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Economic efficiency of fully mechanized timber harvesting in coniferous stands of the 2nd age class

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Abstract: The aim of the study was to determine the unit costs of mechanized timber harvesting in pine stands where early thinning was being performed, and to determine the relationship between the cost level and the volume of harvested trees, the harvester model and field conditions. Analysis focused on timber harvesting with the use of small- and mid-sized harvesters. The tested harvesters were specialized forestry machines (Vimek, Sampo, Profi-Pro, Ponsse) and a construction machine (Fao-Far). Terrain accessibility variants were distinguished in relation to furrows between which trees had been planted in the past: flat terrain with the depth of unevenness up to 20 cm, up to 40 cm, and over 40 cm. The operating costs of the analyzed harvesters varied significantly, an hour of operation of the machine that was the cheapest to use (Fao-Far) cost nearly 2.5 times less (37.3 €) than the Profi-Pro harvester, which was the most expensive in operation (89.1 €). In stands without furrows, the lowest unit costs were noted for the Sampo harvester: 8.4 €·m^{-3}. The other small harvesters, Vimek and Fao-Far, were slightly more expensive to use: 10.3 €·m^{-3} and 9.1 €·m^{-3}, respectively. In areas where furrows were up to 20 cm deep, the cheapest solution was timber harvesting with the Fao-Far harvester (9.9 €·m^{-3}). In areas where furrows were up to 40 cm deep, timber harvesting was the cheapest with the Sampo harvester (10.7 €·m^{-3}), while harvesters Vimek and Fao-Far were characterized by a similar cost intensity, amounting to just over 12 €·m^{-3}. In stands with furrows deeper than 40 cm, it was cheapest to use the Ponsse harvester (10.4 €·m^{-3}). The cost of operation of the Profi-Pro harvester was higher by approx. 25% (14.0 €·m^{-3}). With the current level of the financing of mechanized timber harvesting in Poland (about 11 €·m^{-3}), small harvesters Vimek, Sampo and Fao-Far are cost-effective when single tree volume exceeds 0.05-0.06 m^3. Medium harvesters, Profi-Pro and Ponsse, are cost-effective when unit volumes of harvested trees reach 0.08 and 0.11 m^3 respectively. The cost-effectiveness of the tested harvesters increased when working shifts were extended.

Keywords: cut-to-length, harvesters, unit costs, timber harvesting efficiency, early thinning in pine stands

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Introduction

Silviculture in managed stands should consider two criteria: improving the technical quality of wood and increasing its resistance to the harmful effects of environmental factors, both abiotic and biotic ones. By reducing the slenderness coefficient of individual trees, the thinning maintenance cuts improve the stability of crop trees, which constitute the future foundation of the stand (Fahlviket al. 2015, Primicia et al. 2016, Novák et al. 2017). An important goal of thinning, which improves the stability of the entire stand, is also to support biodiversity, naturally forming biogroups, in which future trees are often characterized by high growth dynamics and good technical quality (Jaworski 2013, Thurn & Pretzsch 2021). Timber harvesting in thinning stands has its economic justification due to the growing demand for timber in the timber and energy industry (Holzleitner et al. 2019). In young stands, Eliasson (1999) and Bergström et al. (2007) used simulation models to determine the effect of cutting intensity on the efficiency of the harvesting process. These authors documented the benefits of large-area thinning, especially in younger age classes and in the case of biomass demand. In Poland, the area of stands where thinning is performed has increased in the last 10 years by approx. 10%, reaching 354 thousand ha in 2020. Over 13,920,000 m^3 of merchantable timber are harvested in thinned stands, including the majority of medium-sized assortments important for the timber sector (Statistical Yearbook of Forestry 2020). Mechanized logging with harvesters and forwarders, has its particular justification in thinning stands, primarily due to its ecological, economic and ergonomic advantages (Sowa et al. 2007, Spinelli et al. 2010, Dvořák et al. 2011, Zinkevičiuset al. 2012, Kulak et al. 2017, Kováč et al. 2021, Mederski et al. 2018, Szewczyk et al. 2020, Kormanek & Dvořák 2022).

In Poland, approximately 45% of timber is obtained by means of harvesters. Although the number of harvesters in Poland has increased several times since 2000 and currently amounts to approx. 530 machines (Mederski et al. 2016, Moskalik et al. 2017), their use in younger stands is limited. In 2016 and 2019, the introduction of legal regulations obliging the administration of state forests to provide access to stands through a network of skid trails is conducive to the introduction of machines and to some extent facilitates the designation of trees for removal (Order no. 35/2016, ZHL 2019). Nowadays, it is common for mechanized logging to make stands accessible by skid trails at 20-meter intervals (Stempski & Rutkowski 2021). In stands previously accessed by skid trails at intervals greater than the double overhang of hydraulic cranes (about 30 m), it is recommended to cut trees inaccessible to harvester heads with chainsaws (midfield method) (Mederski 2006).

High tree density in thinning stands and low unit volume of felled trees, as well as the need to reduce the purchase costs of machines, have led to the introduction of many design solutions in harvesters (Spinelli & Magagnotti 2010, Więsik 2015). Single-grip harvesters are best suited to working in dense stands of younger age classes. Due to their high mobility, achieved thanks to the application of the usually wheeled running gear and advanced traction control systems, these machines are widely used, also in early thinning (Dvořák et al. 2011, Lazdiņš et al. 2016, Zimelis 2017, Mederski et al. 2019). The problem is the high purchasing costs of single-grip harvesters, especially medium-sized ones (Tylek & Poroszewski 2015, Apăfăian et al. 2017, Proto et al. 2018), and tender requirements for technical equipment, as well as technical non-price criteria for forestry entrepreneurs (Rutkowski et al. 2022). Many cheaper solutions have appeared on the market, including farm tractors or construction machines used as carriers for harvester cranes and processing heads equipped with computer systems controlling the processes of tree felling and processing. In easier working conditions, such as those in flat areas and in stands of younger age classes, farm tractors with harvester heads are used increasingly (Russell & Mortimer 2005, Wójcik 2010). In addition to standard forestry equipment (e.g. ROPS: *Roll-Over Protective Structures* and FOPS: *Falling Object*

Protective Structures), the adaptation of farm tractors to felling and processing tasks involves the installation of a swivel seat and the ability to control the tractor when it is turned by 180o. The share of harvesters for which construction machinery is used as a carrier is also gradually increasing (Kormanek & Baj 2018, Leszczyński et al. 2021). Their adaptation to work in forest conditions is similar to that of farm tractors.

In early thinning, timber harvesting is particularly difficult. This is due to both the high density of such stands and the small volume of the harvested trees (Grodecki 1988, Kärhä et al. 2004, Mederski 2006, Mederski et al. 2016, Labelle 2017, Laitila & Väätäinen 2023). For this reason, it is in stands of younger age classes that the greatest difficulties lie in determination of the standards of time-consumption and the level of labor costs (Szewczyk 2014, Szewczyk et al. 2014, Rosińska et al. 2022). The aim of our research was to estimate the unit costs of mechanized timber harvesting in pine stands of the 2nd age class, where early thinning was performed, and to determine the relationship between the cost level, volume of harvested trees and the type of harvester used.

Methods

The research was conducted in the southern part of Poland, in the Rudy Raciborskie Forest District, which is part of the Regional Directorate of State Forests in Katowice (Figure 1).

Field work was carried out in the Kotlarnia and Borowiec forest units. Selected forest valuation features of the areas in which the research was done are presented in Table 1.

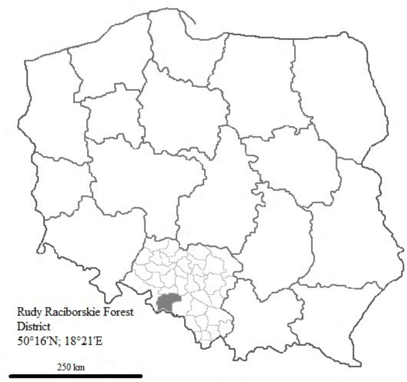

Figure 1 Location of research plots, Rudy Raciborskie Forest District, Poland.

Table 1 Valuation features of the forest compartments in which the research was carried out.

Forest unit	Compart. Location	Area [ha]	Forest site type	Stand composition*	Age [yrs]	DBH [cm]	H [m]	M.timber [m³·ha⁻¹]	Thin.int [%]
Kotlarnia	24b 50.255 N, 18.405 E	15.72	Moist coniferous forest	100% Scots pine	24	12	11	157	18.3
Kotlarnia	31a 50.250 N, 18.417 E	13.10		60% Scots pine 20% European larch 10% Common birch 10% Black alder	26 26 26 26	15 16 13 13	13 15 13 13	99 36 18 13	17.3
Kotlarnia	31b 50.247 N, 18.419 E	7.63		80% Scots pine 10% Common birch 10% European larch	26 26 26	15 13 16	13 13 16	145 18 18	15.9
Borowiec	93b 50.227 N, 18.413 E	29.40		60% Scots pine 30% Common birch 10% European larch	24 24 24	11 10 13	12 10 13	66 22 14	28.1
Borowiec	100b 50.224 N, 18.373 E	22.25		90% Scots pine 10% Common birch	24 24	8 9	8 10	49 9	29.5
Borowiec	142a 50.210 N, 18.376 E	28.03		60% Scots pine 30% Common birch 10% European larch	23 23 23	12 10 13	11 11 13	62 22 9	30.9

Note: Comartp.: compartment; H: height; M.timber: merchantable timber; Thin.int: thinning intensity. * - within compartment 24b the stand resulted from natural regeneration, in other compartments, stands were created by planting in rows.

We analyzed the process of timber harvesting in the CTL harvesting method with the use of Vimek, Sampo, Profi-Pro, Ponsse, and Fao-Far harvesters. The machines tested were specialized harvesters from the groups of small and mid-sized machines (Vimek, Sampo, Profi-Pro, Ponsse) and a construction machine (Fao-Far) (Table 2). The timber was cross-cut into logs that were 2.5 m long. All of the tested machines were equipped with specialized hydraulic cranes as well as felling and delimbing heads. Harvesters were in good technical condition, 2-5 years old, and had worked 2000-8000 hours. The tasks were performed by well-trained operators, in their thirties and with 5-10 years of work experience, who had undergone appropriate training concerning timber quality prior to the commencement of this research. They had also been informed about the aim of the research and the method of data collection.

Before starting the research tasks, we had selected parts of the stands that were homogeneous. Here we designated research cutting plots with an area of 1.5 ha each, one for each of the tested machines. The trees intended for felling had been designated by field workers of the forest administration and marked with paint in such a way that they were clearly visible to machine operators. The main thinning treatment was planned in the upper layer of the stand according to the principles of the selective crown thinning based on Shädelin's method (ZHL 2012). The intensity of thinning on each research plot was approximately 30 $m^3 \cdot ha^{-1}$.

The machines moved along straight-line skid trails set up at a distance of approx. 20 m or 10 m, depending on the reach of the crane and the width resulting from the type of machine (machine width plus 0.5-1.0 m). The arrangement of skid trails in the stands where the measurements took place was correlated with the occurring terrain unevenness which had a linear nature (planting ridges, beds), i.e. traces of soil preparation for planting, visible in the field. Accordingly, the following terrain accessibility variants were distinguished: 0 - without obstacles, 1 - with unevenness up to 20 cm deep, 2 - with unevenness up to 40 cm deep,

Table 2 Technical data of the harvesters that were subjected to the tests.

Equip	Param	Unit	Vimek	Sampo	Profi-Pro	Ponsse	Fao-Far
Machine	Model	-	404 T5	HR46	50	Beaver	6840
	Carrier	-	harvester	harvester	harvester	harvester	construction machine
	Power	[kW]	44	124	120	129	57
	ERevol	[rpm]	2700	2100	2200	1600	2200
	Width	[m]	1.8 / 2.15	2.1 / 2.4	2.65	2.65/2.93	2.0
	Wheels	[pcs]	4	4	6	6	4
	Clearance	[cm]	40	67	62	67	47
	Weight	[kg]	4100	7450	12500	14900	5760
Crane	Model	-	Movi 2046	Kesla 671H tilt	Logmer 1095	Ponsse C2	Fao-Far
	Range	[m]	4.6	7.1	10.2	10.0	7.5
Harvesting head	Model	-	Keto Forst Silver	Keto 51 Eco Supreme	Maskiner SP 561LF	H5	Arbro 400S
	Delimbing method	-	continuous	continuous	continuous	continuous	cyclic
	Timber movement	-	chain tracks	chain tracks	rollers	rollers	delimbing stroke 0.75 m
	Max cutD	[cm]	30	37	60	64	40
	S.Length	[inch]	14	18	24	26	16
	TMSpeed	[$m \times s^{-1}$]	4.0	3.8	5.4	6.0	0.6-0.75
	Weight	[kg]	300	490	980	900	300

Note: Equip: equipment; Param: parameter; ERevol: engine revolutions; Wheels: number of wheels; Max.cutD: maximum cutting diameter; Saw lenght: the length of saw bar; TMSpeed: speed of timber movement

3 - with unevenness over 40 cm deep (Table 3).

The tested machines were selected according to the terrain conditions. Machines of the medium group worked in terrain with unevenness of class 3, while small harvesters in easier terrain conditions with unevenness of class 0-2 (Table 3).

During the operation of the machines, a time study was performed (Szewczyk & Sowa 2017) with the use of the DOD LS 430W video camera (DOD Tech, ON, Canada). The films documenting the operation of the machines were then transferred to the Timer Pro Professional software (Applied Computer Service, USA). This software made it possible to collect time measurement data according to the categories defined at the stage of configuring the individual measurement sessions. The software allows for free pausing of the film and multiple, time-lapse scrolling of the material as well as precise selection of break points when a specific work activity occurs. We measured the duration of repetitive work cycles (productive work time) (Dvořák et al. 2011, Szewczyk 2014, Szewczyk et al. 2014, Kulak et al. 2017). The break points were superimposed on the film track, which precisely defined the beginning and end of each observed work activity (work element). In the tested work cycles, we distinguished three work activities (work elements): felling: from the moment of tree gripping by the harvester head to the start of tree movement done by the feeding rollers in the head, processing: from the start of tree movement through the feeding rollers in the head to cutting off the tree top, moving: from the start of the machine passage until the next tree gripping by the harvester head. The time consumption database (work cycles) covered almost 4 thousand observations.

Table 3 Variants of terrain accessibility depending on the height of obstacles and the layout of skid trails and utilization of tested harvesters according to the terrain accessibility variants and height of obstacles.

Var	Obstacle height [cm]	Layout of skid trails	Symbol	Harvester				
				Vimek 404 T5	Sampo HR46	Profi-Pro 50	Ponsse Beaver	Fao-Far 6840
0	no obstacles	trees not growing in rows	0NR	+	+			+
		paralel	0PARA	+	+			+
1	up to 20	paralel	1PARA	+	+			+
		perpendicular	1PERP	+	+			+
2	20 - 40	paralel	2PARA	+	+			+
		perpendicular	2PERP	+	+			+
3	40 - 60	paralel	3PARA	+	+	+	+	
		perpendicular	3PERP			+	+	

Note: Var: terrain accessibility variants; Layout of skid trails in relation to the rows of trees; trees not growing in rows – the stand resulting from natural regeneration.

When performing the time study, we noted the number of logs with the standard length of 2.5 m, harvested from individual trees. Due to the impossibility of reading reports from the on-board computers of small harvesters (Vimek, Sampo, Fao-Far), the volume of merchantable timber obtained from each tree was calculated as the product of the number of logs obtained and the mean volume of the logs determined on the basis of measurements of 50 of them for each stand. This method tends to reduce the volume of bolts compared to measuring all harvested bolts. However, due to the impossibility of interfering with the timber extracting process, performed with forwarders, immediately after harvesting, it was decided to use this method for the entire experiment.

We assumed that the economic efficiency of the tested machines would be characterized by unit costs, expressed in €·m^{-3}, with the following elements of operating costs of machines C_o calculated for the operation of machines in productive work time (productive machine hours PMH) (Sowa et al. 2007, Glazar & Wojtkowiak 2008, Szewczyk & Kulak 2013, Ackerman et al. 2014, Triplat & Krajnc 2020). Other overhead costs, such as company management costs, the cost of transporting machines between cutting areas, or the cost of working equipment for machine operators were not considered when calculating operating costs (formula 1).

$$C_o = C_d + C_i + C_b + C_{fl} + C_w + C_r \quad (1)$$

where:
C_o - operating cost [€·h^{-1}];
C_d - depreciation cost [€·h^{-1}];
C_i - insurance cost [€·h^{-1}];
C_b - cost of the bank loan [€·h^{-1}];
C_{fl} - cost of fuel and lubricants [€·h^{-1}];
C_w - cost of wages [€·h^{-1}];
C_r - repair cost [€·h^{-1}].

The above components were calculated as follows:

$$C_d = \frac{P_p}{T \cdot H} \quad (2)$$

where:
P_p - purchase price of the machine [€];
T - period of use [years];
H - time of use in a year [h].

$$C_i = \frac{\frac{P_p}{2} \cdot r_i}{H} \quad (3)$$

where:
r_i - insurance rate [%].
The remaining symbols as in (2).

$$C_b = \frac{\frac{P_p}{2} \cdot r_l}{H} \quad (4)$$

where:
r_l - loan interest rate [%].
The remaining symbols as in (2).

$$C_{fl} = (1 + i_{fl}) \cdot D_f \cdot P_f \quad (5)$$

where:
i_{fl} - index of costs of oils and lubricants used in relation to the costs of fuel used [%];
D_f - fuel consumption [dm^3·h^{-1}];
P_f - fuel price [€·dm^{-3}].

$$C_w = r_w \cdot (1 + i_w) \cdot \quad (6)$$

r_w - the rate of net wage [€·h^{-1}];
i_w - index of social markups on wages [%].
The remaining symbols as in (2).

The data adopted for the calculation of labor costs are presented in Table 4.

The empirical distributions of unit cost values were not consistent with the normal distribution. Therefore, the unit costs of timber harvesting with the analyzed harvesters were calculated as the median of unit costs of all work cycles in a given field variant. We analyzed the impact of the machines or field conditions on the level of unit costs based

Table 4 Figures adopted for cost calculation.

Cost components	Unit	Harvester				
		Vimek 404 T5	Sampo HR46	Profi-Pro 50	Ponsse Beaver	Fao-Far 6840
P_p - purchase price	[€]	173333	260000	397778	424444	115555
T - period of use	[years]	6	6	6	8	6
H - time of use in a year (8-hour working shifts)	[h]	1600	1600	1600	1600	1600
r_l - loan interest rate	[%]	5	5	5	5	5
i_r - repair cost index	[%]	50	50	50	50	50
r_i - insurance rate	[%]	2	2	2	2	2
i_{fl} - index of costs of oils and lubricants used	[%]	20	20	20	20	20
D_f - fuel consumption	[dm^3·h^{-1}]	8	10	10	13	8
P_f - fuel price	[€·dm^{-3}]	1.19	1.19	1.19	1.19	1.19
r_w - rate of net wage	[€·h^{-1}]	20	20	20	20	20
i_w - index of social markups on wages	[%]	48	48	48	48	48

on the Kruskal-Wallis or U Mann-Whitney nonparametric tests, depending on the number of variables compared. The dependence of the unit costs of timber harvesting on the volume of merchantable timber of the trees being removed was described as a logarithmic function with the following form (8).

$$C_u = a + b \cdot log10\,(VOL_{mt}) \cdot \qquad (8)$$

where:

C_u - unit costs [€·m^{-3}],
a, b - function parameters,
VOL_{mt} - volume of merchantable timber of harvested trees [m^3].

Results

The operating costs (productive machine hour - PMH) of the tested harvesters varied significantly. The lowest operating cost of the Fao-Far harvester was nearly 2.5 times lower than the highest operating cost of the Profi-Pro harvester (Table 5).

Table 5 Hourly operating costs of the tested harvesters (productive machine hour - PMH).

Harvester	C_o - operating cost [€·PMH^{-1}]
Vimek 404 T5	47.4
Sampo HR46	65.1
Profi-Pro 50	89.1
Ponsse Beaver	80.9
Fao-Far 6840	37.3

Figures 2-8 present the level and variation of C_u unit costs calculated for all the tested harvesters, considering terrain accessibility variants, assuming an 8-hour work shift.

The unit costs of timber harvesting with the Vimek 404 T5 harvester showed a differentiation between the analyzed terrain accessibility variants ($H = 222.92$; $p = 0.00$) (Figure 2).

Using the multiple comparison test, we distinguished groups that did not show statistically significant differentiation: plots 0_{NR}, 0_{PARA}, 1_{PARA}, 1_{PERP}, for which a common value of $C_{u0\&1}$ = 10.3 €·m^{-3} was established; plots 2_{PARA} and 2_{PERP}, for which unit costs were higher and amounted to C_{u2} = 12.4 €·m^{-3}; and plot 3_{PARA}: the one where the unit costs of harvester operation were the lowest, i.e. C_{u3} = 6.8 €·m^{-3} (Figure 3).

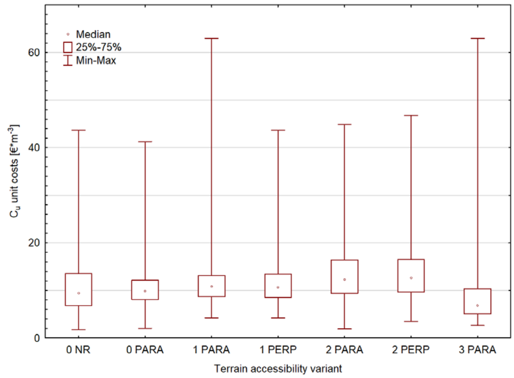

Figure 2 Unit costs of timber harvesting with the Vimek 404 T5 harvester for all terrain accessibility variants

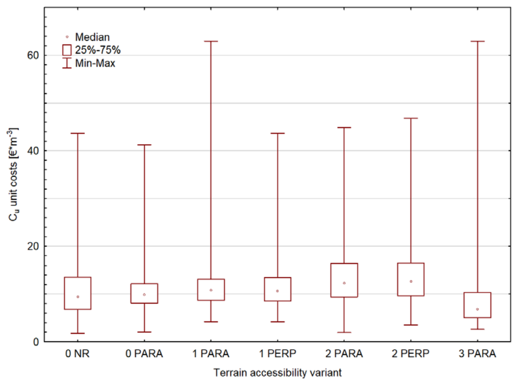

Figure 3 Unit costs of timber harvesting with the Vimek 404 T5 harvester, accepted for further analyses after consolidation of homogeneous groups of terrain accessibility variants.

The differentiation in the level of unit costs of timber harvesting with the Sampo HR46 harvester, presented in Figure 4, was reflected in the test results ($H = 249.97$; $p = 0.00$). Three groups of terrain accessibility variants were distinguished, in which unit costs for this harvester differed significantly ($H = 190.16$; $p = 0.00$) (Figure 5). The first group, characterized by a higher level of unit costs, included plots 1_{PARA}, 1_{PERP}, 2_{PARA} and 2_{PERP} – $C_{u1\&2}$ = 10.7 €·m^{-3}, the second group included plots 0_{NR} and 0_{PARA} - C_{u0} = 8.4 €·m^{-3}, while the third group included the plots with the largest depths of furrows 3_{PARA} – C_{u3} = 6.3 €·m^{-3}.

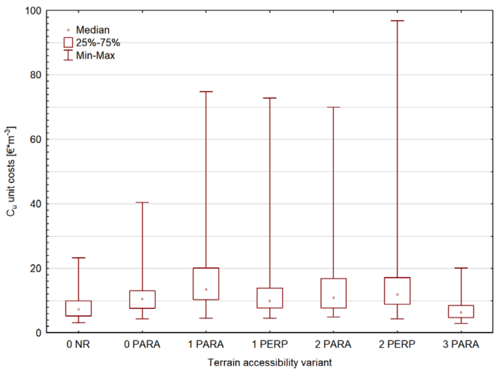

Figure 4 Unit costs of timber harvesting with the Sampo HR46 harvester before merging homogeneous groups.

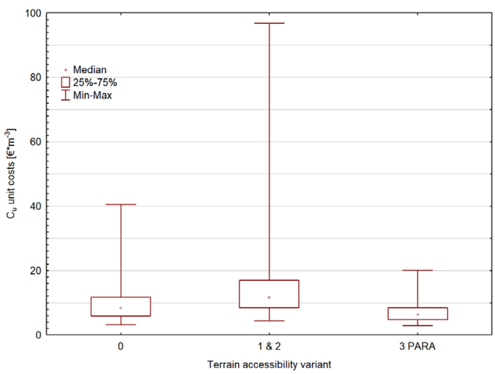

Figure 5 Unit costs of timber harvesting with the Sampo HR46 harvester, accepted for further analyses after merging homogeneous groups of terrain accessibility variants.

As presented in Figure 6a, differences in unit costs of timber harvesting with the Profi-Pro 50 harvester on the skid trails located parallel and perpendicular to the furrows of the 3rd depth class were not statistically significant (U = 19892; p = 0.86). Therefore, we decided to use the median value calculated from all data in further analyses, regardless of the layout of the skid trails: C_{u3} = 14.0 €·m^{-3}. A similar situation occurred in the case of the Ponsse Beaver harvester (Figure 6b). The U Mann-Whitney test showed (U = 17195; p = 0.54) that the work in the analyzed layout of skid trails did not significantly differentiate the unit costs of harvesting with this machine. In further analyses, we used the median value calculated from all data, regardless of the layout of the skid trails: C_{u3} = 10.4 €·m^{-3}.

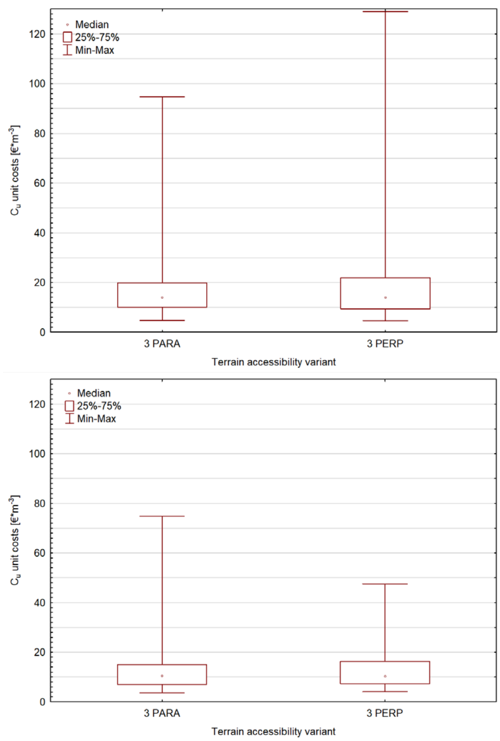

Figure 6 Unit costs of timber harvesting with the Profi-Pro 50 (a) and Ponsse Beaver (b) harvesters.

The unit costs of timber harvesting with the Fao-Far 6840 harvester on the research plots that differed in the presence and depth of the furrows as well as in the direction of the trails in relation to the furrows showed significant differentiation (H = 141.09; p = 0.00) (Figure 7). The multiple comparison test allowed for the identification of three groups of plots that differed in the level of unit costs (H = 116.70; p = 0.00): group one (marked 0), including plots without furrows with the lowest unit costs

(C_u = 9.1 €·m^{-3}); group two (1 & 2_{PARA}) with average costs (C_u = 10.1 €·m^{-3}), in which we included all plots with furrows with the depth of 1 and the depth of 2, but with a parallel (2_{PARA}) layout of trails; and the group with the highest costs (C_u = 14.8 €·m^{-3}), in which we included the plots of the 2_{PERP} type (Figure 8).

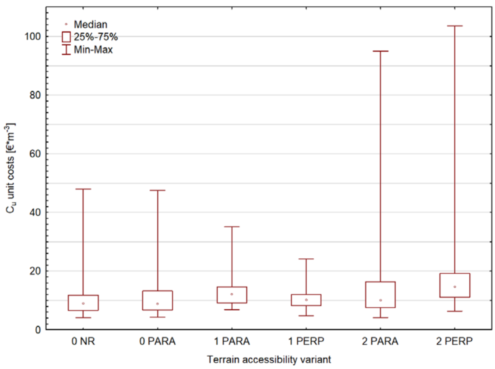

Figure 7 Unit costs of timber harvesting with the Fao-Far 6840 harvester before merging the homogeneous groups.

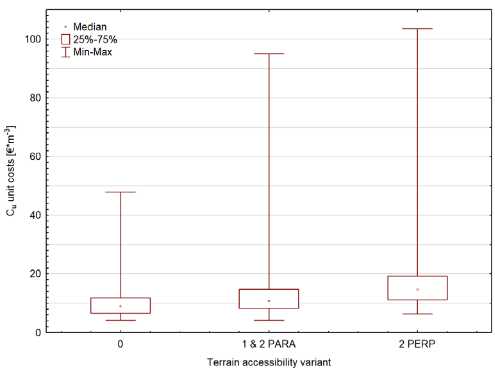

Figure 8 Unit costs of timber harvesting with the Fao-Far 6840 harvester, accepted for further analyses after merging homogeneous groups of terrain accessibility variants.

In stands without furrows (terrain accessibility variant 0), the lowest unit costs were recorded for the Sampo harvester - 8.4 €·m^{-3}. The other small harvesters tested, Vimek and Fao-Far, were slightly more cost-intensive: 10.3 €·m^{-3} and 9.1 €·m^{-3}, respectively. On plots with furrows of the 1st terrain accessibility variant, the cheapest solution was timber harvesting with the use of the Fao-Far harvester (9.9 €·m^{-3}). While the difference in unit costs between the Vimek (10.3 €·m^{-3}) and the Sampo (10.7 €·m^{-3}) harvesters was small at 4%. Under working conditions on plots with furrows of the 2nd terrain accessibility variant, harvesting with the use of the Sampo harvester turned out to be the cheapest (10.7 €·m^{-3}), while the harvesters Vimek and Fao-Far were characterized by a similar cost intensity, amounting to just over 12 €·m^{-3}. In stands with furrows of the 3rd terrain accessibility variant, the cheaper solution tested was the Ponsse harvester (10.4 €·m^{-3}). The cost intensity of the Profi-Pro harvester was higher by approx. 25% (14.0 €·m^{-3}).

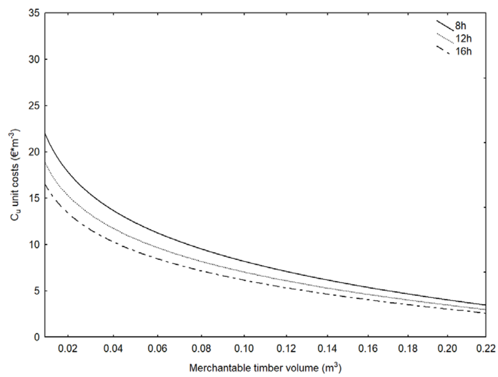

Figure 9 Relationship between the merchantable timber of harvested trees and unit costs for the Vimek 404 T5 harvester depending on the length of working shifts.

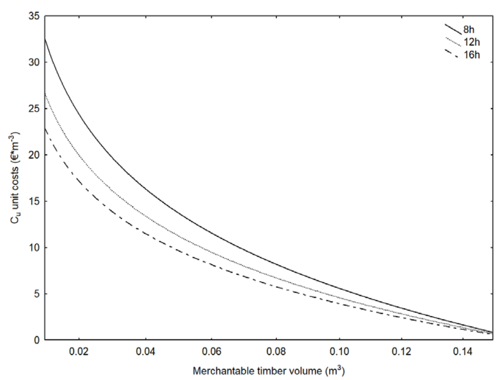

Figure 10 Relationship between the merchantable timber of harvested trees and unit costs for the Sampo HR46 harvester.

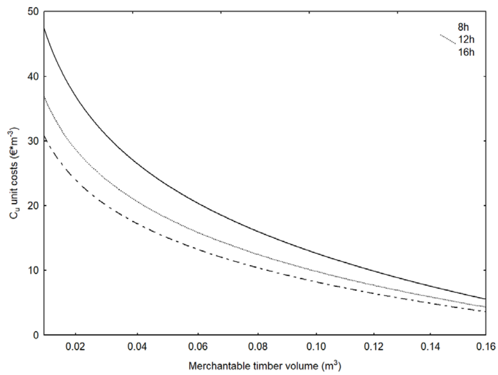

Figure 11 Relationship between the merchantable timber of harvested trees and unit costs for the Profi-Pro 50 harvester.

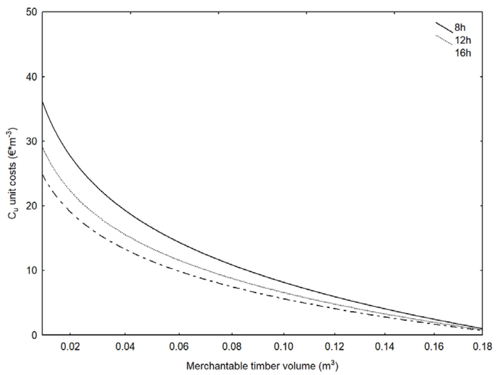

Figure 12 Relationship between the merchantable timber of harvested trees and unit costs for the Ponsse Beaver harvester.

Figures 9-13 present our analysis of the dependence of the unit costs of harvesting with the use of harvesters depending on the volume of merchantable timber of the felled tree. Additionally, we considered the extent to which the extension of the working shift (8-12-16 hours) would affect the unit costs. Table 6 is a compilation of the parameters of the estimated equations.

With the current level of financing for machine timber harvesting in Poland (11 €·m^{-3}), small harvesters: Fao-Far, Vimek and Sampo are cost-effective when tree volume exceeds 0.05-0.06 m^3. The tested medium harvesters, Ponsse and Profi-Pro, are cost-

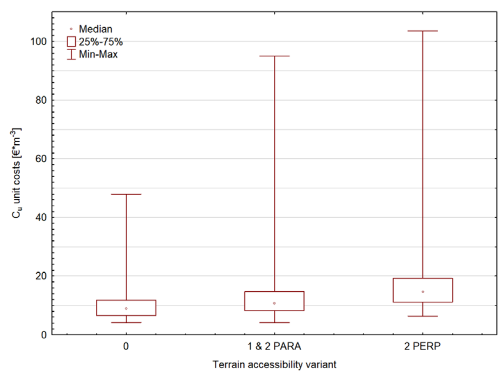

Figure 13 Relationship between the merchantable timber of harvested trees and unit costs for the Fao-Far 6840 harvester.

Table 6 Parameters of the regression equations between the merchantable timber of trees and the unit costs of harvesting them with the tested harvesters (significance level p<0,001).

		Harvester									
		Vimek 404 T5		Sampo HR46		Profi-Pro 50		Ponsse Beaver		Fao-Far 6840	
test F		397.21		531.27		253.74		219.02		423.68	
R^2		0.20		0.32		0.38		0.36		0.33	
Eq.par. (8 h shift)	Par.	a	b	a	b	a	b	a	b	a	b
		-5.63	-13.81	-21.39	-26.95	-22.14	-34.77	-19.82	-29.78	-19.16	-24.56
	t-test	-6.27	-19.93	-14.26	-23.04	-8.62	-15.93	-8.67	-14.80	-11.92	-20.58
Volume of merchantable timber above which the value of the service (11 €) is lower than unit costs											
Shift length [h]	8	0.06		0.06		0.11		0.08		0.06	
	12	0.05		0.05		0.09		0.06		0.05	
	16	0.03		0.04		0.07		0.05		0.05	

Note: test F (value); R^2: Coefficient of determination; Eq.par: equation parameters; Par: parameter; t-test (value).

effective in the case of larger unit volumes of harvested trees: 0.08 and 0.11 m^3, respectively. The cost-effectiveness of the tested harvesters increased when working shifts were extended, but the above-described ranking of machines in terms of cost-effectiveness of their use was maintained.

Discussion

The average productivity of timber harvesting in the analyzed stands was approx. 3.35 $m^3 \cdot h^{-1}$. Moskalik et al. (2017), who analyzed the efficiency of mechanized timber harvesting systems in Central European countries, provided slightly higher values: from 4.4 to 5.6 $m^3 \cdot h^{-1}$. However, these differences may result from slightly smaller unit volumes of trees in our experiment: 0.05 m^3 as compared to 0.06-0.08 m^3. The slightly lower efficiency of the work observed by us could also be due to the difficulties during harvesting of logs from the top parts of trees.

As in the studies by Mederski et al. (2019), in the case of the mean stand height of 11 m, and considering the minimum average small end diameter of wood adopted in Poland to be 5 cm without bark, the total length of timber assortments obtained from one tree reached an average of 7.5 m.

In the case of timber processing with the use of heads having a minimum delimbing diameter of approx. 5 cm, the delimbing knives do not fit a tree snugly and there are problems with delimbing. Only a few heads, e.g. the one by SP Maskiner (so far rare on the Polish market), have the option of delimbing the wood with a diameter of less than 5 cm while maintaining length measurement accuracy (Nieuwenhuis & Dooley 2006). Therefore, the production of medium-sized assortments with small diameters may be problematic, especially from the top parts of the trees with numerous one-sided or even multilateral curves.

In the group of lower-quality medium-sized timber obtained from the top parts of trees (S2AP in the Polish classification), curvatures may reach 12 and 6 $cm \cdot m^{-1}$, respectively.

Difficulties in delimbing tree fragments with forks were also indicated by Aniszewska et al. (2011) and Witkowska and Jodłowski (2018). The cyclic delimbing system applied in the Arbro head mounted on the Fao-Far harvester was very efficient in those difficult conditions and, despite the lower speed of movement than in the case of heads with roller and crawler feeders, it contributed to the achievement of low unit costs. Stroke harvesting heads also worked well in deciduous stands (Suchomel et al. 2012). The high efficiency of this solution was evident in our experiment particularly clearly in even terrain. Despite these difficulties, the extend of utilization of the stem timber within the scope of merchantable timber was high. As in the studies by Mederski et al. (2019), approx. 75% of the tree height was used.

Linking unit costs and the volume of merchantable timber in a tree characterizes the variability of the harvesting process well (Eriksson & Lindroos 2014). The observed logarithmic relationships of these variables, visible in our experiment, are consistent with the data published by Lazdiņš et al. (2016). However, in these authors' study, the hourly operating costs of a Vimek harvester operating in a stand similar to ours, but without terrain obstacles, were much lower, approx. 27 $€ \cdot PMH^{-1}$.

Due to the small volumes of trees, in the stands of the 2nd age class, the most appropriate is the use of heads designed for the harvesting of the smallest trees. The use of small processing heads is recommended when using small harvesters (Dvořak et al. 2011). As reported by Nuutinen et al. (2010), when heads designed for trees with medium volumes (approx. 0.35 m^3) are used, fuel consumption for harvesting and processing trees with the volume below 0.2 m^3 increases significantly. The reasons for this is the increase in the effective time of the movement of wood being processed, so as the slowest feed rollers were characterized by the highest fuel consumption per cubic meter. Therefore, the use of heads with feed rollers with adaptable plates can reduce fuel consumption by up to 30% as compared to heads with other types of rollers moving the logs (Nuutinen et al. 2010).

The height of planting ridges, visible residues left after preparing the soil for tree planting, clearly influenced the cost intensity of the work of small harvesters. The difficulties were especially evident when the machines travelled across places with major unevenness, where the arrangement of skid trails was perpendicular to the rows of trees. High lateral instability of small machines was also noted by Spinelli and Magagnotti (2010), who, however, emphasized the high operability of those machines in dense stands subjected to early thinning. Following that line of reasoning, in our experiment we consciously used mid-sized harvesters only in the most difficult terrain conditions, with unevenness of more than 0.4 m in depth. The use of these machines, as in the case of small harvesters, was more expensive when skid trails ran perpendicular to rows of trees.

Our research analyzed the work of harvesters actually used by forestry enterprises, machines of different age and with a different number of operating hours. In order to standardize unit labor costs, we assumed that it was new machines that were being used. We established their prices on the basis of declarations of producers or importers of individual machines.

Parameters related to the operation of machines, such as T - period of use, H - period of use in a year, i_r - repair cost index, were adopted on the basis of "Forest Machine System Requirements Sheets" developed by the Polish Forest Research Institute of the State Forests. In this standard approach, visible, *inter alia*, in the research of Miyata (1980), Ackerman et al. (2014), it is assumed that the lower purchase costs of the already used machinery result in higher repair costs and generally lower productivity, reflected in economic efficiency (Abbas et al. 2019). The above relationship is debatable, however, because Holzleitner et al. (2011) found that there is no relationship between the costs of repairs of used machines and the degree of their use, but what matters is the way the machines are being used, e.g. including periodic inspections, etc. This reasoning is appropriate in the case of calculation of the unit costs of timber harvesting for the general time of a shift (Ackerman et al. 2014, Giefing et al. 2012, Glazar & Maciejewska 2008, Lazdiņš 2016). In this way, the characteristic features of work related to a specific share of breaks at work are considered in both by harvesting and forwarding of timber (Dvořák et al. 2017).

The model adopted by us is based on the calculation of the costs of machines in the productive work time (productive machine hour - PMH). This eliminated randomness in the assessment of costs (Giefing & Gackowski 2001) resulting, for example, from the number of failures or the length of rest breaks (Jodłowski 2000).

Conclusion

The shaping of the level of unit costs was influenced by both the harvester models used, with their different operating costs and the possibility of various levels of efficiency, and the terrain conditions: the location of skid trails in relation to furrows of various depths.

The unit costs of timber harvesting with the use of a harvester are directly related to the size of the harvester and the type of head it is equipped with, as well as the volume of merchantable timber of the trees being harvested.

The cost effectiveness of mechanized timber harvesting in pine stands of younger age classes (over 20-year-old trees) can be achieved when the volume of merchantable timber of trees is above 0.05 m^3 for small harvesters and 0.08 m^3 for medium harvesters. Another possibility to increase the cost effectiveness of timber harvesting by harvesters is to work in a system of extended 12 and 16-hour shifts.

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