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Harvester Efficiency During Thinning Operations in Alder Planted Stands with Some of Coppice Origin

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Abstract

In Central European conditions, harvester use becomes more popular for broadleaved tree species, though there are still some difficulties with effective delimbing of satisfactory quality. Considering these issues, economic aspects are ultimately crucial when deciding on the use of harvesters and assessing their productivity. The objective of the present research was to apply different harvesters in thinning of alder stands to determine their productivity level focusing on the use of tree trunk for logs. The study was carried out in alder stands under thinning where five different harvesters were used in nine stands, five of which were of coppice origin. Additionally, in six cases, harvesting was done after the growing season and in three cases during the growing season, when trees were covered with leaves. An average productivity was 14.42 m^3 PMH_0^{-1}, with maximum values of 24.34 m^3 PMH_0^{-1} in a coppice stand, and 23.66 m^3 PMH_0^{-1} in a planted stand. Delimbing was carried out in the tree crowns with the mean diameter as small as 7.9 cm under bark, which shows very good use of the tree trunk for logs. It was also established that the thicker the tree, the bigger the top diameter of the last log, leading to bigger biomass production, e.g. for energy purposes, but also with smaller effectiveness of log processing.

Keywords: cut-to-length, CTL, broadleaved tree species, productivity, harvester head

1. Introduction

Cut-to-length (CTL) technology is already widely used in forests, but is mainly related to coniferous species. A widespread availability of harvesters (Mederski et al. 2016b) leads to their use in young stands (Bergström 2022) or broadleaved forests (Mederski et al. 2022). Due to supportive policies (Bouriaud et al. 2011) and the increasing share of mixed stands in European forests (Buras and Menzel 2019), further expansion of machines used for broadleaved tree species is expected. Moreover, the interest in motor-manual work has declined recently and the use of fully-mechanized harvesting systems has opened the possibility to supply the raw material to wood industry in a sustainable way (Cacot et al. 2006) with limited impact on environment (Picchio et al. 2020) and on remaining stands (Bembenek et al. 2013a, 2013b). Considering the interest to define optimal conditions for the use of mechanized forest operations in broadleaved forests (Coll et al. 2018), the difficulties that the harvester encountered during use in broadleaved and mixed stands make this topic still a research area (Mederski et al. 2022).

Coniferous species, e.g. pine or spruce, are characterized by straight trunk and regular tree crown. These features allow to achieve successful results in terms of harvester productivity (Mederski et al. 2016), trunk utilization and quality of logs (Mederski et al. 2019). Morphological features of many broadleaved species include stem with sweep and thick branches, which are limiting factors not only for timber quality (Karaszewski et al. 2013) but also for efficient log processing (Labelle et al. 2016, Rosińska et al. 2022). Furthermore, several features of the harvesting machinery, i.e. head size, feed rollers type, as well as the number and type of knives, have a substantial impact on delimbing quality (Cacot et al. 2016, Mederski et al. 2022).

The application of fully mechanized harvesting operations is even more difficult when dealing with coppice forests. Coppice forest – management system based on the natural ability of broadleaf tree species to resprout shoots from the stump after cutting – is considered as a flexible management option. It requires low financial inputs, meeting therefore the needs of rural societies and involvement of small or medium businesses enterprises (Venanzi et al. 2019). The intrinsic characteristics of coppice make their mechanized harvesting a burden, considering the usual presence of small, branchy and crooked stems, evident butt sweep, clump structure and, often, steep slope and terrain roughness (Schweier et al. 2015, McEvan et al. 2016).

Considering the growing importance of coppice forests in Europe, there have been several scientific trials aiming at evaluating the possibility of introducing fully mechanized harvesting systems in coppices, in which productivity is still substantially lower than in planted softwood stands (Schweier et al. 2015, Mederski et al. 2016, Spinelli et al. 2016). Additionally, difficulties related to stump damage or high stumps after felling, still represent a major concern in coppice forest harvesting (Suchomel et al. 2012, Spinelli et al. 2017a, Spinelli et al. 2017b). On the other hand, the results of the research on coppice oak stands by Suchomel et al. (2011) showed high productivity of harvesting hardwood.

Black alder (*Alnus glutinosa* (L.) Gaertn.) is a pioneer species found on wetlands, riparian ecosystems and along water courses all over Europe and in north parts of Africa (Kajba and Gračan 2003). Alder plays an important ecological role in managing floods, reinforcing riverbanks, and maintaining river ecosystem operations (Houston Durrant et al. 2016). A high level of resistance to environmental threats and a symbiotic capacity of roots with nitrogen-fixing bacteria *Frankia alni* improves soil fertility and makes alder a valuable species in land reclamation (Piętka and Grzywacz 2018).

In addition to planted stands or those from natural regeneration from seeds, black alder frequently forms coppice. The suitability of alder to create coppice forests can be attributed to the alder robust capability to regenerate from stumps, particularly during its younger years. The most intensive growth in height of black alder trees appears between the years of five and ten, and the diameter intensively increases between fifteen and twenty (Kajba and Gračan 2003). Its rapid growth coupled with its favourable wood qualities can meet the increasing demand for wood and fiber (Rożkowski et al. 2019).

The timber of black alder is characterized by a soft and porous structure. However, it displays resilience when submerged in water. Such properties make it ideal for underwater applications, including jetties, bridge pilings, and crafting small boats. When young, the tree grows quickly, and it can be effectively coppiced. The resultant material is apt for biomass production and high-quality charcoal (Houston Durrant et al. 2016).

As published by Claessens et al. (2010), some research at the turn of the 20^{th} and 21^{st} centuries confirm that it is possible to produce high-quality timber from black alder. The optimum rotation on good sites has been defined as (30) 40–65 years. It allows to achieve *DBH* target of ca. 40 to 50 (55) cm, avoiding heart rot. Locally, e.g. in Poland, researchers consider that 50 years is a close-to-optimal rotation age. It was concluded that the growth potential of alder, including increment and stem straightness, could be improved by the selection of provenance (Rożkowski et al. 2019). However, in order to increase the overall sustainability of alder forest management, increasing effectiveness of harvesting technology is strongly needed (Coll et al. 2018).

Alder is indeed a broadleaf tree species of particular interest in terms of widening the application of CTL technology, considering some unique features. When grown in forest conditions, the tree naturally prunes itself before reaching the age of 10, and this pruning process advances in the crown at a rate faster than the tree's overall height growth (Claessens 2005). Typically, black alder grows straight and without forks. Its branches are of small diameter and, if shaded, they rapidly die and quickly decay, resulting in efficient natural pruning (Claessens et al. 2010), which makes delimbing easier when using a harvester. It is assumed that the tree form of alder, very similar to coniferous species, allows to achieve high harvester productivity. In addition, the log processing should not be limited by branches, thus the maximum utilization of the trunk for logs can be expected. On the other hand, some management issues have to be taken into account in the framework of alder forestry. Indeed, the goal that offers the most lucrative returns from cultivating black alder is producing high-quality timber with a diameter at breast height (*DBH*) of 50–60 cm and a trunk length of approximately 6 m. To achieve this goal, the rotation between 50 and 70 years is required.

Alder is fast growing when young and can give similar stocking as birch and ash. Consequently, it is crucial to ensure enough space around the most promising trees by the time they reach a height of 10 m to facilitate their development for commercial timber purposes. Initial thinning operations should be conducted rigorously and frequently. Optimal competition management can be realized by thinning around the crowns of trees chosen for the final stand.

Despite the growing interest towards alder harvesting, no study has been carried out to analyze, from a scientific point of view, the harvesting efficiency of fully-mechanized thinning operations in such stands. The few literature data on logging productivity in alder stands refer to motor-manual felling and processing by chainsaw (Grzywiński et al. 2020).

Based on the above-mentioned factors on morphological features of alder trees, it was hypothesized that the use of harvester will be very efficient in terms of productivity as well as in processing the trunk for logs (strait trunk like in coniferous trees with thin branches). It was also hypothesized that in coppice stands, in the growing season, harvesting may cause bigger delays due to leaves obstructions, as well as due to difficulties in grabbing a tree with sweep in the butt end (and/or also due to manoeuvrability on wet ground). Therefore, the objective of the research was to determine harvester efficiency in thinning operations in black alder stands. This efficiency was understood as harvester productivity with particular attention to the utilization of tree trunk for logs (how much of merchantable timber was used for logs); the aim was also to find out if there were differences in thinning operations carried out in: 1) planted stand versus coppice forests, and 2) coppice forest during the growing season and non-growing season (in autumn/winter time).

2. Materials and Methods

2.1 Research Areas and Machines Description

The study included nine test trials: four planted stands (PS) and three coppice forests (CF) located in five forest districts in North Poland (Fig. 1). Field studies on two research areas in coppice stands were conducted twice: during and after the tree growing season. Investigations took place during the thinning process in alder-dominant or mixed stands where alders constituted a minimum of 20%. A total of 1583 alder trees were cut for this research (703 in PS and 880 in CF). The volume was deduced from 346 trees (104 in PS and 242 in CF) where precise timber volume was determined. The thinning intensity of harvested trees was based on silvicultural guidelines: thinning ratio (*DBH* of harvested tree by *DBH* of remaining trees) was from 0.78 to 0.91 in planted stands and from 0.74 to 0.95 in coppice forests. Timber extraction was performed by forestry contractors operating in the chosen forest districts. The study sites were selected from stands scheduled for alder harvesting. In the end, the efficiency of five different harvester heads used by five harvesters was evaluated (Table 1).

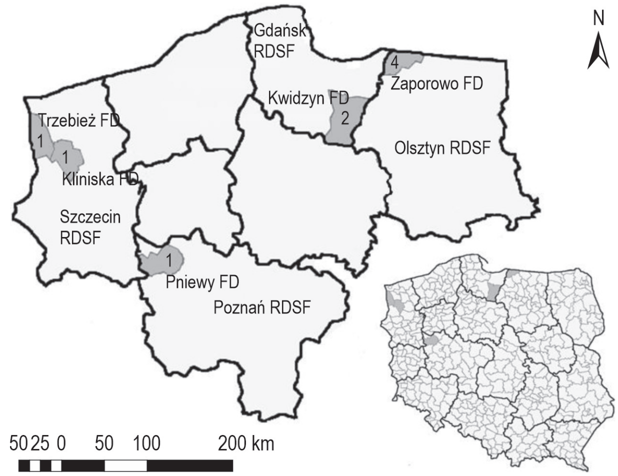

Fig. 1 Location of research areas in North and North-West Poland (RDSF – Regional Directorate of State Forests, FD – Forest District)

Poland is located in a temperate climate zone of the warm transitional type. Four of the five forest districts covered by the research are located in the Baltic Sea

Table 1 Basic data of harvesters

Harvester	Harvester production year	Harvester engine power, kW	Harvester head	Harvester head size maximum cutting diameter, mm	Operator experience years
John Deere 1270E	2013	170	H480C	710	9
Ponsse Ergo	2002	205	H73e	700	4
TBM Preuss 84*	2003	112	Kesla 24RHII	520	4
Timberjack 1070D	2003	136	HTH460	620	2
Valmet 901.3**	2007	140	351.1	600	7

* 4 trials (2 coppice forests, during and after growing season)

* 2 trials (1 coppice forest, 1 planted stand)

Region. In the western part of this region (Forest Districts (FDs): Trzebież and Kliniska), the climate is similar to the Atlantic one, with mild temperatures and high air humidity, and has a positive impact on the development and condition of tree stands. Towards the east of the Baltic Sea Region (FDs: Kwidzyn and Zaporowo), the climate changes to more continental. Pniewy FD is located more inland, to the south, characterized by homogeneous mild climate, but in terms of rainfall, the region is one of the poorest in the country (Zielony et al. 2012).

2.2 Data Collection

Research on the chosen areas was structured into two phases: 1) tree assessments, and 2) time evaluations along with gathering data on timber harvesting. Every tree planned for cutting was visibly marked with paint on either side at eye height. For each earmarked tree selected for felling, the subsequent measurements were taken:

- ⇒ diameter at breast height (*DBH*) – measured twice in different directions towards the north using a calliper, with a precision of 1 mm
- ⇒ the total height of the tree and the starting height of its crown were measured using the Vertex Laser, accurate to 0.1 m. The length of the tree crown was determined from the initial live branch consistent with the crown up to the tree's apex
- ⇒ around 1.5 m off the ground, each tree was labeled with a number.

The initial procedures typically encompassed the complete tree stand of an entire compartment. When the area was extensive, the test focused on the area around 250 trees intended for extraction. Tree harvesting was performed along parallel strip roads set 20 meters apart from each other.

The next phase of the study focused on tree felling and the processing of logs. As the harvester operated, a time analysis was conducted (accurate to 1 second) comprising three primary work intervals:

- ⇒ T_A – approach to the tree, crane extension, head positioning, tree felling, and preparing the tree for delimbing
- ⇒ T_B – initiation of delimbing, concluding with the removal of the tree top
- ⇒ T_C – pauses such as replacing chains, minor fixes, making phone calls, and other breaks.

The T_B work time was of particular interest to find delimbing and processing as depending on tree features, mainly branching. Throughout the harvesting process, the logs count and the obtained assortments were documented. A majority comprised logs for paper mills, measuring 2.5 meters, and firewood logs either 1 or 2 meters in length. In high-quality areas, occasionally, large logs were also processed, with their length being determined by the operator based on the harvester computer display. To compute the collective length of logs from an individual tree, all processed types and leftover wood (tree tops) from that specific tree were put aside in the felling area. After completing the tree felling and log processing, the harvested timber was quantified. For at least 30 successive trees with visible numbers on the primary log, the length of all wood categories (accurate to 1 cm) and the top diameters of the top log (below the bark, measured twice in different directions, accurate to 1 mm) were measured to determine log volume and top diameter where delimbing was stopped.

2.3 Data Analysis

The timber volume obtained from a single tree was divided into three categories:

- ⇒ a total merchantable timber volume processed by a harvester
- ⇒ an unprocessed merchantable timber volume (up to 5 cm under bark at the top, thinner end)
- ⇒ an energy biomass volume with less than 5 cm diameter under bark.

The volume under bark (V, m^3) was calculated based on Huber's formula:

$$V = \frac{\pi * d^2 * l}{40000} \tag{1}$$

Where:

d mid-point diameter under bark, cm

l total log length, m.

The mid-length diameter under bark of total log length processed by a harvester (d_{sort}, cm) and the mid-length diameter under bark of merchantable timber left after processing (d_{top}, cm) was determined by a tree taper – the degree to which a tree stem or bole decreased in diameter. The degree was calculated for the total log length (C_{sort}, cm m^{-1}) and for unprocessed top length (C_{top}, cm m^{-1}) separately.

$$C_{sort} = \frac{DBH - dtl}{tll - 1.3} \tag{2}$$

$$C_{top} = \frac{dtl}{utl} \tag{3}$$

$$d_{sort} = DBH - \left[C_{sort} * \left(\frac{tll}{2} - 1.3 \right) \right] \tag{4}$$

$$d_{\mathrm{top}} = dtl - \left(C_{\mathrm{top}} * \frac{utl_{\mathrm{mer}}}{2} \right) \quad (5)$$

Where:

DBH diameter at breast height under bark, cm (a deduction for the bark was applied by the coefficient for alder *t*=1.1, Suchanek 2016)

dtl diameter of top log under bark, cm

tll total log length, m

utl unprocessed top length, m

utl_{mer} unprocessed merchantable top length, m.

The timber volume processed by a harvester and the time study were used to calculate the operational productivity (P, m^3 PMH$_0^{-1}$), including the effective time (without delays):

$$P = \frac{V_{\mathrm{sort}}}{T_{\mathrm{A}} + T_{\mathrm{B}}} \quad (6)$$

Where:

V_{sort} timber volume processed by a harvester, m^3

T_A total of work time category *A*, h

T_B total of work time category *B*, h.

Statistical analyses were carried out using Python libraries for scientific computation: *SciPy*, *NumPy*, *Matplotlib* and *xlrd* for reading data collected in Microsoft Excel 2019 spreadsheets. Data distribution was plotted, linear and non-linear, simple and multiple regression analysis was applied to test the factors affecting the level of harvesters productivity. Box plots and the Mann-Whitney *U* test were used to compare T_A and T_B working time in planted stands and coppice forest, and the growing and non-growing season. The Spearman's coefficient was used to check the correlation between the presented variables.

3. Results

The age of harvested trees ranged between 29 and 73 with the mean *DBH* from 14.5 to 26.4 cm (Table 2). The obtained mean productivity was 14.42 m^3 PMH$_0^{-1}$, and varied from 5.72 to 24.34 m^3 PMH$_0^{-1}$.

Log processing was very effective in terms of trunk use, and reached up to 10.1 cm (under bark) diameter in tree top part. As it was aimed to process logs up to

Table 2 Parameters of harvesting effectiveness and main characteristics of harvested trees

Sample plot	Model of harvester	Number of harvested trees	Productivity, m^3 PMH$_0^{-1}$	Diameter of top log, cm	Share of tree crown used for logs, %	Volume of merchantable timber not used for logs in total merchantable timber, %	Age, years	*DBH*, cm	Height, m	Height at crown base, m
1 PS, NL	TJ	212	23.66	13.5	36.12	8.76	73 (50%) 66 (50%)	26.4	19.9	10.5
2 PS, NL	PE	169	18.25	10.9	42.56	5.24	73	23.4	21.6	15.0
3 CF, WL	V	152	24.34	10.4	32.64	5.57	55	21.3	21.8	14.3
4 CF, WL	TBM	209	9.10	10.5	53.53	10.86	42	20.2	16.1	10.0
5 PS, NL	JD	102	19.14	10.0	19.68	11.49	64	19.8	22.0	14.7
6 PS, NL	V	220	11.15	10.1	36.45	8.00	45	18.2	17.1	10.0
7 CF, NL	TBM	202	7.64	10.0	39.34	13.56	42	18.0	14.0	8.6
8 CF, NL	TBM	172	10.75	7.9	24.34	8.43	29	15.6	17.3	11.7
9 CF, WL	TBM	145	5.72	8.0	28.67	9.24	29	14.5	17.5	12.6
$\bar{x}$	–	176	14.42	10.1	34.81	9.02	52	19.71	18.59	11.93
Minimum	–	102	5.72	7.9	19.68	5.24	29	14.5	14.0	8.6
Maximum	–	220	24.34	13.5	53.53	13.56	73	26.4	22.0	15.0
Median	–	172	14.70	10.3	36.29	8.60	55	20.0	18.6	11.1
Standard deviation	–	38.85	6.65	1.54	10.51	2.87	15.65	3.38	3.02	2.49

WL – with leaves = during growing season; NL – no leaves = after growing season; PS – planted stand; CF – coppice forest

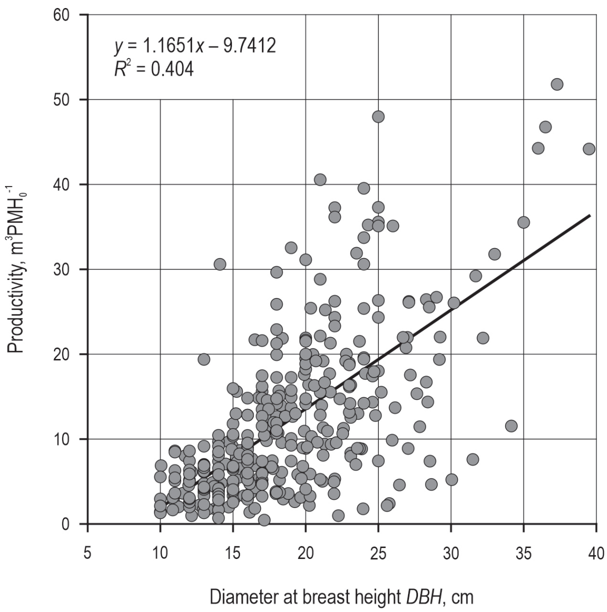

Fig. 2 Linear statistical model of productivity related to *DBH*, regression analysis parameters: r=0.6357, r^2 =0.4042, $r^2_{Adj.}$= 0.4024, F(1.337)=228.62, p<0.0001, *Std. Err.*: 7.6818, the two regression parameters had a p-level<0.001. Spearman's correlation r=0.622 (p=1.23*10^{-37})

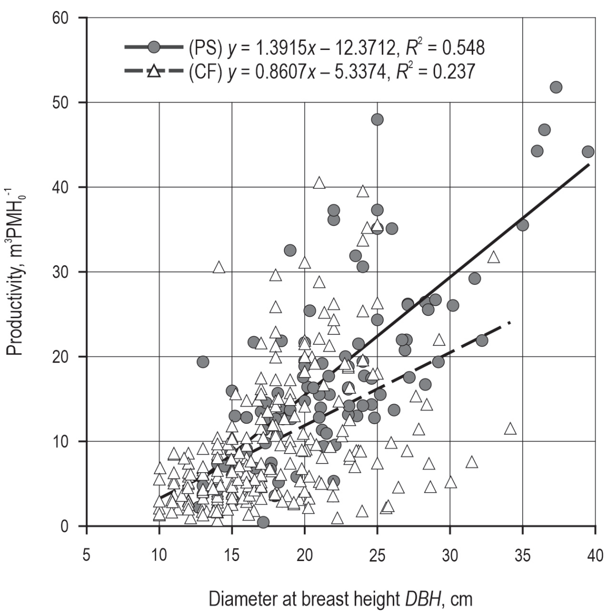

Fig. 3 Linear statistical model of productivity related to *DBH* in planted stands (PS) and in coppice forests (CF), regression analysis parameters: (PS) r=0.7402, r^2=0.5479, $r^2_{Adj.}$=0.5434, F(1.101)=122.40, p<0.0001, *Std. Err.*: 7.1857; (CF) r=0.4864, r^2=0.2366, $r^2_{Adj.}$=0.2334, F(1.234)=72.530, p<0.0001, *Std. Err.*: 7.5143. For both functions, the two regression parameters had a p-level <0.01. Spearman's correlation (PS) r=0.721 (p=8.78*10^{-18}) and (CF) r=0.513 (p=2.93*10^{-17}).

5.0 cm under bark, there were some remaining parts of the trunk, which on average amounted to 9.02% in volume (Table 2).

Distribution of productivity as a function of *DBH* was linear and well correlated (Fig. 2). The obtained function presents a typical piece-law, where the larger the tree, the higher the productivity. However, there is no point at which productivity goes down (which can be observed when a too large tree is being processed) after reaching maximum value. This is a clear indication that the limits of the machines were not exceeded in the forest sites studied.

Further analysis, considering the division to planted stands and coppice forests, showed that in the former stands higher productivities were obtained than in the latter ones (Fig. 3). It is worth noticing that the bigger the trees, the bigger is also the difference in favour of alder compared to planted forests.

Even if the two regressions (Fig. 3) had different determination coefficients, for PS good r^2 and for CF low r^2, all the linear regression parameters are

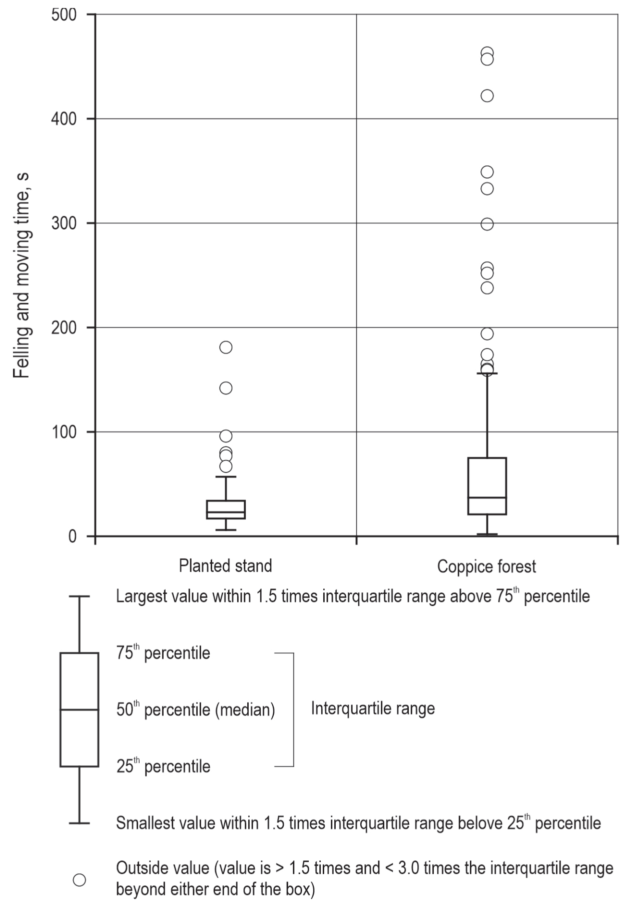

Fig. 4 Felling and travel time per tree in planted stands (PS) and in coppice forest (CF)

Table 3 *U* Mann-Witney test details, level of confidence $p < 0.05$

Variable	*U*-value	*Z*-score	*p*-value
Felling and moving time in PS and CF	7786.0	5.10966	<0.00001
Processing time in PS and CF	7188.0	–6.06763	<0.00001
Felling and moving time in CF when WL and NL	5396.5	1.89207	0.05876
Processing time in CF when WL and NL	5731.0	1.29938	0.1936

PS – planted stand; CF – coppice forest; WL – with leaves = during growing season; NL – no leaves = after growing season

statistically significant. Therefore, we decided to show these two linear models. The above relationship could be explained by different distribution of felling and moving time in relation to processing time. In fact, in coppice forests, felling and moving time was on average longer in comparison with the same time category in a planted stand (Fig. 4), and this difference was statistically significant (Table 3).

When the processing time of PS was compared with that time category in CF, it could be stated that it was longer in PS (Fig. 5) and these differences were statistically significant (Table 4). Also in the case of PS, the processing was much more variable in comparison with CF.

Further analysis of harvester work during the growing and non-growing season (CF only) did not reveal differences in felling and travel time nor in processing time (Figs. 6 and 7, Table 4).

In analyzing productivity, the use of a trunk for logs is an important factor. In this case, a strong correlation

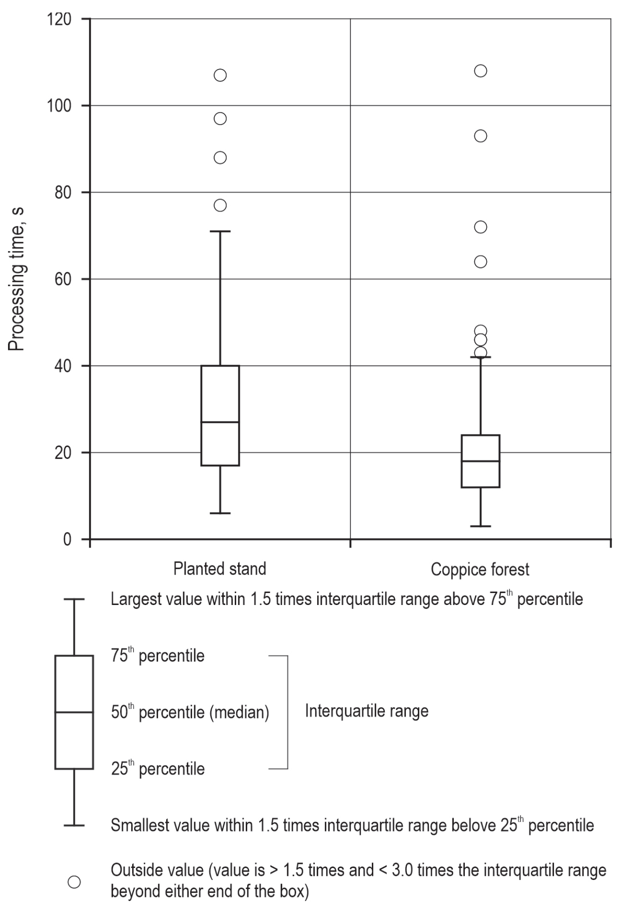

Fig. 5 Processing time analysis in planted stands (PS) and in coppice forest (CF)

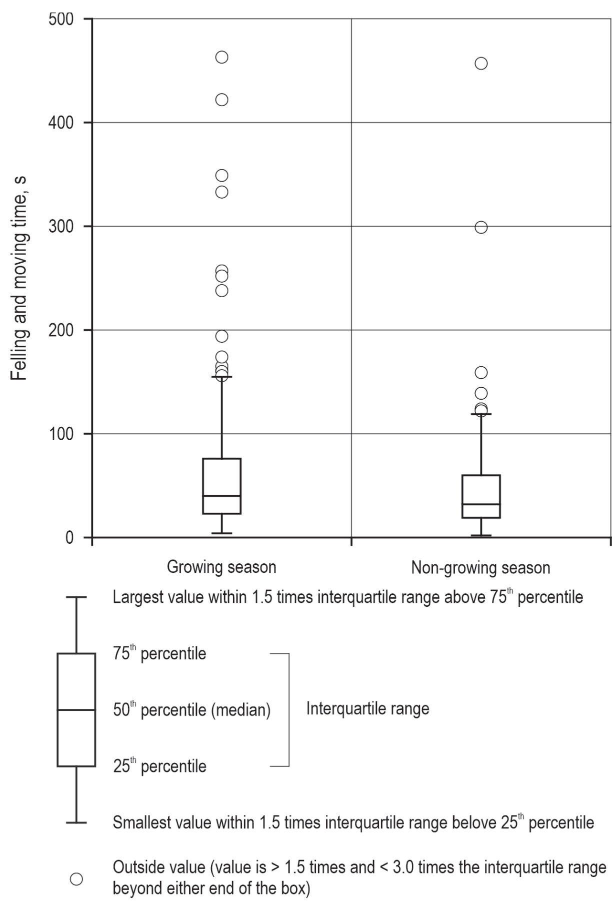

Fig. 6 Felling and moving time analysis in coppice (CF) during growing season and non-growing season

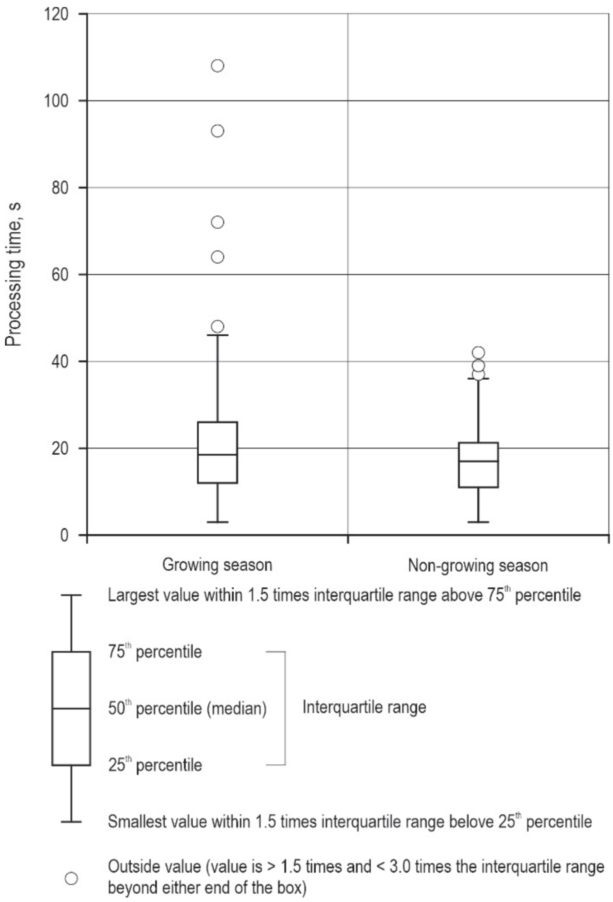

Fig. 7 TB analysis in coppice (CF) during growing season and non-growing season

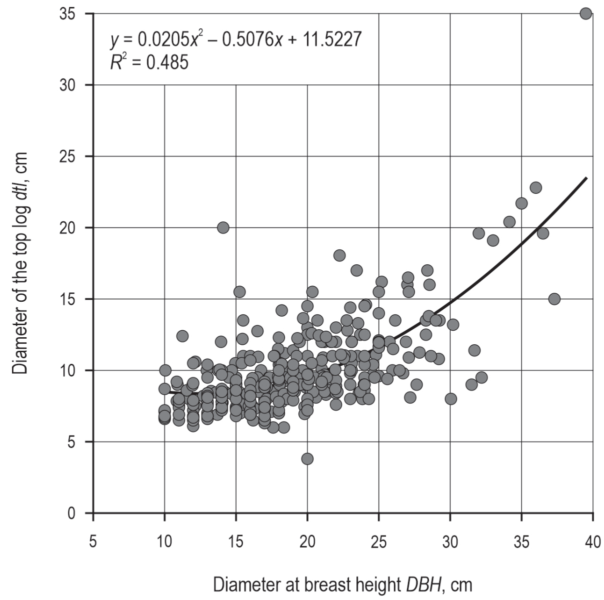

Fig. 8 Top diameter of the top log (*dtl*) non-linear statistical model related to *DBH*, regression analysis parameters: r=0.6997, r^2=0.4896, $r^2_{Adj.}$=0.4865, $F(2.336)$=161.17, p<0.0001, *Std. Err.*: 2.1983, the three regression parameters had a p-level <0.001. Spearman's correlation r=0.592 ($p=4.52*10^{-34}$)

was observed between *DBH* and top diameter of the last log (Fig. 8). It is also worth noticing that for thicker trees, over 20 cm *DBH*, top diameter of the last log increased faster.

As the diameter of the top log was correlated with *DBH*, it was also tried to find out if there was any relationship between *dtl* and productivity. The correlation was observed for that relationship, too, but with low coefficient of determination (Fig. 9).

4. Discussion

Study on harvester efficiency in alder stands has been undertaken recently, e.g. in Finland, Italy and Poland (Mederski et al. 2022). As the trunk of black alder (*Alnus glutinosa* (L.) Gaertn.) is straight and similar to that of coniferous species, black alder could be recognized as a tree that can be easily processed by a harvester. In the present study, tests carried out in north Poland in planted stands and coppice forests mostly gave satisfactory results. Mean productivity of 14.42 m^3 PMH_0^{-1} (without delays) in stands with

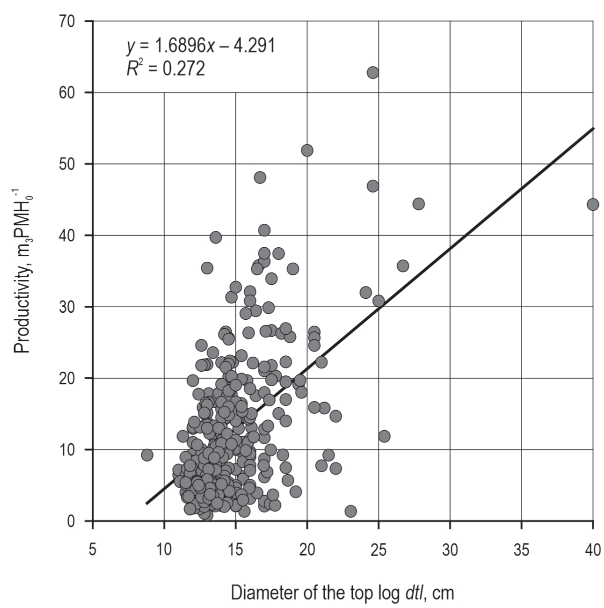

Fig. 9 Linear statistical model of productivity related to top diameter of the top log (*dtl*), regression analysis parameters: r=0.5216, r^2=0.2721, $r^2_{Adj.}$=0.2699, $F(1.337)$=125.97, p<0.0001, *Std. Err.*: 8.4908, the two regression parameters had a p-level <0.01. Spearman's correlation r=0.43 ($p=1.03*10^{-16}$)

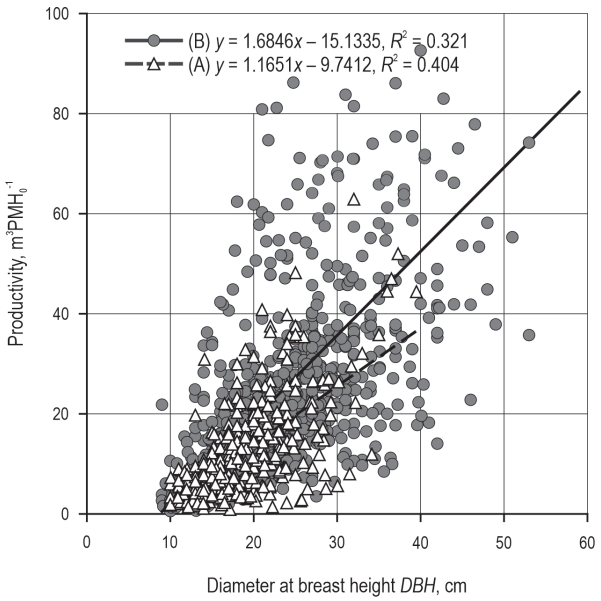

Fig. 10 Linear statistical model of productivity related to *DBH* in birch stands (B) with Spearman's correlation $r=0.722$ ($p=2.91*10^{-152}$) and alder stands (A) with Spearman's correlation $r=0.622$ ($p=1.23*10^{-37}$)

harvested trees with *DBH* from 14.5 to 26.4 cm can be satisfactory, reaching the maximum of 24.34 m^3 PMH_0^{-1} in coppice and 23.66 m^3 PMH_0^{-1} in planted stands (Table 2). The productivity achieved in alder stands was however lower in comparison with that obtained in birch stands as shown in a previous study by Rosińska et al. 2022 (Fig. 10).

Generally, higher productivity is achieved when thicker trees are felled (Mederski et al. 2016, Magagnotti et al. 2021), and this was not the case in our study (Table 2). Variations from that principle could appear due to different harvesters and operators with various experience and working method (Schmiedel et al. 2022), especially in broadleaved stands involved in the study, as well as in different stand conditions selected in the country or intensity of removed volume (Fernandez-Lacruz et al. 2023, Mederski et al. 2016).

In planted stands, higher productivity was achieved in comparison with coppice forests, and these differences were bigger when thicker trees were harvested (Fig. 3). Felling and travel time per tree was longer in coppice forests, however processing time per tree was longer in planted stands (in both cases differences were statistically significant). This suggests that the former had greater impact on lower productivity in coppices, which can be confirmed by detailed analysis of *DBH* impact on productivity: greater in planted stands versus coppices for trees with the same diameters (Fig. 3). Detailed analysis of time spent on felling and processing during growing/non-growing season did not show any differences, even though it was expected. It was hypothesized that, during the growing season, easy-to-remove bark may influence negatively the processing time, and lower visibility due to leaves may lead to longer time spent on felling/moving in the forest, but the results revealed no differences between seasons. However, the influence of the growing/non growing season can also have an influence on different aspects of sustainability. Carrying out forest operations in conditions of high soil moisture can indeed lead to higher magnitude of soil impacts (Tavankar et al. 2021, Hoffmann et al. 2022). Therefore, considering that the season seems not to influence the harvesting performance, this operation should be scheduled in order to avoid harvesting in the presence of moist soil.

It has to be explained that coppice forests in Poland are of different nature in comparison with typical coppicing, e.g. in Italy. In Poland, at the early stage of regeneration (after 2–3 years), most of the sprouts are removed leaving maximum two, of which only one is left in the next treatment. Two or three trees can be present on the stump too, however this are rare cases. However, when even a single tree is grown on one stump until final felling, it can be noticed that the butt end of a tree is with a typical sweep – bent from early stage of sprout growing from the stump. This creates an inconvenient form of trunk when grabbing a tree with a harvester head, leading to few trials and more time spent for effective tree felling.

The results of this study also included the analysis of the use of trunk for logs. It is generally expected to process timber up to 5/7 cm under/over bark in a tree top, leaving the least amount of residues. It was also expected that this could be possible with alder, whose trunk is straight with relatively thin branches. In the present results, the minimum diameter under bark (*ub*) was 7.9 cm on average, which is very good, better than with pine of similar age, where processing stopped at 9.4 cm over bark (Mederski 2013). This suggests good use of the tree trunk for logs, when e.g. processing of birch in thinnings stopped at mean top diameter of 11.7 cm *ub* (Rosińska et al. 2022) or 12.3 cm with bark (Mederski 2013). It was also found that the bigger the *DBH*, the bigger the diameter of the top log (*dtl*), which also means that more biomass is left from thicker trees that can be used e.g. as energy source (Garren et al. 2022). This relationship suggested to the authors that, except the strong relationship established between *DBH* and productivity, there may be (or there is) a relationship between *dtl* and productivity. It was expected that the remaining larger tree tops may positively impact on productivity by using the thickest tree part for logs with limited delimbing (Fig. 8). Consequently, productivity was defined as a function of *dtl*, and it showed that there is a relationship between those two, expressed by the correlation factor of 0.43; however, the model was rather weak with r^2=0.272 (Fig. 9).

To better analyze the present findings, it is possible to carry out some comparisons to previous studies with a similar topic. In his study in a coppice oak forest, Suchomel 2011 demonstrated high efficiency in hardwood harvesting of an HSM 405H 6WD harvester equipped with a CTL 40HW head designed specifically for broadleaved species. The presence of a multiple stem structure, common in coppice forests, did not lead to technical issues or a significant increase in the harvester's time consumption, although handling and felling multi-stem trees required marginally more time compared to single-stem trees. Consequently, the research indicated that a hardwood harvester head with a single grip can be effectively used for felling and processing oaks up to 40 cm in diameter in mature coppice stands, where the trees are with sweep and a multiple stem structure from resprouting. On the other hand, other research in the topic still highlight some limitations of fully mechanized harvesting in coppice. Apart from low working performance (Schweier et al. 2015, Mederski et al. 2016, Spinelli et al. 2016), substantial damages to stumps and high cutting height still represent major issues to be solved (Suchomel et al. 2012, Spinelli et al. 2017a, Spinelli et al. 2017b).

5. Conclusions

The findings of the present study in alder stands highlight that the mean harvester productivity of 14.42 m^3 PMH_0^{-1} was achieved, with maximum values of 24.34 m^3 PMH_0^{-1} in coppice and 23.66 m^3 PMH_0^{-1} in planted stands. The mean value was 11% lower compared with the average productivity of 16.19 PMH_0^{-1} achieved in pine stands of similar age (Mederski et al. 2016). Delimbing was carried out in the tree crowns up to the mean diameter of as little as 7.9 cm under bark, which shows very good use of the tree trunk for logs. It was also found out that the thicker the tree, the bigger the top diameter of the last log, leading to bigger biomass production, but also with lower effectiveness of log processing. Season seems not to influence harvesting performance, therefore it should be scheduled when soil bearing capacity is high, avoiding autumn with heavy rains.

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