models. A quadratic model predicted productivity precisely ($R^2 = 0.95$) and explained the effective-hour productivity in cutting cycle with dummy variables of harvesting conditions. The productivity was explained by tree size and cutting cycle time, while effects of operator and harvester were eliminated by statistical analysis. In loblolly pine (*Pinus taeda* L.) plantations on flat terrain, cutting method B was 4.8 m^3/E_0h (effective working hour) more productive than method A, and 6.7 m^3/E_0h than method C. In Sydney blue gum (*Eucalyptus saligna* Sm.) plantations, cutting method E was 1.8 m^3/E_0h more productive than cutting method D on sloping terrain. Of the time-cycle variables, time consumption of the "moving of tree" changed significantly between the cutting methods, of which the ones that used the sideways felling technique inside cutting edge were most efficient. This quadratic modeling structure can be recommended for precise studies in similar harvesting conditions.

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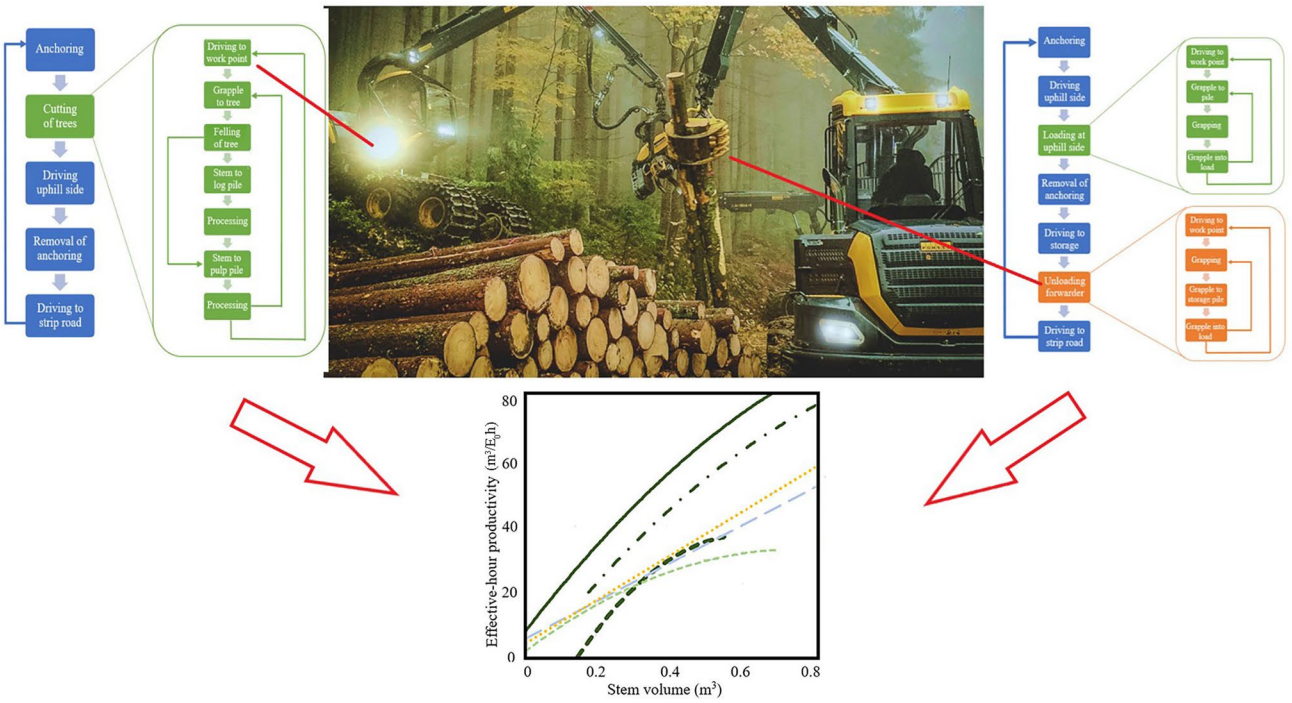
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Graphical Abstract



Keywords Time and motion study · Effective-hour productivity · Felling technique · Work-phase analysis · Cut-to-length method

Introduction

Regarding the characteristics of the harvester, previous studies have examined the effects of harvester size, the engine power and the felling device. Harvesters of the largest size categories have been found to be the most productive, regardless of the size of the tree to be cut (Eriksson and Lindroos 2014). Increases in the power of the harvester reduce time spent on phases such as "grapple to tree", "felling tree" and "processing tree" in the cutting cycle, which, correspondingly, is directly causing increase productivity (Eriksson and Lindroos 2014). However, the effect of the size of the harvester on productivity varies, depending on the size of the trees, indicating that with small diameter trees, productivity of large machines cannot be fully utilized, and with large diameter trees the power limits of small machines has been reached. Related to these facts, by changing the harvester's settings in software, productivity and thus fuel consumption are be affected (Prinz et al. 2018). No space Jylhä et al. (2019) estimated that the combined effect of the development of machines in terms of reliability and more time-efficient cutting methods have improved productivity by more than 80% compared to the beginning of the 1990s. However, improving the characteristics of timber harvesters is a limited and capital-intensive approach for improving productivity for harvesting companies (Ovaskainen 2009).

Operator data has been found to explain up to 37% of variations in harvesting productivity (Purfürst and Erler 2011). Therefore, operator influence has been considered to be the most significant factor affecting harvesting productivity, followed by tree stem size. However, operator impact on time consumption and harvesting productivity varies significantly, depending on harvesting methods. In thinnings, the greatest differences between operators have been found to be up to 40% (Väätäinen et al. 2005; Ovaskainen et al. 2006). The difference due to the operator decreases significantly in clear- cuttings, with the maximum productivity difference slightly more than 20% (Väätäinen et al. 2005). Both age and work experience the operator increase productivity. This increase due to operator's work years has been found to increase slowly up to 15 years of work (Malinen et al. 2018).

Efforts have been made to explain the differences in productivity caused by experience with, for example, the development of cutting device handling skills and operator-specific work technique choices (Ovaskainen 2009). Experienced operators effectively apply their wide-ranging knowledge in their work, which can be seen, for example, in quick decision-making and in avoiding unnecessary work

movements and breaks. In particular, the work phases that require effective decision-making, such as the "grapple to tree" i.e., moving of the cutting device to the base of the tree, and the "processing of stem", speed up as the operator's experience increases. In addition, the operator's personal skills and cognitive abilities are believed to cause variation in productivity (Väätäinen et al. 2005; Ovaskainen 2009). With thinnings, Väätäinen et al. (2005) estimated that the handling skills of the harvester can explain 20–30% of the differences in productivity of the harvester-operator system and operator-specific choices 10–15%.

Effects of harvesting conditions on productivity

When considering the impact of harvesting conditions on productivity, stand characteristics are important. For example, it is not feasible to fully utilize all the capabilities of large-sized harvesters when thinning stands (Sirén and Aaltio 2003). In addition, tree size has been found in numerous studies to be the most significant factor that increases the productivity in cut-to-length harvesting (Nurminen et al. 2006; Jiroušek et al. 2007; Gerasimov et al. 2012; Visser and Spinelli 2012; Eriksson and Lindroos 2014). However, when the size of stems is very large, productivity may decrease due to the limited capacity of the harvester. The effect of species on productivity has also been examined (Nurminen et al. 2006; Gerasimov et al. 2012) and have an indirect effect on productivity through different size and quality requirements for timber assortments. For example, as the number of timber assortments to be cut increases, productivity decreases (Nurminen et al. 2006). Considering the work phases of cutting, the time required for a cutting cycle decreases as the length of the log increases due to the reduced number of stem cuts. In addition, quality characteristics and branches of stems among species cause differences primarily time consumption of the work phase of "processing of the stem".

Terrain is an important harvesting condition that affects productivity. Based on previous studies, the use of winches has been carried out in conditions where mechanized harvesting without it would not be safe or if soil impacts are to be avoided (Garren et al. 2019; Holzfeind et al. 2020). Winch assistance enables the use of forest machines in the cut-to-length method on steep terrains. Research has confirmed that winch-assisted harvesting is significantly more productive than traditional slope harvesting methods such as manual felling and short-distance transport using a cable system (Strimbu and Boswell 2018; Holzfeind et al. 2020). However, increasing productivity with winch-assisted harvesting may be uncertain because it has been found to decrease productivity from 11 up to 36 m^3/E_0h compared to flat terrain harvesting (Green et al. 2020; Palander et al. 2024).

The most significant work phases that reduce the productivity of winch-assisted harvesting are related to the attaching and removing of the winch-assist (Holzfeind et al. 2020). Additional work phases that increase the effective working time for harvesting have been reported to take 10–23% (Brandtner 2018; Holzfeind et al. 2018; Strimbu and Boswell 2018; Palander et al. 2024). Time consumption of the work phases varied significantly from 4 to 23 min. The differences in the additional work phases may be explained by the different winch systems used in the studies; the work phases required to anchor and remove are possibly not wholly comparable.

Felling techniques in harvesting methods

The work method can be considered as one of the operator-specific characteristics. In principle, there are as many work methods as there are forest machine operators (Ovaskainen 2009). Some work methods reduce the number of work phases needed for harvesting and the time spent in the work

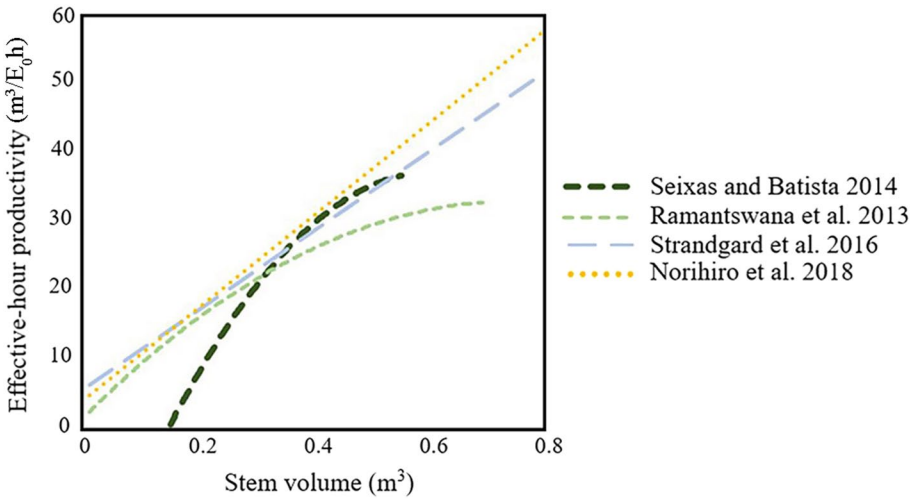


Fig. 1 Comparison of productivity models of harvesting in eucalyptus plantations; dark green dashed curve depicts productivity of the wheeled harvester. Other curves depict productivity of tracked excavator-based harvesters

phases at the same time. Previous research has created alternative work methods suitable for different harvesting conditions, in which the individual way of work is described as unambiguously as possible so that it can be easily repeated (Ovaskainen 2009, 2012).

The main difference in different work methods is the felling direction of trees in relation to the moving direction of the harvester. Felling to the side and forward felling are the main directions. In felling to the side, the chances of the tree becoming caught in other tree crowns are reduced and enables the placement of cutting residues on the logging trail. This type of harvesting method is suitable for dense stands where the soil may not bear the weight of a harvester or forwarder. However, sideways felling makes it difficult to observe the quality of the stem but, on the other hand, it makes it easier to sort different quality of logs into separate piles (Ovaskainen 2012). In the forward felling technique, trees are felled parallel to the logging trail. This has been recommended for use in forests where the residues are collected as energy wood. It also enables efficient observation of stem quality, and the cutting residues accumulate beside the logging trail (Ovaskainen 2009, 2012).

In wood harvesting in Brazil, the operator has little influence on the method of work, as it is important to strictly follow the guidelines of a pre-defined way of work. This might also have an impact on productivity.

Modeling of harvesting productivity in eucalyptus plantations

In Brazil, the cut-to-length method has become the most important mechanical harvesting method (Seixas and Batista 2014). In addition, a significant part of the studies on productivity modeling have been carried out with tracked excavator-based harvesters (Spinelli et al. 2002; Ramantswana et al. 2013; McEwan et al. 2016; Norihiro et al. 2018). When the productivity of wheeled harvesters has been compared to that of tracked excavator-based machines (Fig. 1), there were no significant differences in productivity between these machine types (Seixas and Batista 2014).

In addition to machine characteristics, the impact of harvesting conditions are important factors on productivity modeling (Spinelli et al 2002; Ramantswana et al. 2013; Acuna et al 2017; Norihiro et al. 2018). However, operator impacts have not been emphasized as much as it is in Europe (McEwan et al. 2016). As noted previously, a slight increase in slope has a minor effect on the harvesting productivity share of work phases, however, its effects are important in steep terrains. Therefore, the effect of slope has been modeled in several studies (Spinelli et al. 2002; da Silva Leite et al. 2014; Ackerman et al. 2018; Norihiro et al. 2018).

Table 1 Characteristics of the study stands

Stand	Tree species	Slope	Trees per ha	Trees' age	Planting geometry	Diameter Breast Height	Height	Volume
		%	number	years	m × m	cm	m	m^3
1	Es	17.5	1650	7	3.0 × 2.0	18.4	21.3	0.416
2	Pt	22.5	1350	7	3.5 × 2.0	20.5	13.3	0.315
3	Es	7.5	1650	7	3.0 × 2.0	17.8	22.1	0.386
4	Pt	7.5	1350	7	3.5 × 2.0	21	15.1	0.366

Pt = *Pinus taeda*, Es = *Eucalyptus saligna*

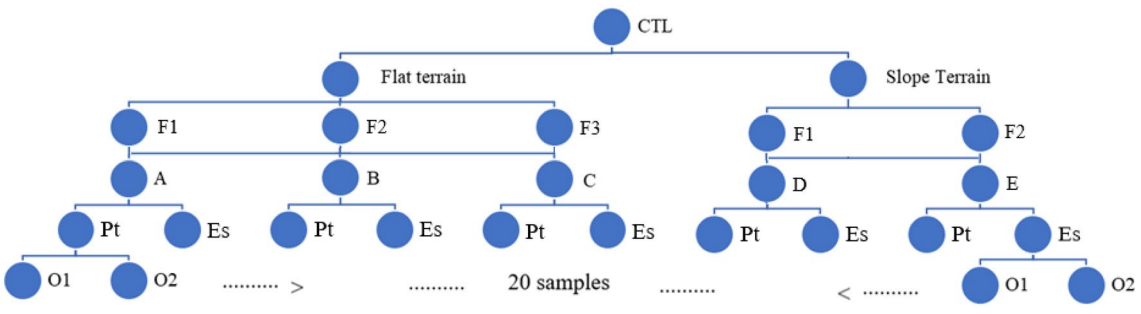


Fig. 2 Outline of F1, F2, and F3 felling techniques in five work methods A, B, C, D and E for testing on flat terrain and slopes; Pt = pine, Es = eucalyptus, O1 = operator 1, O2 = operator 2

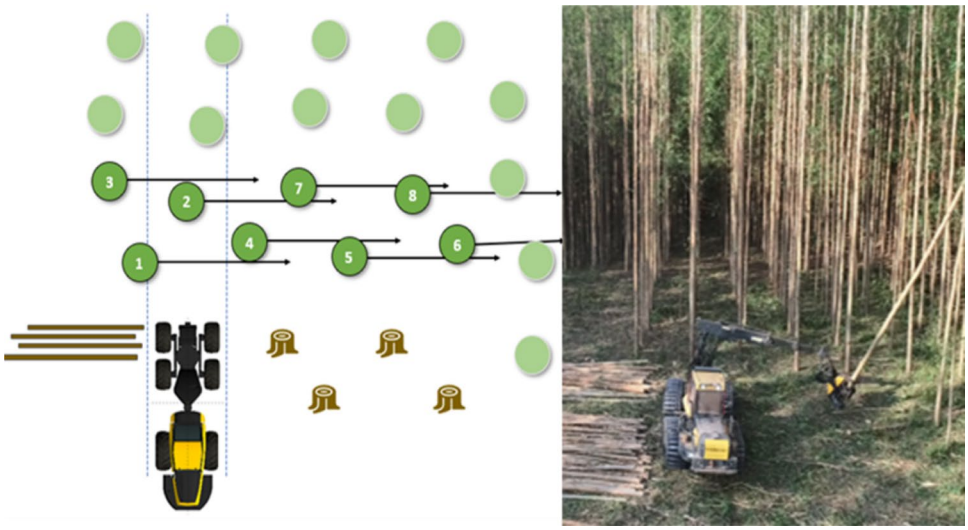


Fig. 3 Eucalyptus harvesting on flat terrain using method A (sideways cutting at the edge of the cutting front)

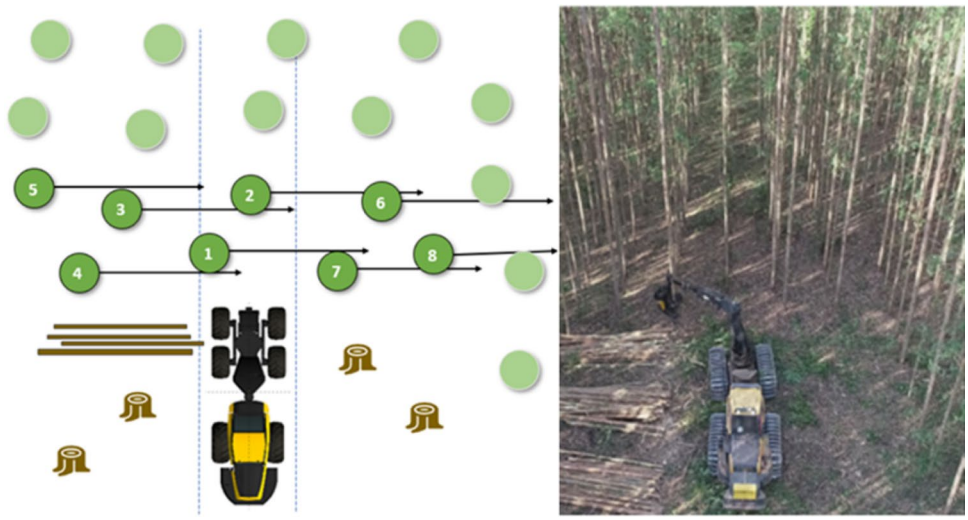


Fig. 4 Eucalyptus harvesting on flat terrain using method B (sideways cutting inside the cutting front)

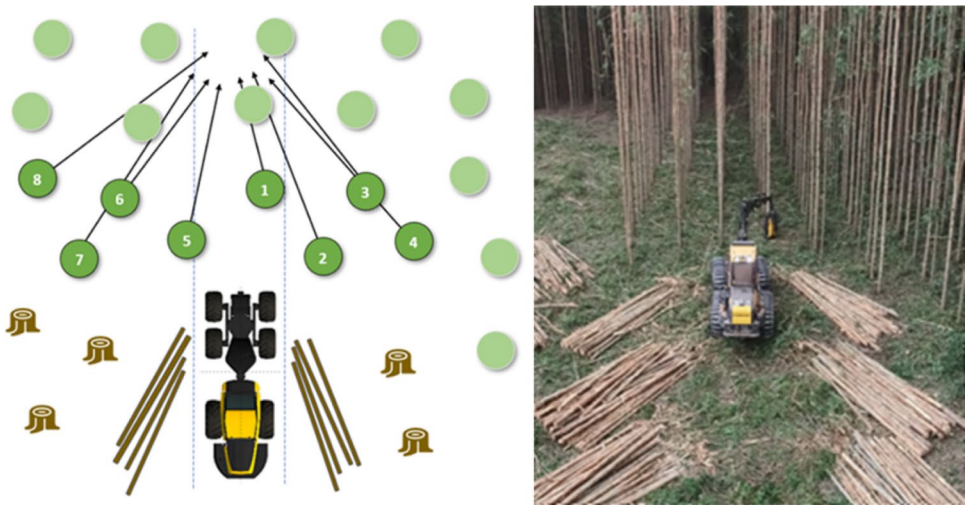


Fig. 5 Eucalyptus harvesting on flat terrain using method C (forward felling in the middle of the cutting front)

Material and methods

Harvester and stand data

The plantations were in the State of Paraná in southern Brazil, near the border between Argentina and Paraguay. The study used a Ponsse Ergo wheeled harvester to carry out cut-to-length harvesting. This made it possible to ignore the impact of machine characteristics on the productivity study. The year model of the harvester was 2016 and had reached 22 235 operating hours. The harvester was equipped with the H7 Euca harvesting head developed for eucalyptus trees with a boom reach of 9.5 m. The operating mass of the harvester (with accessories) was 24 650 kg, the engine power 205 kW and traction force 195 KN. The harvester's wheels were also equipped with tracks.



Fig. 6 Eucalyptus harvesting method D (sideways cutting at the edge of the cutting front with traction assistance) on slopes

Four stands were selected for a comparison of the harvesting methods (Table 1). The study's species, eucalyptus and pine clearly differed in stem shape. The pines were conical and the eucalypts longer and thinner. In addition, the thick pine branches extended lower on the stems. The trees had been planted and were evenly distributed. The density of the stands was the same as the planting density as these short-rotation stands were not thinned during the growing rotation.

Study layout of cut-to-length harvesting

Three felling techniques were compared using a study outline on combinations of different harvesting conditions, cutting methods and operators (Fig. 2). Five work methods consisted of three felling techniques on flat terrain and two on slopes. In addition, characteristics of the harvesting conditions varied in relation to species and the terrain. The study also included two equipment operators.

In work method A, sideways cutting, the working point of the harvester was located close to the edge of the cutting front (Fig. 3). When felling sideways, the direction of the trees was perpendicular to the strip road. Depending on the direction, the trees were always processed either on the left or right side of the strip road. The log pile was placed at 90° to the direction of the strip road. Harvesting started from the tree closest to the cutting front, after which the operator proceeded further along the cutting front.

In the sideways cutting method inside the cutting front (B), the cutting changed so that the working point of the harvester was moved from the edge of the cutting front towards the center (Fig. 4). Felling and processing of trees were carried out in the same work phases of the cutting

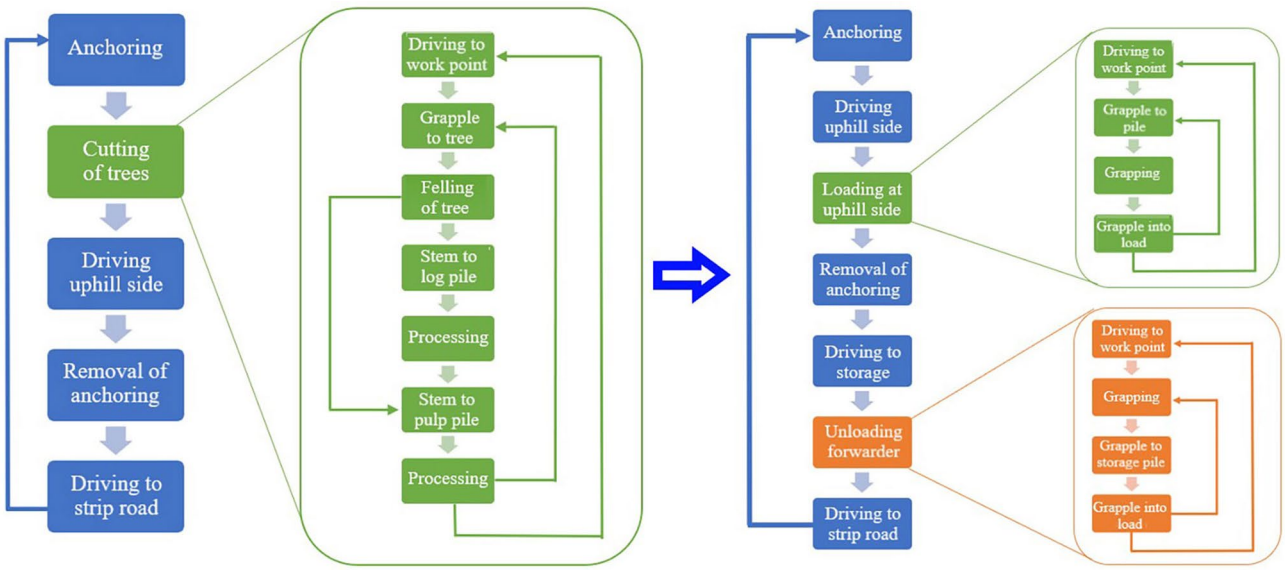


Fig. 7 Work phases and study cycles. The left side describes the harvester operator's work, the right the forwarder operator's work

cycle as in method A, perpendicular to the strip road and to one side of the strip road. In the order of the working point, the necessary work area was opened first. The trees were cut in front of the machine and from the place of the pile, after which the rest of the trees at the working point were processed into the same pile.

Cutting method C is forward felling technique in the middle of the cutting front. Similar to method B, the harvester's working point is inside the cutting front (Fig. 5). If necessary, work starts by opening the area for the harvester. The trees were processed from the front and sides of the harvester and the working point is on the strip road, directly in front of the harvester. The cutting of trees is either parallel or diagonally to the strip road. Log piles are built parallel to the strip road in a position resembling the shape of a fish bone.

Figure 6 shows the work situation when stands were harvested on slopes. In cutting method D, the working point of the operator-harvester system was located close to the edge of the cutting front (Fig. 6). In addition, traction assistance was used and was named D instead of A.

Harvesting method E differs from method D in respect to sideways cutting that happened inside the cutting front. Traction assistance was used in this method and therefore was named E instead of B.

Work research

The methods of Niebel (1993) were used for efficiency comparisons which applied combined time consumption and productivity analysis. In addition, comparisons were made both at the stand and at the tree level. During data collection and analyses of harvesting methods, a designed motion chart, i.e., a dynamic system description of the work phases was used (Fig. 7).

Calculations and tests used the time data of the work phases of the harvesting cycle. It was assumed that time spent in separate work phases would be different using different felling techniques in the operator's work method. Therefore, an analysis of time data was done before productivity analysis and was used for comparing harvesting methods and a selection of the most suitable felling technique in different harvesting conditions. The conclusions were based on the effective-hour productivity (m^3/E_0h), which does not include brakes.

An efficient harvesting method requires machine operators to be educated for their work and their work must be productive. In this study, experienced operators were selected to reduce any variation in the results. One operator, with seven years' experience, was from a local forest industry company that owns the plantations and forest machines, and another, was from a forest machine manufacturer with 17 years' experience.

Calculation of cutting time and productivity

The number of work phases in the various harvesting methods was different. Therefore, time consumption was calculated separately for harvesting on flat terrain and for slopes where a winch was used. On slopes, the work phases also included driving before anchoring of winch of machine, anchoring the machine to tree, removing the anchoring, and driving from the last work point back to the anchoring place. Averages of time consumed of the work phases of harvesting were calculated separately for each study time unit. The basic harvesting cycle of tree did not include the work phases of "driving to working point" and "additional auxiliary time".

To calculate productivity, the effective working time was divided into separate elements (y_1–y_5). As the time spent on driving, moving, anchoring and auxiliary activities was not focused on individual trees, the working time outside the cutting cycle was divided by the total number of trees in the stand. The effective work time of each tree in flat terrain operations was calculated using the formula (1):

$$T = y_1 + y_2 + y_3 \tag{1}$$

where T is the effective work time of the entire harvest cycle (s/stem), y_1 the time of the cutting cycle (s/stem), y_2 the driving time to working point (s/stem) and y_3 the additional auxiliary time (s/stem).

With winch assistance, the effective work time per tree was calculated using the formula (2):

$$T = y_1 + y_2 + y_3 + y_4 + y_5 \tag{2}$$

where T is the effective work time of the harvesting operation (s/stem), y_1 the time of the harvest cycle (s/stem), y_2 the driving time to working point (s/stem), y_3 the additional auxiliary time (s/stem), y_4 the time spent on anchoring (s/stem) and y_5 driving time (s/stem).

The effective work time for harvesting the trees was converted into stem-specific effective-hour productivity using the following formula (3):

$$Pstem = \frac{3600 * Xstem}{Tstem} \tag{3}$$

where *Pstem* is the effective-hour productivity for the stem (m^3/E_0h), *Xstem* is the cubic volume of the stem (m^3), and *Tstem* is the effective work time of the stem (*s*).

In calculating productivity per stand, time elements of separate stems were not needed, but the productivity was calculated directly using formula (4):

$$Pstand = \frac{3600 * Xstand}{Tstand} \tag{4}$$

Table 2 Time consumption of work phases of clear cutting (*h*) on flat and slope terrain at a stand level

Work phase			Grapple to tree	Felling of tree	Moving of tree	Processing of tree	Additional times	Anchoring	Removal of anchoring	Driving	Effective hours	Interruptions (< 15 min)	Operating hours
Flat terrain		*h*	1.96	0.87	1.24	3.17	0.44	–	–	–	7.94	0.49	8.43
		%	24.7	11	15.7	39.9	5.5	–	–	–	100	6.2	
Slope terrain	With winch	*h*	1.88	0.8	1.19	2.81	0.58	0.42	0.21	0.36	8.56	0.9	9.47
		%	22	9.33	14	32.8	6.83	4.91	2.49	4.24	100	10.7	
	Without winch	*h*	1.88	0.8	1.19	2.81	0.58	–	–	–	7.56	–	–
		%	24.9	10.6	15.7	37.2	7.7	–	–	–	100	–	–

h = Working hour, % = Cumulative share as percent

where *Pstand* is the effective-hour productivity per stand (m^3/E_0h), *Xstand* is the total cubic volume of stems of stand (m^3), and *Tstand* is the total effective work time of stand (*s*).

Statistical analysis

This consisted of statistical tests, correlations, and causality analyses performed using SPSS-25X (SPSS Inc. 1988). The statistical differences between the harvesting methods were compared with regards to factors affecting the time consumption of the work phases in those units where the same species or operator had been used. Statistical differences between the time study units (stands) were examined with the Kruskal–Wallis's test (K-W) and the Mann–Whitney U-test (M-W) (Hollander and Wolfe 1973).

In addition to time-consumption data, only stem volume (m^3) and the commercial length of the stem (m) were continuous tree- related variables. Because the terrain, the tree species, the operator, and the cutting method were discrete variables, the examination of the causality and correlation between them was not reasonable nor meaningful (Heikkilä 2001). The decision to use stem volume in regression analysis was made after correlation analyses of continuous explanatory variables, which used Spearman's correlation coefficient suitable for asymmetric distributions (Schober et al. 2018).

Statistical modeling uses mathematical models and assumptions to predict the real world (Henley et al. 2020). In the regression analysis, the predictor variable that contributed the most to the prediction equation in relation to the increase of the multiple-correlation value was entered first. The modeling process was continued if additional variables added R^2 value or anything statistically meaningful to the regression equation. It was also possible to drop nonsignificant control variables from the regression equation if statistical significance decreased. In the modeling, the *p*-value of statistically meaningful variables was lower than 0.05. For the solution of research issues, several kinds of models were developed for operations at stand and tree level:

- Linear regression model at the stand level,
- Quadratic model at the stand level,
- Quadratic model at the tree level,
- Quadratic model for flat terrains at the tree level,
- Quadratic model for slopes at the tree level.

Table 3 Time consumption of work phases in harvesting methods and statistical differences between them on flat (F) and sloping (S) terrains

Work phases	Species_ Operator	F				S		
		A	B	C	K-W	D	E	M-W
Grapple to tree	Es1	6.17	5.49	6.17	0.001*	6.96	7.34	0.207
	Es2	5.69	5.86	5.95	0.444	6.19	7.10	0.000*
	Pt1	–	–	–	–	6.92	6.94	0.923
	Pt2	6.56	6.89	6.55	0.730	6.86	6.65	0.410
Felling of tree	Es1	3.23	2.46	3.27	0.000*	3.54	3.09	0.003*
	Es2	2.67	2.89	2.83	0.297	3.05	3.13	0.666
	Pt1	–	–	–	–	3.04	3.00	0.813
	Pt2	3.27	2.75	2.84	0.008*	3.24	2.70	0.017*
Moving of tree	Es1	4.06	4.69	3.29	0.000*	3.81	4.79	0.000*
	Es2	3.70	3.88	2.91	0.000*	3.27	3.66	0.009*
	Pt1	–	–	–	–	4.92	4.24	0.005*
	Pt2	3.93	4.08	4.21	0.045*	4.38	4.73	0.267
Processing of tree	Es1	11.4	10.5	12.4	0.019*	12.3	11.7	0.518
	Es2	9.71	10.6	11.5	0.001*	11.9	10.9	0.070
	Pt1	–	–	–	–	8.81	9.18	0.150
	Pt2	7.39	6.34	10.0	0.000*	9.18	9.02	0.703

A = sideways cutting at the edge of the cutting front, B = sideways cutting inside the cutting front, C = forward cutting in the middle of the cutting front, D = sideways cutting at the edge of the cutting front with traction assistance, E = sideways cutting inside the cutting front with traction assistance, Es = eucalyptus, Pt = pine, 1 = operator and 2 = operator 2, K-W = Kruskal–Wallis test, M-W = Mann–Whitney U-test. * Statistical difference at the significance level 0.05

Results

Time distributions of clear cutting on flat and sloping terrains

The additional work phases for winch assistance in hours of time consumption (8.6 h) on the slope was 11.6% (Table 2). The other work phases of the harvesting methods on flat terrain were slightly higher than those on slopes. If anchoring time is not included, the time shares are almost the same. Further, higher percentage shares were measured for "driving to working point" and "driving" on slopes compared to flat terrain. The "processing of tree" was the most time-consuming phase, both on flat terrain (39.9%) and on slopes (32.8%). The time spent for "grapple to tree" was the next highest on flat (24.7%) and sloping terrains (22.0%). In both, the "felling of tree" and "moving of tree" (stem to log pile and stem to pulp pile) consumed less time than the work phases mentioned above.

On flat terrain, "additional (auxiliary) times" (5.5%) typically consisted of processing broken stems or for interrupted work cycles, which were counted as the "additional times" if the cutting work was interrupted and which, after the operator continued directly to process the next tree. On the slope, "additional times" (6.8%) typically consisted of arranging the log piles and reducing the stumps.

The "interruptions" measured in the study were mechanical in nature and related to the maintenance of the cutting device. The occurrence of mechanical "interruptions" during cutting was irregular, and there were no "interruptions" in stands on flat terrain. With the winch assistance, "interruptions" of varying length were measured after anchoring, before the cutting started, and after "driving" before removing the anchoring. Consequently, the share of "interruptions" in the operating time was 4.5% units higher on the slope compared to the flat terrain.

Time consumption analysis of work phases of cutting methods

Table 3 shows the time consumption of work phases in the cutting cycle and the statistical differences between harvesting methods regarding affecting variables on flat and slope terrains. Results on the flat terrain are considered first. When the time consumption of "grapple to tree" is considered, it differed significantly between the harvesting methods only in one comparison of time study units. The difference was observed in eucalyptus plantations in operator 1's work (K-W, $p = 0.001$). However, when looking at the time consumed, only the lower consumption of "grapple to tree" (11%, 0.7 s) by method B clearly distinguishes the cutting methods A and C.

Table 4 Correlation matrix of tree characteristics and time consumption of harvesting are compared

Variables	Correlation (r_s)		
	V	L	T
V	1.000	0.770**	0.886**
L	0.770**	1.000	0.680**
T	0.886**	0.680**	1.000

V = stem volume, (m^3); L = stem length, (m); T = time consumption (sec.).

** = Statistical difference at the significance level < 0.001

There were two statistical differences in time consumption of "felling of tree" between the harvesting methods. Differences were a maximum 0.8 s. Again, this was in eucalyptus plantations by operator 1 (K-W, $p < 0.000$). Another difference was observed in pine plantations with operator 2 (K-W, $p = 0.008$). There was a statistically significant difference between the harvesting methods in all time comparisons for analyzing the "moving of tree" (stem to log pile and stem to pulp pile). This difference was observed in eucalyptus plantations for both operators, where time consumption of the "moving of tree" was the lowest in method C (max 1.4 s), which was 19–30% lower than the other methods. In addition, in the pine plantations, time consumption of "moving of tree" by operator 2 was 3.2% higher (K-W, $p = 0.045$).

There were statistically significant differences in all time consumptions of "processing of tree" between the cutting methods. With operator 1, the differences were observed for both eucalyptus (K-W, $p = 0.019$) and pine plantations (K-W, $p = 0.001$). For operator 2, differences between cutting methods were in pine plantations (K-W, $p = 0.001$). When these time consumptions were compared, the lower time consumption with method B (max. 3.6 s.) stands out from the other methods, particularly from method C. The situation was the same when the time consumptions of "felling of tree" were compared because in method C, time consumed was often higher compared to methods A and B.

There were significant differences between harvesting methods D and E in time consumption of work phases in stands on slopes. In the first phase, for operator 2 in the eucalyptus plantations, a statistically significant difference (M-W, $p < 0.001$) was observed in the time consumption of the "grapple to tree" (0.9 s) step. Otherwise, there was no clear advantage of either cutting method in time consumption. Significant differences between the cutting methods were also observed in the "felling of tree" phase, for example, for operator 2 working in the pine plantations (M-W, $p = 0.017$). The time consumption for this work phase was brief compared to other work phases. Even the significant differences between the cutting methods were slight in working time (0.5 s.), and it is not possible to make firm recommendations in favor of either harvesting methods.

In the third work phase "moving of tree" (stem to log pile and stem to pulp pile), there were significant differences between the harvesting methods. With operator 1, the difference was in the eucalyptus plantation (K-W, $p < 0.001$). However, when looking at the average time consumptions, the "moving of tree" phase did not stand out in favor of either cutting methods. In the last work phase "processing of tree", there were no differences (max 1.0 s.). Although the processing time did not clearly favor either harvesting methods, in the eucalyptus plantations the average processing

Table 5 Linear regression of effective-hour productivity (m^3/E_0h) in all data

Number of trees	Parameter	Estimate	Error	*T*-value	*P*-value	R^2
2130	β_0	1.02	0.47	23.51	0.000*	0.89
	β_1	97.55	1.07	91.25	0.000*	

β_0 = constant term, β_1 = regression parameter for stem volume. * = Statistical difference at the significance level 0.05

Table 6 Quadratic regression model of effective-hour productivity (m^3/E_0h) for comparison of harvesting methods in all harvesting cycle data

Number of trees	Parameter	Estimate	Error	*t*-value	*p*-value	R^2
2130	β_0	7.07	0.71	9.93	0.000*	0.93
	β_1	144.69	3.06	47.26	0.000*	
	β_2	–54.86	3.41	–16.12	0.000*	
	β_3	–11.26	0.43	–26.51	0.000*	
	β_4	0.12	0.41	0.30	0.768	
	β_5	2.21	0.39	5.70	0.000*	
	β_6	1.30	0.41	3.20	0.001*	
	β_7	–0.89	0.58	–1.55	0.122	

* = Statistical difference at the significance level 0.05

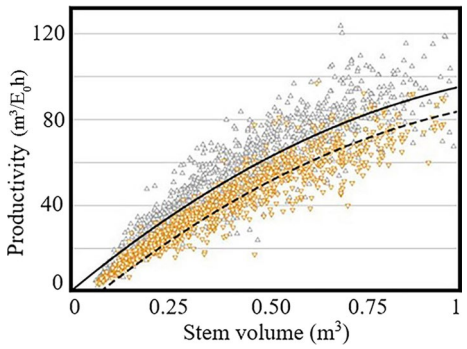


Fig. 8 Effect of terrain and stem size on effective-hour productivity (m^3/E_0h); solid line is flat terrain, dash line is sloping terrain, grey triangles = flat terrain, yellow triangles = sloping terrain

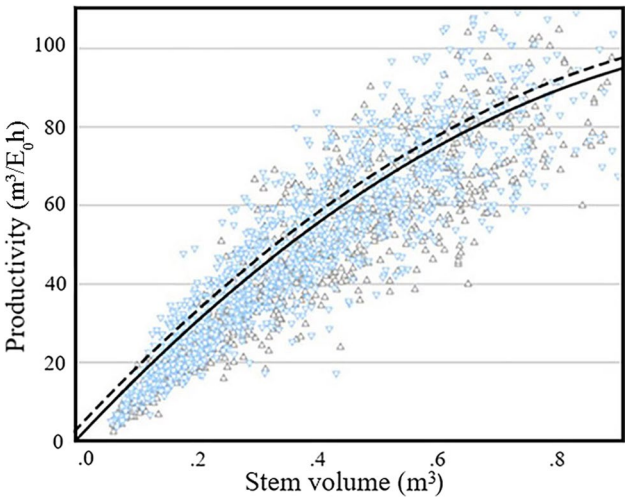


Fig. 9 Effect of operator and stem size (m^3/E_0h) on effective-hour productivity ($m.^3/E_0h$) at all harvesting phases; solid line is productivity curve for operator 1; dashed line is productivity curve for operator 2. Brown triangles depict work of operator 1; blue triangles work of operator 2

times of method D were slightly less compared to method E. In addition, the variation between the observations, i.e., time consumptions in stands, were large.

Productivity analysis of harvesting methods

Table 4 shows the linear dependence between the variables of tree size and time consumption of the cutting cycle by correlation analysis. The correlation (r_s) between continuous variables of tree size indicates a significant dependence between stem length and volume (Table 4). A strong positive correlation indicates that the volume of the stem increases almost linearly as the length of the stem increases. Both continuous variables can, therefore, be assumed to behave in the same way in the regression analysis. In statistical terms, there is a strong multicollinear relationship between them.

The linear correlation between the stem length and the time consumed was significant. However, since the linear correlation between stem volume and time was stronger, they were chosen as explanatory variables for regression modeling of effective-hour productivity. The linear regression model 1 with stem volume (m^3) as an explanation variable is:

$$E_i = \beta_0 + \beta_1 \cdot V_i + \varepsilon_i \quad (5)$$

where E_i is the effective-hour productivity (m^3/E_0h) of tree size i, V_i stem volume (m^3) of tree size i, β_0 a constant, β_1 a regression parameter for stem volume (m^3) of tree size i.

Table 5 shows the dependence of effective-hour productivity on the constant and stem volume of trees based on model 1. This model explains 89% of the harvester-operator system effective-hour productivity in all stands.

The combined impacts of the continues variables (stem volume) and the discrete variables (terrain, species, operator, cutting method) on effective-hour productivity were examined using a general quadratic regression model 2 (Table 6).

Table 7 Regression analysis of effective-hour productivity for comparison of harvesting methods A, B and C at tree level in eucalyptus and pine stands on flat terrain

Terrain	Species	Trees	Parameter	Estimate	Error	*t*-value	*p*-value	R^2
Flat	Eucalyptus	930 pcs	β_0	4.72	1.11	4.26	0.000*	
			β_1	161.76	5.13	3.56	0.000*	
			β_2	–68.07	5.66	12.04	0.000*	0.92
			β_3	0.79	0.79	0.99	0.320	
			β_4	–1.20	0.74	–1.63	0.103	
Flat	Pine	314 pcs	β_0	2.28	2.13	1.07	0.284	
			β_1	161.94	12.06	13.43	0.000*	
			β_2	–61.41	16.23	–3.78	0.000*	0.90
			β_3	4.81	1.29	3.76	0.000*	
			β_4	–1.87	1.36	–1.38	0.170	

* = Statistical difference at the significance level 0.05

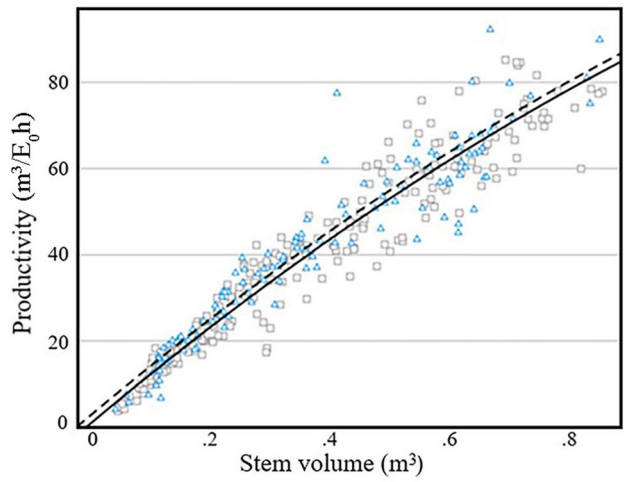


Fig. 10 Effect of stem size (m^3) on effective-hour productivity (m^3/E_0h) for harvesting methods in eucalyptus stands on flat terrain; ——— is method A, – – – – method B,——— method C, Triangles = method A, circles = method B, rectangles = method C

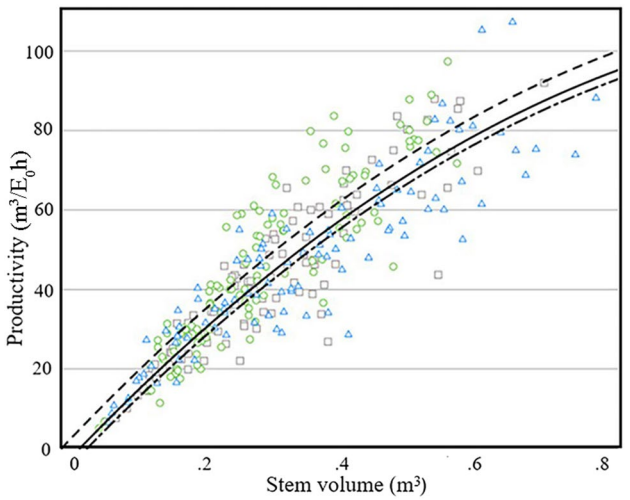


Fig. 11 Effect of tree size (m^3) on effective-hour productivity (m^3/E_0h) for harvesting methods in pine stands on flat terrain; ——— is method A, – – – – is method B,——— is method C, Triangle = method A, Circle = method B, Rectangle = method C

The model 2 was fitted to all cutting cycle stand data which followed the form:

$$P_i = \beta_0 + \beta_1 \cdot V_i + \beta_2 \cdot V_i^2 + \beta_3 \cdot T2_i + \beta_4 \cdot O2_i + \beta_5 \cdot S2_i + \beta_6 \cdot H2_i + \beta_7 \cdot H3_i + \varepsilon_i \quad (6)$$

where P_i is the effective-hour productivity (m^3/E_0h) per tree size i, V_i is volume (m^3) of stem i, $T2_i$ is the dummy variable for flat and sloping terrains, $O2_i$ is the dummy variable for operator 2 of two operators, and $S2_i$ is the dummy factor for pine of tree species. $H2_i$ is the dummy variable for time consumption (s/cutting cycle) of harvesting method B in respect to A of three harvesting methods, and $H3_i$ is the dummy variable for time consumption (s/cutting cycle) of harvesting method C in respect to A of the three methods. Table 6 describes the dependence of effective-hour productivity on the parameters of constant term β_0, tree size, terrain, operators, species, and time consumption based on model 2.

According to the model 2, harvesting method C did not explain significantly the variation of the productivity ($p = 0.122$). However, method B did describe the variation ($p = 0.001$). This regression model was also fitted to the harvesting data which improved the coefficient of determination ($R^2 = 0.93$) of the harvester-operator system's effective-hour productivity at the tree level. Both tree species and terrains were significant explanatory variables ($p < 0.001$). The productivity difference between the plantations on slopes and those on flats using Model 2 is shown in Fig. 8. The average harvesting in stands on slopes was 11.26 m^3/E_0h less than in stands on flat terrain. There was also a significant difference in effective-hour productivity between these two plantation sites (M-W, $p < 0.001$).

The effect of harvester operators on effective-hour productivity was also analyzed using Model 2. Operator was not a significant explanatory variable ($p = 0.768$). This information was used in additional modeling for more precise analysis of harvesting methods. Figure 9 shows operator productivity curves in harvesting in all stand data. Productivity difference between the operators was 0.12 m^3/E_0h in favor of operator 2.

Table 8 Regression analysis of effective-hour productivity for comparison of harvesting methods D and E at the tree level in eucalyptus and pine stands on slopes

Terrain	Species	Trees	Parameter	Estimate	Error	*t*-value	*p*-value	R^2
Slope	Eucalyptus	367 pcs	β_0	3.58	1.06	3.34	0.001*	0.95
			β_1	105.15	5.48	19.19	0.000*	
			β_2	–20.54	–0.20	–3.42	0.001*	
			β_3	1.75	0.04	2.23	0.027*	
Slope	Pine	492 pcs	β_0	2.36	1.18	1.99	0.047*	0.92
			β_1	131.50	5.82	22.59	0.000*	
			β_2	–47.69	6.67	–7.15	0.000*	
			β_3	–0.03	0.63	–0.05	0.996	

* = Statistical difference at significance level 0.05

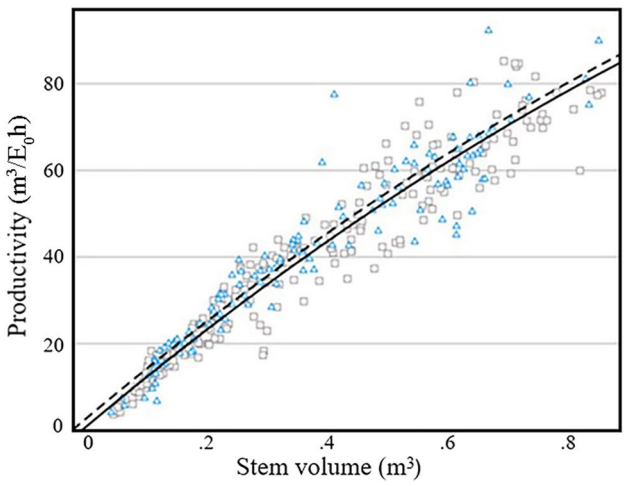


Fig. 12 Effect of harvesting method and tree size (m^3) on effective-hour productivity (m^3/E_0h) for eucalyptus stands on slopes; ——— is method D, – – – – method E. Grey rectangles are observations of method D. Blue triangles depict method E

Effect of cutting methods on productivity on flat terrain

In this study, the impact of harvesting methods on effective-hour productivity was modelled separately for the terrains and tree species. In addition, comparison of harvesting methods was also determined with time consumption. The comparison used the "basic" harvesting cycle, which did not include the work phases of "driving to the working point" and "additional auxiliary times". This was possible because the effective-hour productivity was analyzed at tree level, which produced a new quadratic model 3:

$$P_i = \beta_0 + \beta_1 \cdot V_i + \beta_2 \cdot V_i^2 + \beta_3 \cdot H2_i + \beta_4 \cdot H3_i + \varepsilon_i \quad (7)$$

where P_i is the effective-hour productivity (m^3/E_0h) for stem i, V_i is volume (m^3) of stem i, $H2_i$ is the dummy variable for time consumption of cutting method B (s/basic cutting cycle) in respect to method A of three harvesting methods for stem i, and $H3_i$ is the dummy variable for time consumption of cutting method C (s/basic cutting cycle) in respect to method A of three harvesting methods for stem i. The dependence of effective-hour productivity (m^3/E_0h) on stem size (m^3) and time consumption of harvesting methods (s/basic cutting cycle) in pine and eucalyptus stands on flat terrain based on Model 3 is shown in Table 7. The regression models for pine and eucalyptus plantations explain clearly the variation in effective-hour productivity in respect to harvesting method, tree size and harvesting cycle time in the tree specific data ($R^2 = 0.90$–0.92).

Figures 10 and 11 show effective-hour productivity curves for harvesting methods A, B, C as a function of stem size (m^3) in clear cuttings on flat terrain for eucalyptus and pine stands based on model 3. When the regression model was fitted to the stand data of the eucalyptus plantations, harvesting methods were not significant explanatory variables (Table 7, Fig. 10). In the eucalyptus plantations, productivity differences varied between 0 and 1.99 m^3/E_0h, with method B being the most productive, and method C the least. However, when model 3 was adapted to the pine plantations on flat terrain (Fig. 11), method B was a significant explanatory variable ($p < 0.000$) (Table 7). Method B was 4.81 m^3/E_0h more productive than method A, and 6.68 m^3/E_0h more productive than method C. In addition, method C did not explain the variation in productivity in pine plantations ($p = 0.170$).

Effect of harvesting methods on productivity on slopes

Effects of harvesting methods D and E were determined based on a basic cutting cycle. The effect of the different

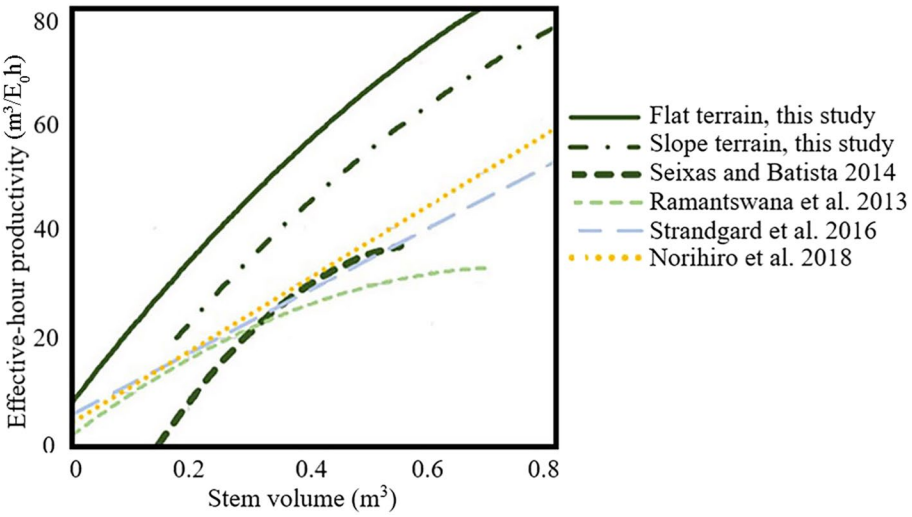


Fig. 13 Comparison of harvesting productivity (m^3/E_0h) with previous studies in eucalyptus plantations

harvesting methods was analyzed using model 4, which resulted in a new quadratic model.

$$P_i = \beta_0 + \beta_1 \cdot V_i + \beta_2 \cdot V_i^2 + \beta_3 \cdot H2_i + \varepsilon_i \quad (8)$$

where, P_i is the effective-hour productivity (m^3/E_0h) for stem i, V_i is volume (m^3) of stem i, $H2_i$ is the dummy variable for time consumption of method E (s/basic cutting cycle) in two harvesting methods for stem i. Table 8 shows the solution parameters of regression model 4 in harvesting conditions on sloping terrain. Again, the regression models for the plantations clearly explain variations in effective-hour productivity in respect to method of harvesting, tree size and harvesting cycle time ($R^2 = 0.92–0.95$).

When regression model 4 was adapted to the methods of harvesting the pine plantations, methods D and E were not statistically significant for the determination of wood harvesting productivity. In the pine plantations on slopes, productivity variation between methods was minimum ($\beta_3 = -0.03$). In the eucalyptus plantations, method E was a significant explanation variable ($p = 0.001$), 1.75 m^3/E_0h more productive compared to method D (Fig. 12).

Discussion

Effects of felling technique in tree cutting cycle

The strength of harvesting of a harvester-operator system are clearer when the differences in cutting cycle work phases between different harvesting methods are described precisely (Fig. 7). In addition, time consumption of cutting methods was measured at the tree work phase level which enabled an accurate and detailed analysis. Of the work phases, time consumption of the "moving of tree" changed most significantly between the types of harvesting methods (Table 3), of which the sideways felling technique inside cutting edge (method B) was most effective both on flat terrain and on slopes.

This conclusion needs to be supported by explanatory comments about the changes in other work phases and the influence of relationships of the work phases that caused the changes. When the felling technique was changed, it affected the time spent on "felling of tree" only a little but affected the "moving of tree" more because the tree was in a different position in relation to the harvester and to the pile. In addition, the tree was moved immediately after "felling of tree" phase. Consequently, on the end of the work phase chain, the "felling of tree" affected "processing of tree" indirectly through the "moving of tree" because "processing of tree" took place later in the work phase.

Harvesting productivity in plantations

Previous harvesting productivity models for plantations are reviewed in Fig. 1. When the productivity curves of this study are compared to previous studies, productivity was clearly at a higher level (Fig. 13). If the average stem volume was between 2.0 and 0.3 m^3, the harvesting productivity for eucalyptus was between 10 and 20 m^3/E_0h in previous studies, while in this study, the effective-hour productivity was between 23 and 45 m^3/E_0h on slopes and 34–47 m^3/E_0h on flat terrain. The comparison used productivity model 2 that was adapted to all the research material, where the harvesting conditions of the terrain was described as dummy variables for flat terrains and slopes. Considering previous studies included in the comparison: three curves described the productivity for excavator-based harvesters (Ramantswana et al. 2013; Strandgard et al. 2016; Norihiro et al. 2018) and one described the productivity for a wheeled harvester (Seixas and Batista 2014).

As there are still numerous excavator-based harvesters in use in the research area, the comparison of the results with a wheeled harvester to excavator-based harvester can be considered appropriate here (Fig. 13). Ramantswana et al. (2013) compared the harvesting of eucalyptus plantations established under different regeneration methods in South Africa. A productivity model was selected for planted trees when the number of trees was more than 540. The average stem diameter and stand density were slightly lower, but the harvesting conditions can be considered comparable in this study in terms of data. Strandgard et al. (2016) established a productivity model for eucalyptus plantations in Australia. The data was collected from 47 harvesters working on plantations on slight slopes with lower densities. Norihiro et al. (2018) created a tree-specific productivity model for eucalyptus plantations in South Africa. The data was compiled from five separate studies, some of which were with stands with flat terrain and some on slopes. Seixas and Batista (2014) compared productivities for excavator-mounted and wheeled cut-to-length harvesters in Brazilian eucalyptus plantations. The curve of their model describing the productivity of a wheeled harvester was chosen for this comparison.

A reliable productivity model also has been developed for harvesting conditions in South American plantations that reports productivities of cut-to-length harvesting by wheeled harvesters (Olivera et al. 2016). However, productivity in their study was modeled as a function of stem diameter and was omitted in this comparison.

Validity of data and modeling

As a research environment, tree plantations are uniform stands and it was not possible to consider all environmental factors such as seasonal variations, soil conditions, and

weather, which can significantly affect logging operations. In spite of this, average stem size varied between the harvesting methods (Table 1). This weakened the reliability of time consumption analysis of work phases of harvesting methods. It should be noted, however, that the deviant observations in the data may significantly disturb statistical comparisons (Palander et al. 2012). One option could be to collect a sufficiently large data set so that the impact of outliers is reduced. In this respect, the material of this study could be larger for comparison of work phase time variations at the stand level because making unequivocal conclusions was difficult (Table 3). Therefore, diameter differences may also have an influence on significant differences between harvesting time consumptions. Another option could be additional studies with environmentally specific data for consideration of possible environmental factors.

Manual time studies such as this, in which work was observed visually using a video during wood harvesting, have established a good method for time and motion studies, although automatic time study has recently become common (Nuutinen 2013; Palander et al. 2013). With an automatic time study, the division of work phases could not have been carried out to the extent required by these harvesting conditions. As an example, measuring time consumption of work phases, such for winch anchoring, requires the collection of video material and manual recording.

Time distributions of the work phases provided poor and unambiguous information on the impact of felling technique on efficiency of harvesting methods, especially for comparisons between flat terrain and slopes. Therefore, a more precise productivity analysis was necessary. The common quantitative statistical methods used in this study have been successfully applied in previous studies (e.g., Ovaskainen 2009; Nuutinen 2013). However, even if research methods of productivity analysis have been established, statistical modeling is always accompanied by uncertainty. Therefore, the remaining discussion considers issues related to precise modeling. For evaluating the reliability of the results, this study used a significant level of 5% ($p < 0.05$) in the interpretation of models.

A quadratic polynomial model used in this study has commonly been used in Nordic harvesting conditions (e.g., Nurminen et al. 2006). In previous studies of plantations, linear regression models and quadratic polynomial models have been used successfully for describing productivity (Visser and Spinelli 2012). In addition, Ramantswana et al. (2013) used a quadratic polynomial model ($R^2 = 0.88$) (Fig. 13). In comparable studies, Strandgard et al. (2016) and Norihiro et al. (2018) used linear models to explain productivity, which produced coefficients of determination of $R^2 = 0.79$ and $R^2 = 0.62$, respectively. It appears that the R^2 values of the models in this study justify better coefficients of determination for describing productivity in tree plantations. Obviously precise modeling was a useful approach, in which explanatory variables of productivity were selected carefully for separate harvesting conditions. While the results are relevant for plantations in Parana in Brazil, the direct applicability of the same methods to different geographical or climatic conditions may be limited without additional studies.

Linear regression models were tested first to explain effective-hour productivity and were adapted to all research material. In the linear regression Model 1, with stem volume (m^3) as an explanatory variable, the coefficient of determination was high ($R^2 = 0.89$). This justified the selection of stem volume (m^3) as a variable for polynomial regression models that explained the effective-hour productivity for cutting methods in different harvesting conditions. At the stand level, the quadratic polynomial model, (Model 2), was best suited to all data ($n = 2130$). The model was chosen for the study because it was considered to explain the variations to a sufficient degree when dummy variables were used to reveal the effects of the discrete variables of harvesting conditions (terrain, species, operator and cutting method) on effective-hour productivity. In the regression model of this study, relatively high coefficients of determinations were achieved (R^2 was 0.93).

Identifying the most productive felling technique of cutting methods required the tree-level approach in modeling (Models 3 and 4). With respect to harvesting conditions, modeling should be done separately for terrains and tree species. In addition to tree size (stem volume), modeling was done using the time consumption of the cutting cycle as an explanatory variable. The modeling used the "basic" cutting cycle which did not include the work phases of "driving to the working point" and "the additional auxiliary times". When the relations between input and output data of the effective-hour productivity model were analyzed, this model predicted the effective-hour productivity at 95% (R^2 was 0.95). However, this study focused only on *Pinus taeda* and *Eucalyptus saligna*. Applying the same methods to other tree species may not be as effective and would require further investigation.

Correlation tests are an important part of precise modeling. After consideration of tests between tree characteristics, stem volume was chosen as the most useful continuous variable for the regression analyses, as a function of which the effective-hour productivity curve was depicted graphically in the causality figures. Spearman's correlation is the commonly used measure of correlation between two ordinal level variables as well as continuous level variables. According to an interpretation of Spearman correlation coefficients, the relationship between cutting cycle time (sec) and stem volume (m^3) was very strong ($r_s = 0.886$) (Dancey and Reidy

2004). This showed their importance for modeling productivity (m^3/E_0h).

In this precise modeling, the operator phase was eliminated, and terrain and tree species were considered separately. These decisions may increase the coefficient of determination. Traditionally, for increasing validity in comparative time studies, there should be at least three operators, each of whom would work with all the investigated harvesting conditions and machines. Contrary to the original plan of the study, however, the number of test operators was reduced from three to two. Therefore, the effect of operator successfully reduced in the modeling of effective-hour productivity. The productivity difference between the operators was 2.21 m^3/E_0h in favor of operator 2. This difference was statistically insignificant ($p=0.768$) in model 2. Therefore, operator influence was eliminated by using experienced workers, because 'operator' did not explain the variation of effective-hour productivity in the data used in model 2. However, the influence of operator training and experience are important factors which could be critical for fully understanding productivity variations. Therefore, this could be studied more in-depth with less experienced operators. To control the operator effect, some studies have used average operators (Harstela 1991) which makes their selection a challenging task. In choosing the operators for this study, they were required to work with the old method (Method A) and were considered best at that work. Even if the operators had learned the new method quickly, it is possible that the former method still influenced the results (Palander et al. 2012). For this reason, the results of the first two research days could have been removed from the data (Harstela 1991). However, there were insufficient financial resources for removing data in this study. Moreover, it is important to note that the combination of operator-machine systems produces productivity differences (Palander et al. 2022). Therefore, the variability by the harvester was reduced by using the same harvester and adjusting the speed of the boom to a constant, which might increase accuracy of modeling.

Conclusion

The most productive felling techniques for eucalyptus and pine plantations on flat and on sloping terrains were identified. The aim of this study compared modeling approaches. A linear model used at stand level explained 89% of the variations of observations. With the same data, a quadratic regression model performed better (93%) and may be used for examination the impacts of the continuous variable (stem volume) and the discrete variables (terrain, species, operator and cutting method) on effective-hour productivity. In addition to stem volume, modeling must use the time consumption of the cutting cycle as an explanatory variable. In this study, the "basic" cutting cycle was used which did not include the work phases of "driving to the working point" and "the additional auxiliary times". Further, modeling should be done separately for different terrains and tree species. Thereafter, significantly affecting the work phase "moving of tree" on productivity could be identified. When the relations between input and output data of effective-hour productivity were analyzed, this application of a quadratic model predicted the productivity precisely and therefore it is recommended for work studies for eucalyptus and pine plantations on flat and on sloping terrain.

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Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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