Estimating and Modelling Harvester Productivity in Pine Stands of Different Ages, Densities and Thinning Intensities

Piotr S. Mederski, Mariusz Bembenek, Zbigniew Karaszewski, Agnieszka Łacka, Anna Szczepańska-Álvarez, Martyna Rosińska

Abstract

In economic terms, the main limiting factors in harvester application in thinning operations are the stand age and thinning intensity with respect to tree size. Furthermore, harvested mean tree size depends on initial stand density but also on the number of trees cut per hectare. The objective of the research was to estimate the impact of:

- ⇒ *stand age (class),*
- ⇒ *increasing stand density in each age class (*AC*),*
- ⇒ *increasing number of trees for harvesting in each* AC*,*
- ⇒ *thinning intensity,*

*on harvester productivity. 17, 19 and 20 sample plots were established within 3rd (*AC3*) 4th (*AC4*) and 5th (*AC5*) age classes, respectively. In each* AC*, sample plots were selected that had an increasing number of trees per hectare: 563÷1603, 323÷868 and 476÷836 trees* ha^{-1}*, in* AC3*,* AC4 *and* AC5*, respectively. Also, in each* AC*, an increasing number of trees per hectare for harvesting was selected: 130÷853, 80÷315 and 108÷282, in* AC3*,* AC4 *and* AC5*, respectively, with the relevant increasing thinning intensity: 35÷84, 21÷77 and 34÷88* $m^3\ ha^{-1}$*. In each* AC*, the stands were divided according to different thinning intensity (*THI*):* $a<30$*,* $30 \le b \le 60$ *and* $c>60$ $m^3\ ha^{-1}$*, respectively. A Komatsu 931.1 harvester was used for the thinning operation in each stand. The lowest mean productivity was observed in* AC3 *(18.57* $m^3\ h^{-1}$*), which was statistically different to* AC4 *and* AC5 *(22.24 and 22.60* $m^3\ h^{-1}$*, respectively). Within each* AC*, productivity lowered as the number of trees per hectare increased in the initial stand. The productivity decreased in* AC3 *and* AC5 *with the increasing number of trees for harvesting, which was not the case in* AC4*. In relation to the* THIs*, the lowest mean productivity was obtained in* THI*a (16.19* $m^3\ h^{-1}$*), which was statistically different to* THI*b and* THI*c (21.44 and 21.98* $m^3\ h^{-1}$*, respectively). An increasing THI only influenced productivity positively in* AC4 *and* AC5*. It can be concluded that the productivity of the Komatsu 931.1 harvester increased along with:*

- ⇒ *older* AC*,*
- ⇒ *decreasing number of trees in the initial stand in each* AC*,*
- ⇒ *lowering number of trees for harvesting in* AC3 *and* AC5*,*
- ⇒ *increasing* THI *in only* AC4 *and* AC5*.*

Finally, in the present model, the larger the mean DBH *of the trees for harvesting, the greater the productivity. However, the mean* DBH *has to be considered in conjunction with the number of trees for harvesting (which depends on* AC *and* THI*, as variables in the model) when productivity is analysed.*

*Keywords: thinning operation, productivity curves, Scots pine (*Pinus sylvestris *L.)*

1. Introduction

Working on harvester productivity curves for Polish conditions is meaningful at this stage, as a large number of harvesters are in operation. Since 1987, when the first harvester was introduced in Poland (Moskalik 2002), their numbers have grown considerably. Between 2006 and 2008, the number of harvesters grew from 21 to ca. 170 (Kusiak 2008, Sowa 2009). A survey from 2011 and 2012 revealed that there were 351 harvesters in Poland, 16 of which were owned by the State Forests (Żabierek and Wojtkowiak 2012). Currently, it is estimated that there are ca. 450 harvesters operating in Poland, which are able to harvest ca. 30–35% of the total annual volume, estimated to 38 million m^3 of timber. For this reason, competition between forest contractors is very high, which leads to a lowering of the price of timber harvesting within an open tender process. Therefore, it is in the interests of entrepreneurs to find out which thinning intensity is acceptable for a low price.

Estimating harvester productivity is a basic step towards calculating the costs of forest operations. Special attention has to be paid to harvesters, the purchasing cost (ca. € 400,000) of which has to be balanced with sufficient working hours and an annual cut of 24,000 m^3 in thinnings (Więsik 1998). It is essential, therefore, to allocate the appropriate machine for thinning operations in order to achieve satisfactory productivity.

Studies completed so far have taken into account various factors, which have a direct impact on harvester productivity. These factors can be divided into four main groups:

⇒ stand conditions,
⇒ tree characteristics,
⇒ terrain conditions,
⇒ operator skills.

Within the first group, »stand conditions«, productivity depends on: stand density and thinning intensity (Eliasson 1999), type of thinning and harvested volume per hectare (Suadicani and Fjeld 2001), frequency of tending operations or lack of them (Gerasimov et al. 2012), standard cuttings or stand damaged by wind (Szewczyk et al. 2014) and the spatial distribution of strip roads (Mederski 2006). Within the second group, »tree characteristics«, productivity depends on: size of selected trees (Iwaoka et al. 1999, Wang and Haarla 2002, Visser and Stampfer 2003, Nurminen et al. 2006), tree species, especially conifers versus broadleaves (Mederski 2006, Spinelli et al. 2010, Danilović et al. 2011, Visser and Spinelli 2012, Mederski 2013, Bembenek et al. 2015), tree shape and its morphological features (Evanson and McConchie 1996, Suchomel et al. 2012), thickness of branches (Glöde 1999) and criteria for tree selection for thinning (Eliasson and Lageson 1999). The third factor influencing productivity »terrain conditions« includes studies on slope gradient, terrain configuration and bearing capacity (Stampfer 1999, Picchio et al. 2012). Finally, harvester productivity also depends on the level of operator skills (Purfürst 2010, Purfürst and Erler 2011).

Additionally, it should be noted that harvester productivity has to be referenced to a certain decade or point in time. Nurminen et al. (2006) point out that progress in harvester development in time can positively influence productivity. Nurminen et al. (2006) confirmed that higher productivities were achieved for pine (by 14–35%), spruce (by 12–34%) and birch (by 5–21%) in comparison with data collected in the previous decade by Kuitto et al. (1994, as cited by Nurminen et al. 2006).

From the above mentioned factors influencing productivity, tree size is the most common and most often studied. The influence of tree size on productivity is referred to as »piece-size law« – the bigger the piece (tree), the higher the productivity, as described by Visser and Spinelli (2012). Initially, this concept was described by Speidel (1952, as cited by Berg et al. 2014) as the »law of mass per piece«. It is also important to mention that at some point a piece, which is too large, can influence productivity negatively: a tree which is too large for machine capacity (size and power) may not be processed effectively; a point which was explained well by Visser and Spinelli (2012).

Taking into account the above mentioned research results, it was hypothesised that higher productivity can be achieved when:

⇒ the stand is older,
⇒ there is a smaller number of trees for cutting, although with the same mean thinning intensity (*THI*),
⇒ the *THI* is higher.

In fact, all of these three factors include the »piece-size law«. Therefore, the aim of this paper was to find out the differences in productivity in pure pine stands characterised by increasing:

⇒ age,
⇒ number of trees per hectare in the initial stand in each age class (*AC*),
⇒ number of trees for harvesting in each *AC*,
⇒ thinning intensity in each *AC*, as all of these factors influence mean *DBH* of harvested trees.

2. Material and methods

Pure Scots pine (*Pinus sylvestris* L.) stands were selected for study in Drawno Forest District, north-west Poland (E 15°50'–16°00', N 53°10'–53°13'). The research was carried out in pure pine stands grown in the same soil, site and weather conditions. The stand compartments were divided according to age class and the number of trees per hectare. 56 sample

Table 1 Stand characteristics

Sample plot	*AC*3							*AC*4							*AC*5						
	Compartment	Whole stand trees		Harvested trees		THI ratio[1]	THI, m^3 ha^{-1}	Compartment	Whole stand trees		Harvested trees		THI ratio[1]	THI, m^3 ha^{-1}	Compartment	Whole stand trees		Harvested trees		THI ratio[1]	THI, m^3 ha^{-1}
		Trees ha^{-1}	Mean *DBH*	Trees ha^{-1}	Mean *DBH*				Trees ha^{-1}	Mean *DBH*	Trees ha^{-1}	Mean *DBH*				Trees ha^{-1}	Mean *DBH*	Trees ha^{-1}	Mean *DBH*		
1	107f I	563	25.9	143	24.0	0.9	53	103k	323	33.1	105	29.8	0.9	51	96h	476	28.2	108	25.0	0.9	34
2	107fII	703	23.4	130	21.3	0.9	35	90d	460	27.5	98	23.6	0.9	35	127a	518	27.5	188	24.5	0.9	88
3	93c	863	19.4	273	17.1	0.9	45	80c	483	28.1	95	24.0	0.9	34	134c	534	25.5	124	21.1	0.8	37
4	31l	917	20.1	250	18.4	0.9	57	95d	513	26.4	98	23.6	0.9	34	170a	564	27.9	170	25.1	0.9	72
5	138h	957	19.5	397	17.1	0.9	62	95a	540	25.7	125	24.0	0.9	39	97b	594	25.7	186	24.6	1.0	61
6	32k	1043	19.7	367	17.8	0.9	38	116c	560	25.5	105	22.8	0.9	27	98hI	594	26.5	172	23.2	0.9	56
7	172c	1070	19.9	403	17.9	0.9	73	151a	570	24.6	153	21.9	0.9	36	99g	596	27.1	264	24.0	0.9	65
8	30i	1083	18.6	360	16.8	0.9	57	152b	593	24.7	138	22.1	0.9	38	122a	618	24.6	176	22.1	0.9	49
9	166g	1097	20.3	410	16.9	0.8	53	93g	625	23.7	185	21.2	0.9	44	13a	632	24.1	212	21.0	0.9	55
10	37aI	1123	19.6	413	16.7	0.9	60	119aI	660	21.3	195	18.3	0.9	26	73f	634	24.6	238	22.0	0.9	53
11	12a	1153	18.5	423	18.1	1.0	72	89b	663	28.9	80	21.4	0.7	21	98hII	640	25.0	154	20.5	0.8	46
12	41a	1270	19.2	567	15.4	0.8	71	153f	663	24.7	193	20.7	0.8	44	155b	644	26.4	162	23.2	0.9	57
13	80g	1270	20.4	397	19.1	0.9	84	14c	683	23.7	200	22.3	0.9	55	154a	648	25.9	200	22.3	0.9	67
14	94aI	1297	17.4	513	14.9	0.9	66	172f	695	25.6	195	23.4	0.9	65	72b	682	24.7	282	22.1	0.9	77
15	37aII	1403	18.3	490	16.6	0.9	64	84c	708	24.3	300	22.0	0.9	77	143d	708	21.8	248	19.0	0.9	59
16	40c	1603	15.4	853	16.8	1.1	62	119aII	708	20.5	200	17.4	0.8	27	5g	720	22.3	238	20.0	0.9	47
17	94aII	1603	15.4	630	13.2	0.9	55	83b	748	24.1	163	21.5	0.9	76	78l	756	21.5	252	19.6	0.9	57
18	–	–	–	–	–	–	–	171h	768	23.8	255	21.0	0.9	61	100f	758	23.7	172	21.1	0.9	68
19	–	–	–	–	–	–	–	46b	868	22.3	315	20.4	0.9	56	6fI	836	21.8	176	21.5	1.0	53
20	–	–	–	–	–	–	–	–	–	–	–	–	–	–	6fII	836	23.6	156	18.8	0.8	48
Mean	–	1119	19.5	413	17.5	0.9	59	–	622	25.2	168	22.2	0.9	44	–	649	24.9	194	22.0	0.9	57
Median	–	1097	19.5	403	17.1	0.9	60	–	660	24.7	163	22.0	0.9	39	–	637	24.9	181	22.1	0.9	56
Min	–	563	15.4	130	13.2	0.8	35	–	323	20.5	80	17.4	0.7	21	–	476	21.5	108	18.8	0.8	34
Max	–	1603	25.9	853	24.0	1.1	84	–	868	33.1	315	29.8	0.9	77	–	836	28.2	282	25.1	1.0	88
Sd	–	280	2.5	174	2.4	0.06	13	–	126	2.9	69	2.6	0.04	16	–	98	2.0	47	2.0	0.04	13
n	–	17	17	17	17	17	17	–	19	19	19	19	19	19	–	20	20	20	20	20	20

[1] thinning intensity ratio – understood us ratio of mean DBH of extracted trees to mean DBH of whole stand trees (Lagesson 1997, Mederski 2006)

plots were selected: 17, 19 and 20 in the *AC*3 (41÷60 y.o.), *AC*4 (61÷80 y.o.) and *AC*5 (81÷100 y.o.) In the compartments, sample plots were marked with an area of 0.3, 0.4 and 0.5 ha in the stands of *AC*3, *AC*4 and *AC*5. Bigger sample plots were selected in older stands characterised by a lower number of trees, though sufficient for the experiment. In each sample plot, the same pattern of strip roads was designed, with a maximum width of up to 4 m and a distance between them of 20 m (from axis to axis of the strip road, Mederski 2006).

The selected sample plots had an increasing number of trees within each *AC* (Table 1). This depended mostly on the stand health (due to pest and fungi development), as all of them grew in similar soil conditions with the same site index. There were 563 to 1603 trees ha^{-1} in *AC*3, 323 to 868 trees ha^{-1} in *AC*4, and 476 to 836 trees ha^{-1} *AC*5. A higher mean number of trees were selected for thinning in *AC*3 (413 per ha), than in *AC*4 and *AC*5 (168 and 194 per ha, respectively). On each sample plot, the *DBH*s of all the harvested trees were measured with an electronic calliper with an accuracy of 0.1 cm. The number was marked with white paint on each measured tree.

The mean *DBH* in *AC*3 was 17.5 cm, which was lower than in *AC*4 and *AC*5 (22.2 and 22.0 cm, respectively). The stands of *AC*5 presented similar mean values in terms of the number of harvested trees per ha as well as the mean *DBH* in comparison with *AC*4 (Table 1). It was found that most of the *AC*5 stands had different thinning schedules in terms of time, and the thinning was postponed to a later time – from *AC*4 to *AC*5.

In each *AC*, division according to thinning intensity (*THI*) was applied: $a<30$, $30\leq b\leq 60$ and $c>60$ m^3 ha^{-1}, respectively. This division was carried out after statistical analysis, which suggested borders at ca. 30 and 60 m^3 ha^{-1}. Finally, in each *AC*, sample plots were of an increasing number of trees and of increasing thinning intensity groups. However, only in *AC*4 all thinning intensities were recorded: *THIa*, *THIb* and *THIc*. In *AC*3 and *AC*5, there were only *THIb* and *THIc*.

Silvicultural treatments were prescribed according to current standards: more intensive thinning was proposed in stands with a bigger number of trees, with the idea that only one intervention was expected in one decade. Positive thinning was applied, which means that trees of lower importance were selected to make the best possible conditions for future trees.

For the thinning operation, a Komatsu 931.1 harvester was used with a powerful 193 kW (7.4 l stroke volume) engine. The machine was equipped with a *CRH* 22 boom, with a reach of up to 9.8 m and a lifting torque (gross) 217 kNm. The Komatsu 365 harvester head had three steel feed rollers and five delimbing knives (four moving). Thinning was carried out by two harvester operators aged 39 and 44, both with a 7-year experience. The two operators worked in different shifts on sample plots selected randomly.

On all the sample plots, the same types of assortments were harvested: 2.85, 2.50 and 2.45 m long saw logs, pulp wood and industrial wood, respectively.

Time studies were carried out with respect to the productive machine hour (*PMH*) without delays (Mederski 2006). Productivity (*P*) was calculated as:

$$P=\frac{V}{T_{\mathrm{PMH}}} \qquad (1)$$

where:

V volume of harvested timber, m^3;

T_{PMH} time of productive machine hour (moving, crane and head positioning, cutting, felling, delimbing and bucking; without delays), h.

All the delays were excluded from the study in order to only compare the pure productive time from each sample plot. In fact, there were some delays and repairs during the study, however, they occurred randomly and were not related to particular stand conditions (*AC* or *THI*); therefore they were excluded from further analysis. Thanks to this, the field studies were more accurate, but the analyses were performed at the level of total *PMH* per sample plot and total volume of harvested timber per sample plot. The timber volume under bark was taken from the harvester computer.

In order to compare the mean productivity with respect to the experimental variables, prior to the variance analysis, the Lilliefors test, for the normal distribution of data (Thode 2002), was done followed by the Bartlett test of homogeneity of variances (Zar 1999) in the analysed model. A multiple analysis of variance was done with respect to the estimated interaction between the analysed factors. Based on the interaction plots, interactions between factors were chosen (Ott 1984). To discover which means were significantly different from each other, the Tukey's post hoc test was used for factors significant in ANOVA (Ott 1984). Statistical inference was performed at significance level α = 0.05.

Pearson's correlation matrix was determined for the studied characteristics. Based on the results of ANOVA and values of correlation coefficients, the multiple regression was proposed, where the influence of the experimental factors statistically different in the analysis of variance on the mean productivity per PMH was determined. The program package R (3.0.2) was used for the calculations (R Development Core Team 2013).

3. Results

In each *AC*, productivity lowered as the number of trees increased within the considered *AC* (Fig. 1).

As the trend lines show, the highest productivities were mostly in *AC*5 and the lowest in *AC*3. Also in *AC*3, an increasing number of trees in the initial stand had the biggest impact on lowering productivity. In *AC*4, this trend was the weakest. In some of the stands in *AC*4 (end of the curve), higher productivities were achieved than in *AC*5. What is very important here is that, generally, the productivities in *AC*3 were lower than in *AC*5, even though the average THIs were similar: 59 and 57 m^3 ha^{-1}, respectively (Table 1).

Using the Lilliefors test, based on Kolomogorov-Smirnov statistics, it was shown that the analysed factor – productivity – was normally distributed (D=0.1028, p-value=0.1481). With the application of the Bartlett test, it was decided that there was no evidence to reject the null hypothesis for the test of homogeneity of variance for the analysed factors (K-squared=2.1152, df=2,

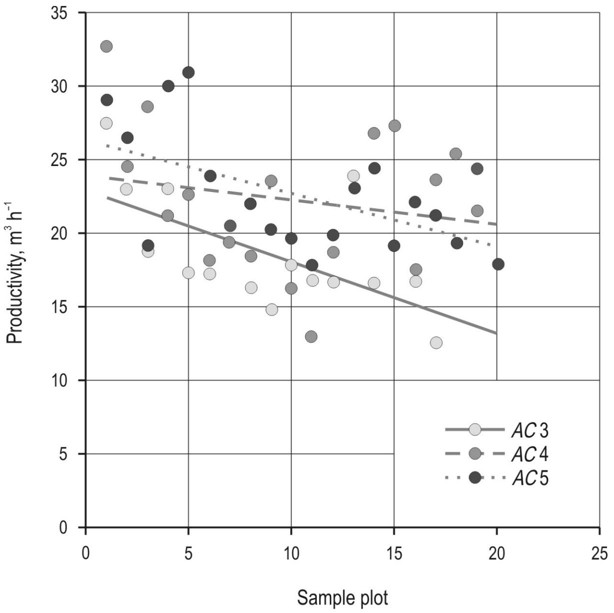

Fig. 1 Changes in productivities in numbered sample plots with trend lines (order of sample plots is according to increasing number of trees in the initial stands, as in Table 1)

p-value=0.3473). The multiple analysis of variance for productivity (Table 2) showed significant differences in mean effects in relation to *AC* and *THI*, and for those factors, Tukey's post hoc tests were carried out (Table 3). In contrast, shift and operator had no significant impact on productivity (Table 2).

Considering the division of stands into age classes, the lowest mean productivity was observed in *AC*3 (18.57 m^3 h^{-1}), which was statistically different to *AC*4 and *AC*5 (22.24 and 22.60 m^3 h^{-1}, respectively, Table 3) as Tukey's test has shown (*HSD*=2.829186; r.harmonic=18.58).

Table 2 Anova Table (Type III tests)

	Sum. sq.	D.f.	*F* value	*p*-value
AC	210.6	2	8.3873	0.0009 ***
THI	218.4	2	8.6975	0.0007 ***
SHIFT	60.4	2	2.4049	0.1032
OPERATOR	7.7	1	0.6171	0.4367
AC: SHIFT	63.2	4	1.2587	0.3022
AC: OPERATOR	25.4	2	1.0101	0.3733
SHIFT: OPERATOR	18.3	2	0.7272	0.4895
RESIDUALS	502.1	40	–	–

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Table 3 Tukey's tests for mean productivities obtained within the analysed *AC*s and *THI*s, $\alpha=0.05$; identical superscripts in column »groups« denote no significant difference between mean values (according to Tukey's *HSD* test)

		Mean	Std. error	*r*	Min.	Max.	Groups
AC	3	18.57	0.9198	17	12.64	27.60	a
	4	22.24	1.0960	19	12.99	32.61	b
	5	22.60	0.8834	20	17.84	30.90	b
THI	a	16.19	1.1337	4	12.99	18.07	a
	b	21.44	0.7398	32	12.64	32.61	b
	c	21.98	1.0793	20	15.56	30.90	b

In *AC*3, a high number of trees were cut (413 per hectare) with a low mean *DBH* of 17.5 cm (Table 1). Low productivity was achieved in *AC*3 even when mean thinning intensity was the highest (59 m^3 ha^{-1}) in comparison with *AC*4 and *AC*5, where on average 44 and 57 m^3 ha^{-1} was harvested, respectively.

At the same time, the mean productivities achieved in the stands within the lowest *THIa* amounted to 16.19 m^3 h^{-1} and were statistically different (Tukey test, *HSD*=4.052411; r.harmonic=9.06) from those from stands of *THIb* and *THIc* (21.44 and 21.98 m^3 PMH^{-1}, respectively, Table 3). These low productivities occurred only in *AC*4, where either a small number of trees per hectare were harvested (sample plots 6 and 11) or they were of small mean diameter (sample plots 10 and 16, Table 1).

In the case of *AC*3, the increasing *THI* did not influence the productivity at all. In fact, it lowered slightly when more intensive thinning was applied (Fig. 2a). Furthermore, in *AC*3, the productivity decreased considerably, when more trees were harvested (Fig. 2d) with a smaller mean *DBH* (sample plots 14, 15, 16 and 17, Table 1). This was not the case in the older stands (*AC*4 and *AC*5 with thicker trees compared to *AC*3, Table 1) and especially in AC4 where increased *THI* had the biggest impact on productivity results (Fig. 2a).

In principle, the productivity depended on the mean *DBH* of the harvested trees: the larger the *DBH*, the higher the productivity (Fig. 2b). In the case of the impact of the mean *DBH* on productivity in each *AC*, the data were more clustered along the curves in comparison with the *THI*, which suggests that »piece-size law« had the biggest impact on the final result within the considered stand conditions.

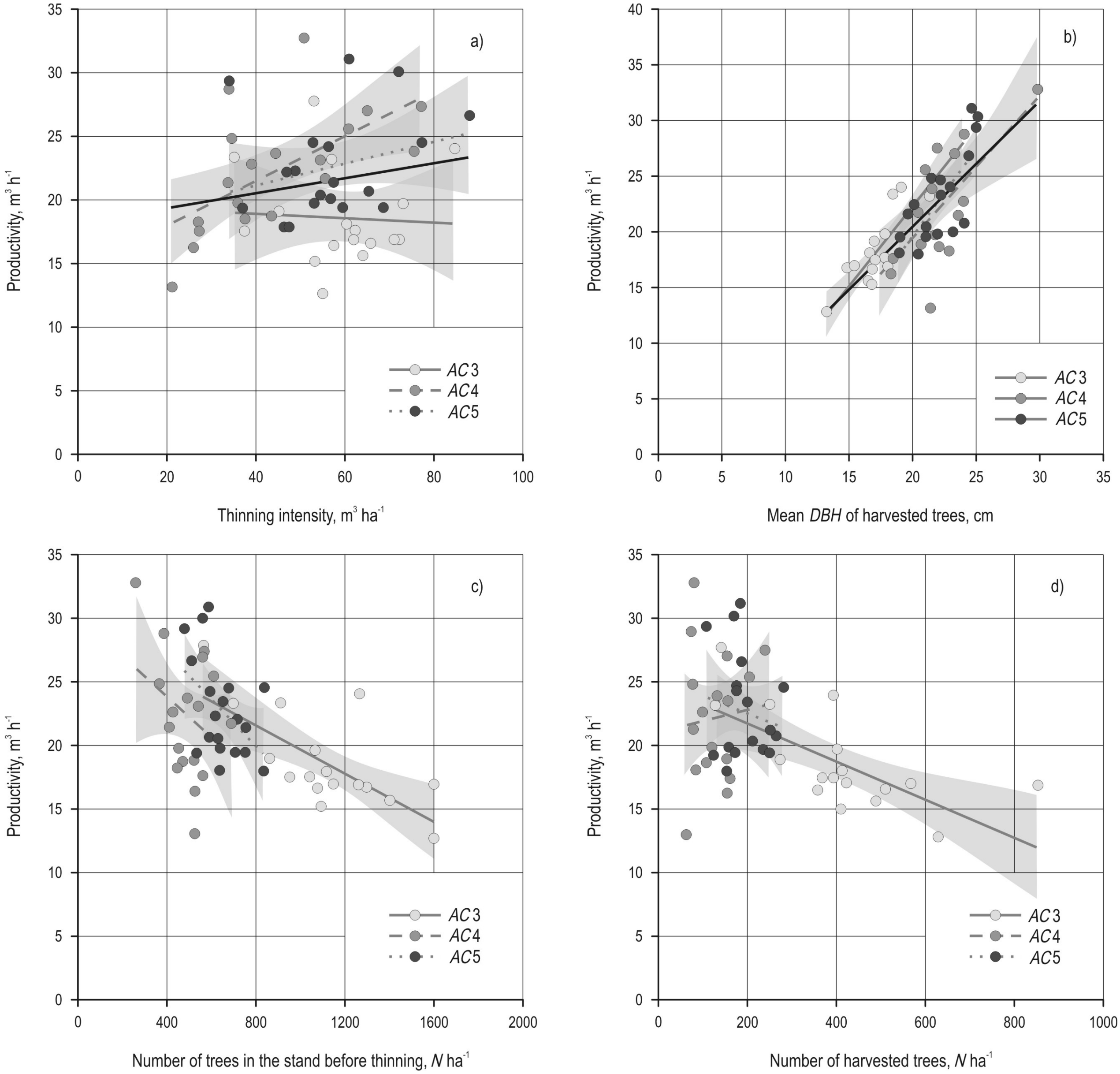

Fig. 2 Productivity as a function of different stand parameters (black curves represent mean values for all data)

Confirmation of this impact was obtained when the correlation matrix was built, where productivity was correlated with the mean *DBH* of the harvested trees (expressed by the highest factor: 0.78, Table 4).

As the *AC* groups (3, 4 and 5) and *THI* groups (*a*, *b* and *c*) had a statistically significant impact on productivity, a model of multiple regression was proposed with the DBH_{mean} of the harvested trees:

$$Y = -7.8920 + 1.2494 \times DBH_{mean} - 0.8587\delta_4 - \\ -1.3237\delta_5 + 3.7631\delta_b + 5.2550\delta_c \qquad (2)$$

where:

Y mean productivity per PMH;
DBH_{mean} mean *DBH* of harvested trees;
δ_i Kronecker's delta,

$$\delta_i = \begin{cases} 1 & stand\ of\ i-age\ class\left(of\ i-thinning\ intensity\right) \\ 0 & in\ other\ case \end{cases}$$

For the proposed model, the determination factor R^2 was 0.7168, and the highest significance of estimated factor: DBH_{mean} (Table 5).

Table 4 Correlation matrix

	Number of whole stand trees	Number of harvested trees	Mean DBH of whole stand trees	Mean DBH of harvested trees	THI	Harvested volume	Mean volume from one tree	Productivity
Number of whole stand trees	1.00	0.81	–0.70	–0.67	0.47	0.11	–0.55	–0.46
Number of harvested trees	0.81	1.00	–0.71	–0.62	0.56	0.04	–0.72	–0.36
Mean *DBH* of whole stand trees	–0.70	–0.71	1.00	0.94	–0.21	0.46	0.83	0.64
Mean *DBH* of harvested trees	–0.67	–0.62	0.94	1.00	–0.09	0.47	0.72	0.78
THI	0.47	0.56	–0.21	–0.09	1.00	0.50	–0.31	0.22
Harvested volume	0.11	0.04	0.46	0.47	0.50	1.00	0.41	0.37
Mean volume from one tree	–0.55	–0.72	0.83	0.72	–0.31	0.41	1.00	0.35
Productivity	–0.46	–0.36	0.64	0.78	0.22	0.37	0.35	1.00

Table 5 Significance of estimated factors

	Estimate	Std. error	*t* value	Pr(>|*t*|)
Intercept	–7.8920	2.7677	–2.851	0.0063**
DBH_{mean}	1.2494	0.1558	8.018	0.0000***
AC4	–0.8587	1.2251	–0.701	0.4866
AC5	–1.3237	1.0956	–1.208	0.2326
*THI*b	3.7631	1.4920	2.522	0.0149*
*THI*c	5.2550	1.5780	3.330	0.0016**

In general, the bigger number of trees in the initial stand (consisting of more trees with a smaller *DBH*), the lower the productivity results (Fig. 2c). This »piece-size law« can also be applied when only trees for extraction are considered (*AC*3 and *AC*5, Fig. 2d). However, in *AC*4, a large number of harvested trees had a positive impact on the average productivity.

4. Discussion with conclusion

Harvester use for thinning operations in the younger (*AC*3) and older stands (*AC*4 and *AC*5) resulted in different productivities. The stands in *AC*3, with a considerably larger number of trees in the initial stand, as well as for extracting, gave a lower productivity in comparison with the older stands. It is interesting that in *AC*3, increased thinning intensity did not raise productivity (Fig. 2a). At this stage of stand development, the trees for harvesting were of a small *DBH*, which in this case, were 17.5 cm on average, but started from as small as 13.2 cm (Table 1), and the mean volume obtained from each harvested tree amounted to 0.14 m^3. In this case, it was not only the »piece-size law« that had the biggest impact on the results obtained, but also the fact that in a stand with a large density, manoeuvring a crane and positioning the head takes more time than in a stand with a low density. Large density stands also require more careful and accurate work as they are more vulnerable to residual damage (Karaszewski et al. 2013, Bembenek et al. 2013a, 2013b, Stańczykiewicz et al. 2015).

In the same figure presenting productivity as a function of *THI* (Fig. 2a), the curve for *AC*4 grew most rapidly. In *AC*4 there were two particular sample plots (14 and 15) with a higher than average number of trees for removal (195 and 300) with large mean *DBH* (23.4 and 22.0 cm, Table 1). Actually, as the mean statistical productivity showed (Table 2), in this particular case, the stands of *AC*4 and *AC*5 were of similar potential. However, in the stands of *AC*5, the average timber volume obtained from one tree was the highest: 0.29 m^3, while in *AC*4 it was 0.26 m^3. A higher mean volume of timber from one harvested tree together with a slightly bigger number of trees harvested per hectare (possibly optimal), eventually led to a slightly larger mean productivity in *AC*5 (22.60 m^3 h^{-1}, Table 2). Also in *AC*5, in comparison with *AC*4, there were smaller standard deviation values for:

⇒ the number of harvested trees,
⇒ the mean *DBH* of the harvested trees,
⇒ the mean *THI*.

Those factors also had a positive impact on the higher mean productivity in *AC*5. However, this higher mean productivity in *AC*5 should not be linked with Fig. 2a, where the *AC*4 trend line presents partially higher productivities than in *AC*5. The lowest thinning intensities (*THIa*<30 m^3 ha^{-1}) on particular sample plots were observed only in *AC*4 (Fig. 2a). This should be considered carefully as this is not a very common case. Currently in Poland, according to silvicultural prerequisites, a maximum of one thinning treatment per 10 years should be applied, which means that much more than 30 m^3 per hectare can be harvested. However, if a very low intensity is achieved, low productivity may be expected.

The productivity curves in the present study were linear, which can also be seen in other productivity studies (Sirén and Aaltio 2003, Nakagawa et al. 2007). The authors of the present work decided to use linear curves for three reasons:

- ⇒ they fitted best to the data distribution,
- ⇒ the linear model was characterised by the highest determination factor R^2,
- ⇒ there was also argumentation based on previous findings: the present study was limited only to thinnings in stands where the harvested trees gave a mean timber volume from 0.14 up to 0.29 m^3.

This was rather at the low end of potential tree sizes to be harvested. As presented in studies by Spinelli et al. (2010) and Visser and Spinelli (2012), using more complex regression models is more suitable when a broad raw data set including harvested trees of small and large volumes (e.g. from 0.3 up 5.2 m^3) is considered. The proposed model (2) also consists of simple factors including *DBH*, which is easy to obtain. Some researchers have used the volume of harvested tree as a variable of productivity (Spinelli et al. 2010, Visser and Spinelli 2012), however in the case of the data presented in this paper, using the mean volume of harvested tree V_{mean}, instead of DBH_{mean}, in a model:

$$Y = 8.607 + 6.990 \times V_{\mathrm{mean}} + 3.901\delta_4 + 2.891\delta_5 + \\ + 7.720\delta_{\mathrm{b}} + 9.401\delta_{\mathrm{c}} \qquad (3)$$

gave a much lower determination factor R^2=0.3934.

The number of trees per hectare is also a limiting factor. Fig. 2c shows that the bigger the initial number of trees before thinning per hectare, the lower the productivity. In this case, it is linked to the natural stand condition: the bigger the number of trees within one *AC* on the unit area, the smaller the diameter of a single tree (in the stand and for harvesting). These kinds of stands are not only less attractive for thinning operations with harvesters giving smaller productivity, but can also give lower income from the timber sold due to a bigger share of timber with small diameters (Bembenek et al. 2014). A large number of trees for harvesting together with high mean *DBH* that have a positive impact on productivity. Fig. 2d shows that it was only in *AC*4 that the increasing number of harvested trees had a positive impact on the growing productivity. This curve has to be taken with caution as data dispersion is high and more tests should be conducted to find out how the increasing number of harvested pine trees influences productivity in *AC*4. Fig. 1 also shows that in *AC*4, the sample plots 14, 15 and 17÷19 had a particularly large number of trees for harvesting with large mean *DBHs* and high mean *THIs*.

It can be concluded that the productivity of the Komatsu 931.1 harvester increased along with:

- ⇒ older *AC*,
- ⇒ decreasing number of trees in the initial stand in each *AC*,
- ⇒ lowering number of trees for harvesting in *AC*3 and *AC*5,
- ⇒ increasing *THI* in only *AC*4 and *AC*5.

Finally, as the model (2) presents, the larger the mean *DBH* of the trees for harvesting, the greater the productivity. The same model also confirms that within the same mean *DBH*, the older the *AC*, the lower the productivity. However, the last factor in the model, *THI*, cannot be changed freely with the same (fixed) mean *DBH*. Increasing *THI* requires the removal of a larger number of trees, resulting in the cutting of thicker trees and, as a consequence, the mean *DBH* of the harvested trees has to increase. Therefore, the mean *DBH* has to be considered in conjunction with the number of trees for harvesting (which depends on *AC* and *THI*, as variables in the model) when productivity is analysed.

Acknowledgements

This study was completed as part of the project: »Productivity of harvester thinning operations in pine stands of different thinning intensities« supported by the Regional Directorate of the State Forests in Szczecin, Poland. The authors would like to thank the two anonymous reviewers for their useful comments which greatly improved the final version of the paper.

5. References

Bembenek, M., Giefing, D.F., Karaszewski, Z., Mederski, P.S., Szczepańska-Álvarez, A., 2013a: Uszkodzenia drzew w następstwie trzebieży wczesnych w nizinnych drzewostanach świerkowych. Sylwan 157(10): 747–753.

Bembenek, M., Giefing, D.F., Karaszewski, Z., Mederski, P.S., Szczepańska-Álvarez, A., 2013b: Uszkodzenia drzew w nizinnych drzewostanach świerkowych podczas zabiegu trzebieży późnej. Sylwan 157(12): 892–898.

Bembenek, M., Karaszewski, Z., Kondradzki, K., Łacka A., Mederski, P.S., Skorupski, M., Strzeliński, P., Sułkowski, S., Węgiel, A., 2014: Value of merchantable timber in Scots pine stands of different densities. Drewno. 57(192): 133–142.

Bembenek, M., Mederski, P.S., Karaszewski, Z., Łacka, A., Grzywiński W., Węgiel A., Giefing, D.F., Erler, J., 2015: Length accuracy of logs from birch and aspen harvested in thinning operations. Turkish Journal of Agriculture and Forestry 39: 845–850.

Berg, S., Schweier, J., Brüchert, F., Lindner, M., Valinger E., 2014: Economic, environmental and social impact of alternative forest management in Baden-Württemberg (Germany) and Västerbotten (Sweden). Scandinavian Journal of Forest Research 29(5): 485–498.

Danilović, M., Tomašević, I., Gačić, D., 2011: Efficiency of John Deere 1470D ECOIII harvester in poplar plantations. Croatian Journal of Forest Engineering 32(2): 533–548.

Eliasson, L., 1999: Simulation of thinning with a single-grip harvester. Forest Science 45(1): 26–34.

Eliasson, L., Lageson, H., 1999: Simulation study of a single-grip harvester in thinning from below and thinning from above. Scandinavian Journal of Forest Research 14(6): 589–595.

Evanson, T., McConchie, M., 1996: Productivity measurements of two Waratah 234 hydraulic tree harvesters in radiate pine in New Zealand. Journal of Forest Engineering 7(3): 41–52.

Gerasimov, Y., Senkin, V., Väätäinen, K., 2012: Productivity of single-grip harvesters in clear-cutting operations in the northern European part of Russia. European Journal of Forest Research 131(3): 647–654.

Glöde, D., 1999: Single and double-grip harvesters – productive measurements in final cutting of shelterwood. Journal of Forest Engineering 10(2): 63–74.

Iwaoka, M., Aruga, K., Sakurai, R., Cho, K., Sakai, H., Kobayashi, H., 1999: Performance of small harvester head in a thinning operation. Journal of Forest Research 4(3): 195–200.

Karaszewski, Z., Giefing, D.F., Mederski, P.S., Bembenek, M., Dobek, A., Stergiadou, A., 2013: Stand damage when harvesting timber using a tractor for extraction. Forest Research Papers 74(1): 27–34.

Kuitto, P.J., Keskinen, S., Lindroos, J., Oijala, T., Rajamäki, J., Räsänen, T., Terävä, J., 1994: Puutavaran koneellinen hakkuu ja metsäkuljetus. Summary: Mechanized cutting and forest haulage. Metsäteho Report 410 p.

Kusiak, W., 2008: Tendencje na rynku harwesterów i forwarderów w Polsce. In: Bezpieczeństwo pracy w nowoczesnym leśnictwie (Romankow, J., ed.), Katedra Inżynierii Środowiska Pracy UP, Poznań, 24–36 p.

Lageson, H., 1997: Effects of thinning type on the harvester productivity and on the residual stand. Journal of Forest Engineering 8(2): 7–14.

Mederski, P.S., 2006: A comparison of harvesting productivity and costs in thinning operations with and without midfield. Forest Ecology and Management 224(3): 286–296.

Mederski, P.S., 2013: The potential of harvester use for thinning operations in mixed birch-pine stands. Wydawnictwo UP w Poznaniu.

Moskalik, T., 2002: Rozwój technik i technologii maszynowego pozyskiwania drewna. Sylwan 146(10): 31–37.

Nakagawa, M., Hamatsu, J., Saitou, T., Ishida, H., 2007: Effects of tree size on productivity and time required for work elements in selective thinning by a harvester. International Journal of Forest Engineering 18(2): 24–28.

Nurminen, T., Korpunen, H., Uusitalo, J., 2006: Time consumption analysis of the mechanised cut-to-length harvesting system. Silva Fennica 40(2): 335–363.

Ott, L., 1984: An Introduction to Statistical Methods and Data Analysis. Duxbury Press.

Picchio, R., Neri, F., Petrini, E., Verani, S., Marchi, E., Certini, G., 2012: Machinery-induced soil compaction in thinning two pine stands in central Italy. Forest Ecology and Management 285: 38–43.

Purfürst, F.T., 2010: Learning Curves of Harvester Operators. Croatian Journal of Forest Engineering 31(2): 89–97.

Purfürst, F.T., Erler, J., 2011: The Human Influence on Productivity in Harvester Operations. International Journal of Forest Engineering 22(2): 15–22.

R Development Core Team, 2013: *R:* A Language and Environment for Statistical Computing. R Foundation for Statistical Computing. Vienna, Austria, http://www.r-project.org.

Sirén, M., Aaltio, J., 2003: Productivity and costs of thinning harvesters and harvester-forwarders. International Journal of Forest Engineering 14(1): 39–48.

Sowa, J., 2009: Współczesne pożytki z lasu. In: Leśnictwo w górach i rejonach poprzemysłowych (Starzyk, J., ed.), Wydawnictwo UR, Kraków, 129–152 p.

Speidel, G., 1952: Das Stückmassegesetz und seine Bedeutung für den internationalen Leistungsvergleich bei der Forstarbeit. Dissertation, University of Hamburg.

Spinelli, R., Hartsough, B.R., Magagnoti, N., 2010: Productivity standards for harvesters and processors in Italy. Forest Product Journal 60(3): 226–235.

Stampfer, K., 1999: Influence of terrain conditions and thinning regimes on productivity of a track-based steep slope harvester. In: Proceedings of the International Mountain Logging and 10th Pacific Northwest Skyline Symposium (Sessions, J., Chung, W., ed.), Corvallis, Oregon, 78–87 p.

Stańczykiewicz, A., Sowa, J.M., Leszczyński, K., Kulak, D., Szewczyk, G., 2015: Uszkodzenia drzew i odnowienia w wyniku pozyskania drewna z użyciem urządzeń agregowanych z ciągnikami rolniczymi w trzebieżowych drzewostanach świerkowych. Sylwan 159(3): 201–210.

Suadicani, K., Fjeld, D., 2001: Single-tree and group selection in mountain Norway spruce stands: factors influencing operational efficiency. Scandinavian Journal of Forest Research 16(1): 79–87.

Suchomel, C., Spinelli, R., Magagnotti, N., 2012: Productivity of processing hardwood from coppice forests. Croatian Journal of Forest Engineering 33(1): 39–47.

Szewczyk, G., Sowa, J.M., Grzebieniowski, W., Kormanek, M., Kulak, D., Stańczykiewicz, A., 2014: Sequencing of harvester work during standard cuttings and in areas with windbreaks. Silva Fennica 48(4): 1–16.

Thode Jr., H.C., 2002: Testing for Normality. Marcel Dekker, New York.

Visser, R., Spinelli, R., 2012: Determining the shape of the productivity function for mechanised felling and felling-processing. Journal of Forest Research 17(5): 397–402.

Visser, R., Stampfer, K., 2003: Tree-length system evaluation of second thinning in loblolly pine plantations. Southern Journal of Applied Forestry 27(2): 77–82.

Wang, J., Haarla, R., 2002: Production analysis of an excavator-based harvester: a case study in Finnish forest operations. Forest Product Journal 52(3): 85–90.

Więsik, J., 1998: Czynniki decydujące o wyborze maszyn do pozyskiwania drewna w Polsce. Przegląd Techniki Rolniczej i Leśnej 6: 6–9.

Zar, J.H., 1999: Biostatistical analysis. Upper Saddle River, N.J.: Prentice Hall.

Żabierek, R., Wojtkowiak, R., 2012: The structure and distribution of harvesters and forwarders in individual Regional Directorates of the State Forests in Poland in the early 2010's. Acta Scientiarum Polonorum. Silvarum Colendarum Ratio et Industria Lignaria 11(4): 67–77.

Received: June 1, 2015
Accepted: September 31, 2015

Authors' address:

Piotr S. Mederski, PhD. *
e-mail: piotr.mederski@up.poznan.pl
Mariusz Bembenek, PhD.
e-mail: mariusz.bembenek@up.poznan.pl
Martyna Rosińska, MSc.
e-mail: martyna.rosinska@up.poznan.pl
Poznań University of Life Sciences
Faculty of Forestry
Department of Forest Utilisation
ul. Wojska Polskiego 71A
60-625 Poznań
POLAND

Zbigniew Karaszewski, PhD.
e-mail: z_karaszewski@itd.poznan.pl
Wood Technology Institute
Wood Science and Application Department
ul. Winiarska 1
60-654 Poznań
POLAND

Agnieszka Łacka, PhD.
e-mail: agnieszka.lacka@up.poznan.pl
Anna Szczepańska-Álvarez, PhD.
e-mail: anna.szczepanska-alvarez@up.poznan.pl
Poznań University of Life Sciences
Faculty of Agronomy and Bioengineering
Department of Mathematical and Statistical Methods
ul. Wojska Polskiego 28
60-637 Poznań
POLAND

* Corresponding author