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Productivity and cost models for the first commercial thinning of a Scots pine stand using an excavator with an Arbro 400S harvester head and a farm tractor coupled to a logging trailer

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Abstract: The objective of the present work was to determine the productivity and costs of timber harvesting and skidding during the first commercial thinning of a Scots pine stand. The analyzed harvesting set consisted of a mini-excavator (34 kW) with an stroke harvester head (gripping range: 4–30 cm), and a farm tractor coupled to an logging trailer with a hydraulic crane. Merchantable timber (roundwood with a minimum diameter of 5 cm inside bark) was harvested from a 25-year old planted Scots pine stand growing on a grid of 1.4×1.8 m. The study showed the productivity of the mini-harvester range from 3.09 to 3.47 m³·PMH⁻¹, and that of the forwarding set to be 4.07 m³·PMH⁻¹. The analyzed model of productivity as a function of individual tree volume and thinning intensity was statistically significant, but the intensity parameter was significant only on plots located along wide access trails (3.7 m) and insignificant on plots located along the narrow access trail (2.5m). The intertree distance was not found to be significant. The calculated net machine costs for the forwarding set and mini-harvester were 36.12 Euro·PMH⁻¹ and 52.47 Euro·PMH⁻¹, respectively. An increase in the utilization rate of the harvesting set to 80% would reduce the timber harvesting and skidding costs to 22.07 Euro·m⁻³.

Keywords: first commercial thinning; merchantable timber; timber harvesting; logging; productivity; costs;

1. Introduction

According to the State of Europe's Forests report [1], Poland has a relatively large forest area (9.4 million ha) with a growing stock density that is higher than the European average (269 m³·ha⁻¹). This translates into a growing stock volume of over 2.5 billion m³, offering a vast source of wood supply for the region. Most of Poland's forests are publicly owned (80.8%), including forests managed by the State Forests National Forest Holding (77.0%). Among the latter, the largest area is occupied by 20–80-year-old tree stands, accounting for approx. 4 million ha, or almost 60% of growing stock available for wood supply. Taking into consideration different climate change scenarios [2] estimated that the highest productivity of Scots pine stands can be achieved at medium thinning intensity (20–40%).

According to Karttunen et al. [3], timber in Scandinavian countries is largely harvested by thinning, which becomes increasingly relevant both to the bioenergy sector and to developing new industrial investments. Considering different harvesting alternatives in the context of the timber supply chain and tree stand lifecycle, the authors concluded that intensive thinning leads to lower stumpage prices, with harvesting technology having the greatest influence on silviculture productivity. They also noted that whole-tree harvesting leads to the greatest biomass production, but also results in lower future stumpage prices and decreases the profitability of forestry. Furthermore, a growing body of research takes into account the effects of forest management on ecosystem development and carbon sequestration, which is of great significance to climate change containment [4–6].

Harvesting constitutes the main and most cost-intensive element in the timber supply chain, with the costs largely depending on thinning intensity, individual tree volume, and type of equipment. Single-grip harvesters seem to be the most effective, especially in older tree stands, while bundling technology appears to be useful for small-diameter thinning as it reduces the cost of transport. However, the high costs of whole-tree harvesting methods indicate a need for identifying more effective operating procedures, such as the two-pile cutting method [3], also known as the part tree system, in which the harvested trees are separated into stump wood and energy wood fractions. Several authors pointed out that the thinning operation in young stands have several dilemmas including operational costs, density of access trips by many variants of applied in field technology, impact on tree damage [7, 8] or the mental workload of a harvester operator [9, 10, 11]. In order to improve their efficiency, new and effective methods of harvesting are sought [12, 13].

In the Polish forestry tradition focused on natural, non-schematic, and comprehensive forest management, silvicultural treatments were usually carried out by means of the cheapest, motor-manual technologies. However, economic growth has led to a situation in which few workers are willing to engage in very demanding manual work of this type. Thus, in view of the increasing deficit in labor supply and the tendency to apply more frequent but less intensive tending treatments, alternative forest technologies are being sought.

Considering the market conditions (the dominant position of the State Forests National Forest Holding) and the prevalence of short-term contracts with a multitude of forest contractors, those contractors are reluctant to pursue state-of-the-art technological solutions due to the high financial risks, the current financial standing of the forest districts (contracting parties), as well as seasonal competition from foreign contractors (in periods of low demand for their services abroad). Therefore, they search for alternative solutions in which they could use the equipment ordinarily applied in agriculture and the construction industry. As a result, such contractors often equip excavators with harvester heads and use farm tractors coupled to logging trailers with hydraulic cranes in place of the more effective specialized forwarders [14 - 16].

The objective of the present work was to determine timber harvesting and skidding productivity and costs during the first commercial thinning, defining the important influences factors of productivity driving on width (3.5 m) and narrow (2.7 m) access trials. The analyzed harvesting set consisted of a 34 kW Kubota KX057-4 mini-excavator with an Arbro 400S stroke harvester head, hereinafter referred to as a "mini-harvester," and an MTZ Belarus 952.2 farm tractor coupled to an FAO FAR 842 logging trailer with a hydraulic crane (outreach of 6.4 m), hereinafter referred to as a "forwarding set." Observations were conducted in a planted Scots pine stand in which parallel access trails were made at the time of planting, spaced evenly at 40 m intervals. During the experiment, additional skid trails were made so that the distance between neighboring trails was 18–20 m.

2. Materials and Methods

The experiment was conducted in a 25-year-old Scots pine stand (N: 50°13'43"; E: 23°12'39") which had the shape of a 120×240 m rectangle with two 3.5 m wide access trails (AT35) made during planting, dividing the shorter edge into three equal 40 m segments. To facilitate machine thinning, three additional 2.7 m wide access trails (AT27) were established in parallel to the existing ones by schematically removing one tree row for each. In this way, the tree stand had a parallel network of access trails spaced every 20 m.

Due to the large number of trees to be removed (a total of more than 1300) and for the sake of observer safety, smaller sample plots were established, which were 25 m long (along the access trails) and 20 m wide (10 m on either side of the access trails). The sample plots were demarcated using a laser optic-system Ledha-Geo produced by Jenoptik (Jena, Germany).

In the first phase of the experiment, timber was harvested from the sample plots located along the wide access trails (AT35). The trees to be cut were selected by foresters and clearly marked with paint at a height of approx. 1.5 m for ease of identification. The trees were processed into 2.5 m long logs (using cut-to-length technology) with a minimum diameter of 5 cm inside the bark, which were then placed along the trails. Thinning was conducted using a mini-harvester consisting of a tracked excavator with an Arbro 400S stroke harvester head (Table 1). Due to the relatively short crane range (6.5 m), the mini-harvester had to move off the trail to perform thinning on the entire area of the designated sample plots.

In the second phase, new narrow access trails were made by schematic cutting single rows of trees (AT27_schemcut). Due to the relatively low ground clearance of the mini-harvester (310 mm, Table 1), the remaining stumps had to be removed and the trail was leveled with a mounted blade.

In the third phase, thinning was performed on the sample plots along the new narrow access trails (AT27) using the same harvesting technology as in the first phase.

The fourth phase involved analysis of the operations of a 66 kW MTZ Belarus 952.2 farm tractor coupled to a FAO FAR 842 logging trailer with a load capacity of 8 tons, equipped with a crane having an outreach of 6.4 m (Table 1). The volume of the transported loads was determined in m³ including bark for each work cycle after unloading at a landing area located near a paved road 700 m away from the analyzed tree stand.

Table 1. Characteristics of the timber harvesting set

	Unit	Kubota KX057-4 excavator with Arbro 400S harvester head	MTZ Belarus 952.2 farm tractor	FAO FAR 842 logging trailer with 3264 crane
Engine	kW (HP)	34 (46)	66 (90)	-
Dimensions length / high / width	mm	5520/2550/1960 Overall	Overall 4090/2840/19 70	Load compartment 4420/1630/1250
Minimum ground clearance	mm	310	465	620
Operating weight	kg	5550 (excavator) 330 (harvester head)	4500	2550 (8 t load capacity)
Maximum outreach	m	6.5	-	6.4
Gripping range	mm m ²	(40, 300)	-	0.16
Maximum angle	mm	360	-	1200
Delimbing speed	m·s ⁻¹	0.3-0.5	-	-
(back-/forwards)	mm	stroke: 660		

In order to precisely determine machine productivity, the present work focused on productive work time as defined in the IUFRO 1995 classification [17]. Productive work time consists of both the main work time (cutting, processing, loading, unloading, loading drive) and complementary work time (root extracting, moving from tree to tree, unloading drive). As has been postulated by many authors [18, 19], a 15 min rest time complying with occupational safety and health standards was added to productive work time, with the resulting time expressed in productive machine hours plus 15 min (PMH₁₅⁻¹). The duration of the various technological operations was measured both in harvesting and skidding work cycles. Given the objective of determining the effects of tree stand characteristics (thinning intensity and tree density) on mini-harvester work time and productivity, as well as other operating parameters, the variables were measured separately for each sample plot. Measurements were done with an accuracy of 1 s using a PSION WorkAbout data recorder with dedicated software.

Individual tree volume was determined indirectly based on a formula for pine stem volume inside bark [20] using parameters such as stand-specific taper factor, outside bark diameter at 1.3 m (DBH), and tree height. DBH was determined directly by measuring all trees selected for felling by means of a digital caliper. The height of individual trees was calculated indirectly from a height curve determined for the tree stand on the basis of the measurement of 5% of trees using a Ledha-Geo laser dendrometer. For the purpose of calculating tree volume outside bark in m³, it was assumed that bark accounted for 12% of the total volume [21].

Homogeneity of the designated sample plots was evaluated by calculating thinning intensity as the volume of harvested merchantable timber relative to total merchantable timber, as well as the Hart-Becking index (or relative spacing index, RSI) for the dominant tree height:

$RSI=100 \cdot AS/H_{dom}$, where AS is mean spacing between trees in meters (trees are assumed to be positioned on a triangular grid) and H_{dom} is the mean height of the highest 10% of trees [22].

The machine costs were computed pursuant to the FAO guidelines [23] and the harmonized procedure proposed by Ackerman et al. [24]. The calculations included, amongst others, purchase cost, operating costs, maintenance cost, garage cost, as well as mean operator wages for southern Poland.

Statistical analysis consisted of descriptive statistics, Fisher's F-test for equality of variances, and Student's t-tests for homoscedastic data (with equal variances) and non-homoscedastic data. The model functions were determined using a generalized linear model (GLM) for natural log-transformed data:

$$\ln Y = \ln b_0 + b_1 \cdot \ln X_1 + b_2 \cdot \ln X_2 + b_3 \cdot \ln X_3 + \varepsilon \quad (1)$$

where Y is the dependent variable (productivity), $X_{1..k}$ is the independent variable (merchantable timber volume outside bark - X_1 , thinning intensity - X_2 , relative spacing index RSI - X_3), and ε is estimation error.

Due to the relatively small differences in the adopted model, statistical significance of differences between marginal means was evaluated by contrast analysis in the form of a priori tests for selected comparisons. Analysis of residuals (ε) of linearized regression functions included testing for normality of distribution using the Shapiro-Wilk test and outlier identification. Statistical analysis was performed using the packages StatSoft [25] and R Core Team [26]. The following power function model was applied to predict productivity in $m^3 \cdot PMH_{15}^{-1}$ (to convert logarithmic values into real values):

$$Y = b_0 \cdot b_1 \cdot X_1 \cdot b_2 \cdot X_2 \cdot b_3 \cdot X_3 \quad (2)$$

3. Results

The experiment involved the harvesting of merchantable timber (roundwood with a minimum diameter of 5 cm inside bark) from a planted Scots pine stand in which trees were growing on a 1.4×1.8 m grid at the time of the tending treatment, which could be classified as the first commercial thinning. The growing stock density was approximately 175 m^3 of merchantable timber outside bark with approximately 2200 trees per ha (Table 2). A total of 50 rectangular sample plots and 15 sample segments along new skid trails were established (AT27schemcut).

Table 2. Summary of stand characteristics

Description	Unit	Sample plots along wide access trails (AT35)	Sample plots along narrow access trails (AT27)	Schematic tree extraction along the rows (within stump removal and level of trial) (AT27schemcut)
Area	ha	1	1.5	0.10
Mean diameter at breast height (DBH) outside bark	cm	11.7	12.3	13.5
Initial tree density	number per hectare	2353	2142	1882
Mean height of removed trees (dominant height of 10%)	m	13.4 (15.0)	13.4 (15.0)	13.4 (15.0)
Mean tree volume	m^3	0.074	0.082	0.103

(95% confidence interval)	outside bark	(0.061, 0.087)	(0.073, 0.090)	(0.095, 0.111)
Thinning intensity volume per sample plot in percent (95% confidence interval)	%	18.8 (15.1, 22.5)	27.8 (24.2, 31.4)	100
Mean relative spacing index RSI / Hart-Becking index (95% confidence interval)	m	12.15 (11.59, 12.72)	12.96 (12.27, 13.65)	12.64 (12.15, 13.12)
Number of sample plots	n	20	30	15
Tree species	-	Scots pine	Scots pine	Scots pine
Age	year	25	25	25
Stand quality	-	IA	IA	IA
Stocking degree	-	1.0	1.0	1.0
Site type		Fresh mixed coniferous forest	Fresh mixed coniferous forest	Fresh mixed coniferous forest

The first step of analysis involved assessing the homogeneity of sample plots established along the wide (AT35) and narrow (AT27) trails. Statistical tests (Table 3) show that neither individual tree volume nor RSI differed significantly between the plots. However, the plots located along the wide access trails exhibited significantly higher RSI variance and lower thinning intensity ($\Delta=8.97\%$).

Table 3. Homogeneity of sample plots along the wide (AT35) and narrow (AT27) access trails

Variable	F-test for equal variances		t-test for equal means	
	F-stat	p-value	t-stat	p-value
Tree volume outside bark [m ³]	0.6551	0.1485	2.0106 ^h	0.3060
Relative spacing index (RSI)	2.0772	0.0339 ^{ss}	1.7667 ^{non-h}	0.0836
Thinning intensity (volume)	1.4275	0.2112	2.0106 ^h	0.0019 ^{ss}

^{ss} - statistically significant at $\alpha=0.05$; ^h - *t*-statistic for equal variance (homoscedasticity); ^{non-h} - *t*-statistic for unequal variance (non-homoscedasticity)

As can be seen from Table 4, the mini-harvester with an Arbro 400S head revealed the lowest productivity (3.09 m³·PMH₁₅⁻¹) for sample plots located along the wide access trails, while achieving the highest productivity (3.47 m³·PMH₁₅⁻¹) in the process of schematic cutting single rows. The productivity of the forwarding set (Belarus 952.2 farm tractor with a FAO FAR 842 logging trailer) was found to be 4.07 m³·PMH₁₅⁻¹.

Table 4. Productivity characteristics of sample plots, m³·PMH₁₅⁻¹

Variable	Harvesting: Kubota KX057-4 with Arbro 400S			Forwarding:
	Sample plots along wide access trails (AT35)	Sample plots along narrow access trails (AT27)	Schematic tree extraction along the rows (within stump removal and level of trial), (AT27schemcut)	MTZ Belarus 952.2 tractor with FAO FAR 842 trailer

Mean	3.09	3.28	3.47	4.07
Std.Dev.	0.93	0.71	1.81	0.66
Max	5.29	5.09	6.43	5.11
min	1.26	1.46	1.07	3.03

The general results (Table 5) indicate the absence of statistically significant differences in mini-harvester productivity between sample plots located along wide (AT35) and narrow access trails (AT27). Therefore, the two types of sample plots were combined with net cost, and productive analyses (Figure 1, Table 6). However, more accurate analysis of performance models showed a higher productivity of up to 12% at narrow trails (AT27) for the same tree volume (Table 7).

Table 5. Contrast analysis for marginal means

Variable	Contrast 1	Contrast 2
AT27	-1	-1
AT35	1	-1
AT27schemcut	0	2
Contrast evaluation	-0.0158	0.3912
<i>t</i> -stat	-0.3781	4.5046
<i>p</i> -value	0.7067	3.1·10 ⁻⁵

Based on these data, the next step of analysis involved estimation of the mini-harvester productivity function. In Model 1 (Table 6), characterizing productivity on sample plots as a function of individual tree volume ($R^2_{adj}=0.91$), the RSI effect was not found to be statistically significant (p -value=0.220); however statistical significance was confirmed both for the intercept and individual tree volume. Model 2 ($R^2_{adj}=0.82$), which was estimated mini-harvester productivity for schematic tree extraction along rows during the clearance of new narrow trails, showed that it was lower as compared to operation on rectangular sample plots. Residual analysis indicated random distribution and absence of bias (p -value for Shapiro-Wilk test was over $\alpha=0.05$, Mean=0). As can be seen from the functions for real values (Eq. 2, Fig. 1), the decrease in productivity amounted to approx. $\Delta=0.58 \text{ m}^3\cdot\text{PMH}_{15}^{-1}$ for the adopted mean individual tree volume outside bark (0.08 m^3).

Table 6. Linear regression analysis of the productivity (Eq. 1) of the mini-harvester with an Arbro 400S head as a function of mean stump volume

Parameter	Value	Std. error	<i>t</i> -stat	Residual, ϵ (Mean, SD)
Model 1: A total of sample plots along with narrow and wide access trials (AT35 and AT27)				
b_0	3.0239	0.0893	33.846*	(0, 0.0868)
b_1	0.7283	0.0340	21.423*	S-W=0.9621 p -value=0.1090
Model 2: Schematic tree extraction along the rows (within stump removal and level of trial) (AT27schemcut)				
b_0	2.8154	0.2312	12.178*	(0, 0.2527)
b_1	0.7224	0.0927	7.791*	S-W=0.9472 p -value=0.4811
* statistical significance at p -value $<1\cdot10^{-3}$				

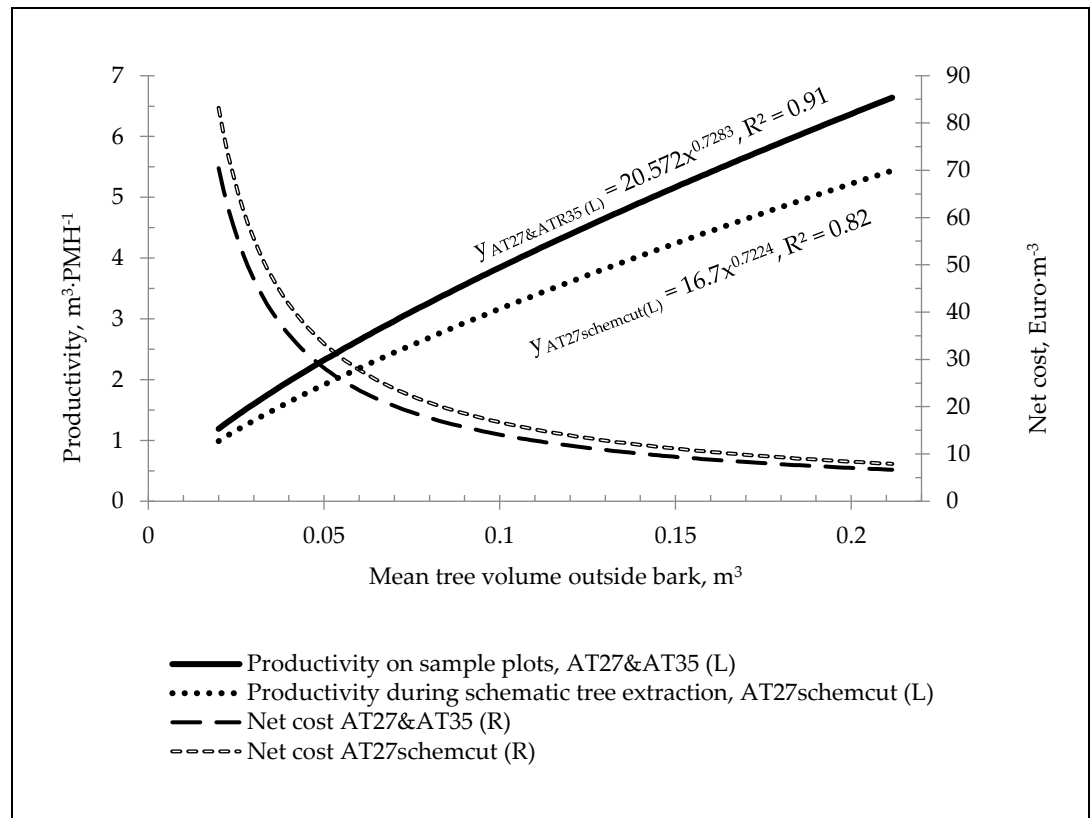


Figure 1. Productivity and net cost of the mini-harvester with Arbro 400S as a function of mean tree volume

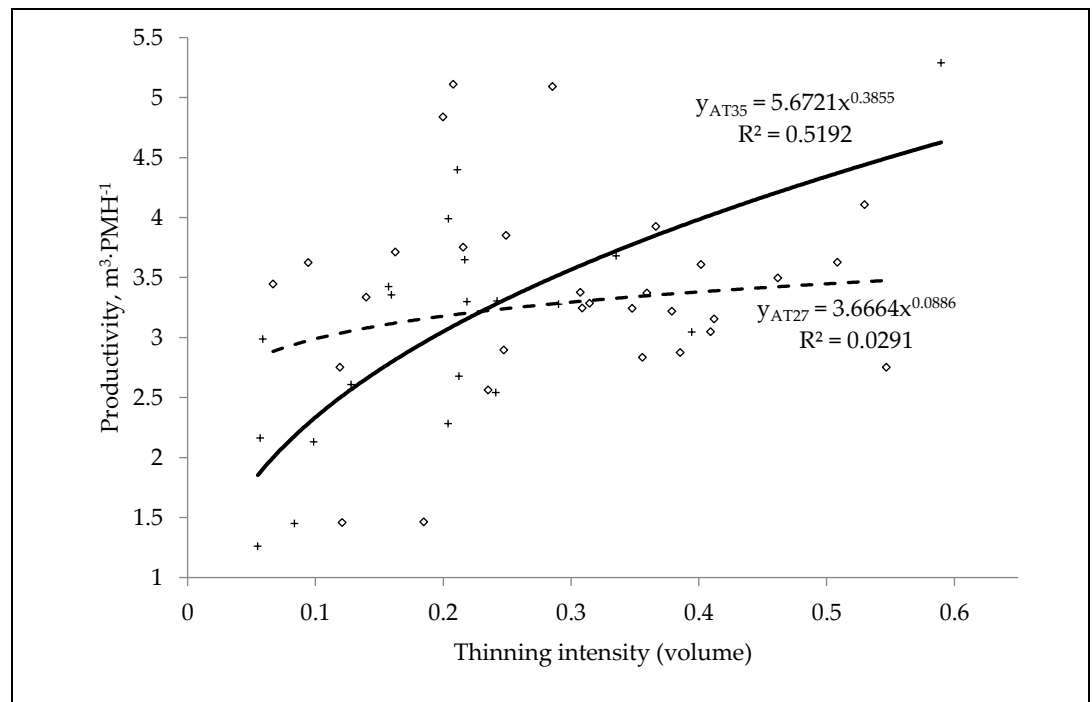
The identified differences in thinning intensity ($\Delta=8.97\%$, Tables 2 and 3) on sample plots located along the wide and narrow access trails (AT35, AT27) was adopted as a basis for estimating further productivity functions taking into consideration variables such as individual tree volume and thinning intensity (Models 3 and 4, Table 7). The obtained parameters were statistically significant for Model 3 describing productivity on sample plots established along the wide access trails (AT35), with the obtained errors being of random nature. In Model 4, which described sample plots located along the narrow access trails (AT27), thinning intensity (b_2) was not statistically significant ($p\text{-value}=0.9514$).

Analysis of marginal productivity functions (Figure 2) showed higher mean productivity for sample plots located along the wide access trails (AT35; $R^2_{\text{adj}}=0.5192$, $F=8.304$, $p=0.008$) at thinning intensity greater than 23%, while at lower thinning intensity higher productivity was observed for sample plots located along the narrow access trails (AT27, $R^2_{\text{adj}}=0.0291$, $F=0.840$, $p=0.367$, not significant).

Table 7

Table 7. Linear regression analysis of the productivity (Eq. 1) of the mini-harvester with an Arbro 400S head as a function of mean stumpage volume (X_1) and thinning intensity (X_2)

Parameter	Value	Std. error	<i>t</i> -stat	Residual, ϵ (Mean, SD)
Model 3: Sample plots along wide access trails (AT35)				
b_0	3.0486	0.1987	15.3439*	(0.000, 0.1189)
b_1	0.6034	0.0830	7.2700*	S-W=0.9388
b_2	0.2021	0.0511	3.9578*	p-value=0,2277
Model 4: Sample plots along narrow access trails (AT27)				
b_0	3.2387	0.2941	11.0122*	(0.000, 0.1660)
b_1	0.8093	0.1151	7.0344*	S-W=0.9508, p-value=0,1779

* statistical significance at p -value $<1 \cdot 10^{-3}$ **Figure 2.** Marginal productivity functions for Model 3 and Model 4 (Table 7; Eq. 2)

The costs presented in Tables 8 and 9 were computed for the Polish market at an exchange rate of 1 Euro=4.23 PLN. The calculation also included the costs of transport and garage as services provided by an external company, as well as the costs of replacing tracks and tires. Repair costs were adopted as 100% for the mini-harvester and the farm tractor and 60% for the logging trailer of the purchase price. Analysis showed that during a one-shift work system (8 h/day, 210 days/year) the machine utilization rate was rather low and did not exceed 65% (Table 8). The estimated net machine cost (excluding profit margin, Table 9) for the forwarding set was 36.12 Euro·PMH⁻¹, and that for the mini-harvester 52.47 Euro·PMH⁻¹. Under the considered circumstances, the total harvesting cost was 25.11 Euro·m³. At an average tree volume of 0.08 m³, the corresponding estimated mini-harvester cost ranged from 17.7 to 20.9 Euro·m³ (Figure 1). Furthermore, for a skidding distance of 300 m the expected productivity of the forwarding set was 4.29 m³·PMH⁻¹ with an estimated net cost of 8.4 Euro·m³ (Figure 3).

Using the cost calculator developed by Ackerman et al. [24], it was estimated that an increase in the machine utilization rate to 80% would lower the timber harvesting and forwarding costs to 22.07 Euro·m³ (Table 10). At an average stumpage price of 35.46 Euro·m³ for timber sold for industrial purposes, the net profit would range from 9.8 to 13.4 Euro·m³ depending on the machine utilization rate (excluding VAT and the internal administration costs of the State Forests National Forest Holding).

Table 8. Basic data used in cost calculation

		Kubota KX057-4	MTZ Belarus	FAO FAR 842
Unit		excavator with Arbro	952.2 farm	logging trailer with
		400S harvester head	tractor	3264 crane
Mean fuel consumption (0.95 confidence interval)	dm·PMH ⁻¹	2.2 ^a (1.4, 3.1)		8.5 ^b
Mean speed on sample plots	m·s ⁻¹	0.43 ^c (0.36, 0.52)		1.45 ^d (1.19, 1.72)

(0.95 confidence interval)				
Purchase price (VAT 0%)	Euro	90000	20000	13800
Estimated annual productivity ^e	m ³ ·year ⁻¹	3028	4307	4307
Expected economic life ^e	year	7.68	9.45	9.45
Salvage value	%	10	10	10
Machine utilization rate ^e	%	62	63	63

^a- own data developed on 94 PMH, ^b - technical data, ^c - calculated from 24 measurements using Ledha-Geo, ^d - calculated from 11 driving cycles, ^e - preliminary calculations according to the cost model by Ackerman et al. (2014)

Table 9. Cost calculations in Euro

Total costs	Annual	Monthly	PMH	m ³	Share in total cost, %
Kubota KX057-4 excavator with Arbro 400S harvester head					
Fixed	20227	1686	19.42	6.01	30.7
Variable	14472	1206	13.89	4.30	21.0
Operator	19953	1663	19.16	5.93	30.3
Net (excluding profit margin)	54651	4554	52.47	16.24	83.0
Gross (including 10% profit margin)	65842	5487	63.21	19.56	100.0
MTZ Belarus 952.2 farm tractor with FAO FAR 842 logging trailer					
Fixed	7660	638	7.24	1.78	16.9
Variable	13057	1088	12.34	3.03	28.7
Operator	17513	1459	16.55	4.07	38.6
Net (excluding profit margin)	38230	3186	36.12	8.87	84.1
Gross (including 10% profit margin)	45471	3789	42.96	10.56	100.0

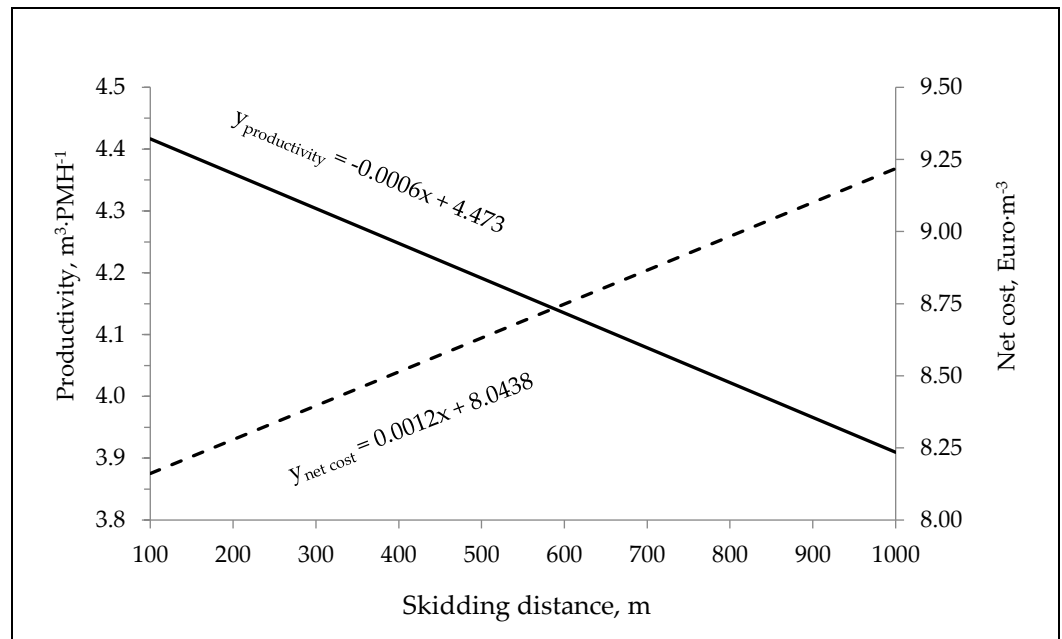


Figure 3. Productivity and costs as a function of skidding distance (MTZ 952.2 universal tractor with FAO FAR 842 trailer)

Table 10. Expected net costs as a function of utilization rate

Utilization rate	Kubota KX057-4 excavator with Arbro 400S harvester head		MTZ Belarus 952.2 farm tractor with FAO FAR 842 logging trailer	
	Euro·PMH ⁻¹	Euro·m ⁻³	Euro·PMH ⁻¹	Euro·m ⁻³
0.6	53.41	16.53	37.15	9.13
0.7	49.24	15.24	34.05	8.37
0.8	46.12	14.27	31.73	7.80

4. Discussion and conclusion

The intensification of timber harvesting (e.g., via tending treatments) is motivated by, amongst others, social expectations and environmental considerations. Over the past years, a considerable body of research on renewable energy sources has shown that small-diameter (DBH <10 cm) thinnings can be an efficient source of biomass in the form of whole trees or stems [27, 28] provided that there exists an efficient access road network [29]. In Poland, whole-tree harvesting is avoided for environmental reasons as it may adversely affect biological habitats [30], with the harvested merchantable timber being mostly used for industrial purposes (chemical processing or manufacture of furniture boards).

The use of an Arbro 400S stroke harvester head and a farm tractor coupled to a logging trailer is obviously less effective than a roller-feed harvester [31]. Despite this, the productivity of the analyzed excavator-harvester head combination was similar to that of some purpose-built feller-bunchers, such as a Moipu 400E, which achieved 3.16 m³·PMH⁻¹ [32]. Importantly, the low overall harvesting costs (22–25 Euro·m⁻³), which were approximately half of those reported for the aforementioned feller-buncher, are attributable to small fuel consumption (2.2 l·PMH⁻¹, Table 8), lower machine purchase costs and regional labor costs, as well as economical technology which did not involve chipping, which is a very energy-intensive step in biomass production [33, 24]. The skidding costs calculated in the present work (7.8–9.13 Euro·m⁻³) are lower by 3–6 Euro·m⁻³ than those determined by Spinelli and Magagnotti [35] for a new mini-forwarder model specifically designed for thinning operations.

It would seem obvious that mini-harvester productivity should increase with thinning intensity because at high intensity a stationary machine can fell several trees within the reach of the crane, especially if the cab can turn 360°, as is the case with the Kubota excavator. The absence of this correlation on sample plots located along the narrow access trails is probably attributable to the

longer time needed to maneuver the mini-harvester into position along narrow trails with a width of 2.7 m, which is the absolute minimum for harvesting [36].

However, at thinning intensity of up to 23%, harvesting productivity was higher on sample plots established along the narrow access trails (AT27) as opposed to those located along the wide access trails (AT35). This fact could be explained by changing the operator behaviour to multi-tree handling technology and the forming of new passages with a width of 1 m and a length corresponding to the crane outreach, which is known in the literature as boom-corridor thinning [37, 31]. Multi-tree handling and geometric thinning may considerably increase harvesting productivity (by up to 30%) and are typically used for felling narrow trees with a DBH of less than 8–10 cm [38, 39]. This technology is less often employed on plots located along wide access trails (AT35). Also Mederski et al. [40] did not find a simple correlation between thinning intensity and productivity. Given the presented results, this appears to be a characteristic feature of young tree stands. Interestingly, according to Ackerman et al. [41], an appropriate planting geometry may enhance productivity by approx. 8% and reduce harvesting costs by up to 7%.

The productivity of the mini-harvester and the tractor-trailer set varied between plots by 22–52% and 16%, respectively (Table 4), which is not much as compared to the productivity discrepancies (0.64–8.3 m³·PSH⁻¹) reported by Erber et al. [38] in small-diameter hardwood thinning by means of multiple-tree processing.

However, it should be stressed that the work assessed the productivity of two-pile cutting in the process of harvesting industrial roundwood with a minimum diameter of 5 cm inside bark. According to a study on aboveground biomass allocation in 60-year-old Scots pines [42], the percentage share of wood ranges from 73% to 77%, depending on the biosocial position of the trees. As can be calculated from tree volume tables for standing 25-year-old Scots pines [43], to ensure mini-harvester productivity, e.g., in a two-pile cutting system with industrial roundwood and energy wood fractions, the obtained results should be multiplied by a factor of 1.36.

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