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Multi-tree cut-to-length harvesting of short-rotation poplar plantations

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Abstract
Small tree size represents the main challenge when designing a cost-effective harvesting system for European short-rotation plantations. This challenge is further complicated by the need to obtain 4-m logs for high-end products, which rules out the possibility of deploying whole-tree chipping. Both challenges can be met through mass or multi-tree handling (MTH), which must begin at the time of felling and continue uninterrupted along the whole supply chain. The objective was to: (1) gauge the productivity and the cost of CTL harvesting applied to these plantations; (2) assess log yield and capacity to match dimensional specifications; (3) determine if MTH applied to CTL technology offers a real benefit compared with conventional single-tree handling. The authors conducted a time study using a block design with a two-machine cut-to-length harvesting system (i.e. harvester and forwarder) in single- and multi-tree handling operations on the clear cutting of a hybrid poplar plantation in Poland, as well as we manually measured the produced volumes of the study. Higher productivity (+ 8%) was achieved under the multi-stem handling mode. The MTH system proved capable of containing harvesting costs below € 15 per green ton, while fulfilling set timber quality requirements in terms of value recovery and log quality specifications. A new, software-based, MTH system is recommended to be used in short-rotation poplar plantation for logs and biomass harvesting. When the coppicing season is over, the system can be deployed for the conventional thinning operations.

Keywords Multi-tree handling (MTH) · Logging · Felling · Forwarding · Productivity · Cost efficiency

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Introduction

Economy of scale favors concentrated production in very large plants, and that is true for all sectors—including the wood industry. Large plants or clusters of multiple complementary manufacturing plants have become a characteristic of the global wood industry, and Europe is no exception. While concentration offers important advantages in terms of production efficiency, it also carries equally important challenges when it comes to logistics. That is seldom more true than when it comes to wood supply, which originates from a typically scattered natural resource—quite unlike mining, for instance. Therefore, it is crucial to find solutions that can guarantee a steady wood supply in large volumes, which is especially critical at a time when the wood market is unsettled by deep structural changes (Hetemäki and Hurmekoski 2016).

In such a predicament, wood industries can benefit from building a strategic feedstock reserve that they can control directly, and use to balance the eventual fluctuations in supply volume and price (Stanton et al. 2002). This has revived

interest in wood crops, established on marginal agricultural land. The idea is not new, having been pioneered in the late 1980s, although with different goals: the capping of the EU agricultural surplus and supplying the new bioenergy sector (Rosenqvist et al. 2000). This resulted in very specific cropping systems, which were meant to satisfy the expectations of farmers (Londo et al. 2004) and to produce low-cost boiler fuel (Lindegaard et al. 2016). Today, the conditions and the goals are quite different, and so must the new wood crops. In particular, the new plantations are grown by the industry primarily for industrial roundwood, which entails using longer rotations and lower establishment density compared with previous types—i.e., 5–8 years versus 2–4 years, and 1200–1600 trees ha^{-1} versus 8000–14,000 trees ha^{-1}. That also has a strong impact on harvesting system design, since trees in the new plantations are too large to be tackled with the largest modified forager harvesters (Spinelli et al. 2011) and the need to manufacture logs automatically excludes whole-tree chipping (Spinelli et al. 2013).

At the same time, most of the new planting occurs in Eastern Europe, in countries such as Poland, Romania and Slovakia, which offer an ideal combination of good soil conditions, moderate land price and a rapidly developing economy (Werner et al. 2012; IPP 2019). These countries also have a sizable and expanding forest contracting sector (Mederski et al. 2016), which can (and must) be involved in the management of the new plantations. However, the rapid development of these regions generates a growing concern about the future availability of manual labor, which determines the strong interest in the further mechanization of timber harvesting. Mechanized harvesting also offers distinct advantages in terms of simplified logistics, enhanced work safety (Bell 2002) and environmental protection (Abbas et al. 2018; Marchi et al. 2018).

The main technical hurdle when harvesting the new wood plantations is represented by the small tree size (≤ 0.1 m^3). The market actually offers small tree harvesting technology (Mederski et al. 2018), but this is designed for trees with an optimum size of around 0.1–0.2 m^3, and its productivity decreases sharply when tree size drops below these values (Visser and Spinelli 2012; Mederski et al. 2018). In this case, the only solution appears to be mass or multi-tree handling (MTH), whereby more than one tree is handled in a single work cycle in order to compensate for the small size (Dahlin 1991; Johansson and Gullberg 2002; Kärhä et al. 2005).

Mechanized cut-to-length (CTL) technology is the most popular form of forest mechanization in Europe (Lundbäck et al. 2018), and it is leading the transition of the logging sector toward mechanized harvesting in Eastern Europe, too (Kocel 2010; Moskalik et al. 2017). Employing CTL technology to harvest the new plantations offers several advantages, namely the machines are already available in most regions, and their use on tree farms may be attractive to owners as a way to make more intense use of their machines; work quality (e.g., delimbing quality, measurement accuracy) is generally good; CTL harvesting chains require smaller landing space and are suited to relatively small lots. On the other hand, CTL technology is relatively expensive and was originally designed for single-tree processing, which is a major limitation when dealing with small trees like those available in the new plantations.

Manufacturers have already faced the same small tree challenge when designing machines for thinning work and have devised new ways for coping with it. Work on multi-tree harvester heads began in the 1990s (Brunberg et al. 1990; Lilleberg 1994), and today most manufacturers offer multi-tree adaptation kits for their most popular machine models (Erber et al. 2016). Some have even designed new work sequencing software programs that can be installed on conventional single-tree harvesters and enable them to perform multi-tree handling without installing supplementary accumulating arms or other hardware (cf. Kärhä 2011; Kärhä et al. 2009, 2011).

Software-based multi-tree handling means that multi-tree handling is based on a program logic which does not necessarily require technical modifications to a harvester head. Functionality is based on the automatic sequential functions of tree bunching in the harvester head. The bunching functionality of tree bundle works in such a way that when gripping a new tree to be cut, the feed rollers of the harvester head hold the trees already in the harvester head and the gripping of the new tree takes place by means of delimbing knives. The rollers then open and close automatically, and the harvester head performs a cross-cutting. Further, the next tree can be collected to the harvester head. Such quick and relatively inexpensive conversion is very interesting, because it maximizes task flexibility and should allow the part-time conversion of the machines already used in conventional forestry for temporary deployment in the new plantations at times of low work demand.

Since no comprehensive information yet exists about the performance of a CTL multi-tree harvesting system applied to the new short-rotation poplar plantations, a trial was organized in order to: (1) gauge the productivity and the cost of CTL harvesting applied to these plantations; (2) assess the resulting timber quality in terms of log yield and capacity to match dimensional specifications; (3) determine if multi-tree handling applied to CTL technology offers a real benefit compared with conventional single-tree handling, and eventually quantify such a benefit.

Material and methods

The system under investigation was a classic CTL combination of a harvester and a forwarder: the former was tasked with felling, delimbing and cross-cutting the trees into 4.0-m

logs, with length tolerance ± 0.15 m, and a minimum small-end diameter of 7 cm over bark; the latter would separately haul the logs and the logging residues to the roadside landing area. The machines used for the test were a Ponsse Beaver with a Ponsse H6 head (harvester) and a Ponsse Elk (forwarder) (Fig. 1). The operating weight of the harvester was 17.7 tons, and that of the forwarder was 17.8 tons (with a payload capacity of 13 tons). The Ponsse H6 head mounted on the harvester could work in two distinct modes: single-tree handling and multi-tree handling, thanks to the specially designed Ponsse software option. The Ponsse Elk forwarder was equipped with articulated biomass stanchions, for the effective extraction of both logs and slash. Both machines were driven by experienced test operators working for the Ponsse company.

This system was tested in Gardeja, near Kwydzyn in Northern Poland (53°60′N, 18°90′E in WGS84), from November 27 to 29, 2018. The test was conducted on an 8-year-old poplar plantation owned by Greenwood Resources Inc. The plantation (first rotation) was established at a square spacing of 3.0 m × 2.0 m with the hybrid poplar (*Populus x euroamericana* Dode (Guinier)) clone AF8. Stocking at the time of cut was 88 green t ha^{-1} or 136 m^3 ha^{-1} (all m^3 figures

Fig. 1 Two machines tested in Gardeja: harvester (top); forwarder (bottom)

in this study are solid m^3 over bark—not bulk m^3). Mean total tree size (including whole above-ground biomass, i.e., the whole stem and the branches) was 56 fresh kg or 0.087 m^3, for a diameter at breast height (DBH) of 12 cm and a total height of 12 m. In total, 1,724 poplar trees were harvested during the study, amounting to 100 tons of fresh wood or 153 m^3 of solid wood equivalent.

The plantation in Gardeja measured 1.12 ha, and for the purpose of the study it was divided into 18 rectangular blocks, containing ca. 100 trees each. Block width was 15 m or 5 tree rows, which was considered the best work frontage for the harvester. Therefore, block length was 20 trees or 40 m, resulting in 600 m^2 block surface area. In the proposed configuration, the harvester had efficient access to all trees in five rows in front of the machine. The DBH of all the trees in each block was measured, while a height-to-diameter curve was built using 31 sample trees. Then, using the proprietary tables developed for this clone and plantation by the landowner, the total volume and mass on each block could be estimated.

Once all the blocks had been measured and properly identified with paint marks, harvesting commenced. Half of the blocks were randomly assigned to multi-tree harvesting, while the other half was assigned to conventional single-tree harvesting. The time to harvest each block was timed with an accuracy of 1/100 min, carefully separating work time from delay time (Björheden et al. 1995). Since the latter is typically erratic and a short-term study conducted on small blocks may fail to represent the actual incidence of delay time in the long-term, delay time was added to work time using a 20% delay factor obtained from long-term studies (Spinelli and Visser 2008). This figure was meant to represent the favorable work conditions presented by a rational plantation in easy terrain, near to all maintenance and repair facilities. Block-level separation was not possible for forwarding, since no blocks produced enough wood volume to make for one forwarder load: therefore, the forwarder time study was a classic cycle-level study, on the assumption that tree-handling mode (single- or multi-tree) had no impact on stack size and distribution, and therefore, it was unlikely to affect forwarder productivity.

The length and mid-length diameter of all the logs produced in each block were determined using measuring tape and a caliper. This allowed for the testing of measurement accuracy, log volume and log yield. Measurement accuracy was expressed as the percentage of logs (number and volume) within the length and diameter specifications, namely (1) small-end diameter ≥ 7 cm over bark and (2) the length tolerance ± 15 cm from the 4 m target. Log yield was expressed as the ratio of the measured log volume to the total tree volume estimated through the tables.

Machine rates were estimated with the Harmonized European Costing Model developed within EU COST Action

FP0902 (Ackermann et al. 2014). Costing assumptions were obtained from the Ponsse machine team and were adapted to Eastern European conditions based on interviews with local experts attending the demo day organized at the end of the test. Calculated scheduled machine hour (SMH) costs were: 105 € SMH^{-1} for the harvester and 82 € SMH^{-1} for the forwarder (Table 1). Nevertheless, readers are warned about the limitations of any generalised costing approach and are encouraged to re-calculate machine rates based on their own cost assumptions.

The data were analysed with the Statview advanced statistics software, in order to draw descriptive statistics and determine estimate error (SAS 1999). Since data distribution violated the normality assumption, non-parametric (Mann–Whitney U test) analysis was used to determine the statistical significance of the eventual differences between treatments (i.e., harvesting systems tested). Regression analysis was used to estimate the relationship between harvester productivity, log yield and tree size. The effect of treatment (single- or multi-tree handling) was introduced in the regression as an indicator variable (Olsen et al. 1998). For all analyses, the significance level was set at $\alpha < 0.05$.

Results

The test data included 7.2 h of harvester work and 5.2 h of forwarder work (delays excluded). These corresponded to 1356 harvester cycles and 15 forwarder cycles (loads).

Overall, mean gross log yield varied between 37 and 42% of the total harvest between two treatments used: however, between 11 and 17% of all logs did not match the set quality specifications, because their small-end diameter was smaller than 7 cm or their length diverged more than 15 cm from the 4 m target (Table 2). Therefore, mean net log yield decreased to 34% (single-stem) and 36% (multi-stem) of the total harvest. The data suggested that the multi-stem treatment resulted in a higher gross log yield but also in higher log rejection, leading to a substantial equality between the two treatments in terms of net log yield. Statistical analysis could not demonstrate the significance of any differences, except for the volume of rejected logs, which was about six percentage points higher (or 81% higher) for the multi-stem treatment. Essentially, there was no significant difference in log yield between the two treatments: in that regard, multi-stem handling was as good as single-stem handling—at least under the circumstances of this study.

Used in the multi-stem mode, the harvester handled between 1 and 4 trees per cycle, with the mean at 1.8 (standard deviation = 0.4; mode = 2). Two trees were treated in 80% of the cycles (Fig. 2). A four-tree accumulation was observed only once (0.2% of the cycles).

Measured as total volume, gross log volume (accepted and rejected logs) or net log volume (accepted logs only) tree size was almost identical for the two treatments, which is not surprising for a test conducted in a clonal stand where tree size is almost identical (Table 3). Nevertheless,

Table 1 Components of cost calculations for the machines used in the study

Cost component	Unit	Harvester	Forwarder
Investment price	€	500,000	350,000
Salvage value	€	100,000	70,000
Service life	Years	8	8
Annual use	SMH	2000	2000
Operator wage	€ SMH^{-1}	16	16
Interest	%	8%	8%
Depreciation	€ year^{-1}	50,000	35,000
Interest	€ year^{-1}	26,000	18,200
Insurance	€ year^{-1}	2500	2500
Maintenance	€ year^{-1}	37,500	26,250
Fuel and lubricant	€ year^{-1}	26,400	22,000
Personnel	€ year^{-1}	32,000	32,000
Overhead and profit	%	20	20
Overhead and profit	€ year^{-1}	34,880	27,190
Total	€ year^{-1}	209,280	163,140
Total	€ SMH^{-1}	104.6	81.6

SMH scheduled machine hour, inclusive of delays

Table 2 Log yield and proportion of rejects by treatment ($n = 18$)

	Single-stem					Multi-stem					
	Mean	SD	Min	Max	Median	Mean	SD	Min	Max	Median	*P* Value
Gross log yield (% m^3)	37.2	6.2	27.7	45.2	37.3	41.5	4.6	33.5	47.7	42.1	0.2332
Rejected logs (% n°)	11.4	6.5	0.0	20.8	12.5	17.0	7.3	5.0	25.7	16.7	0.1118
Rejected logs (% m^3)	7.6	4.6	0.0	13.2	7.5	13.8	6.6	2.5	23.4	13.3	0.0243
Net log yield (% m^3)	34.2	4.3	27.7	40.4	33.7	35.7	4.8	26.5	40.6	37.1	0.4529

Gross log yield = proportion between volume of all logs from a block (irrespective of logs matching quality specifications) and total volume on block; net log yield = proportion between volume of all logs from a block that match set quality specifications, and total volume on block; SD = standard deviation; *U* test = probability that difference between single- and multi-stem treatment is due to chance, according to Mann–Whitney non-parametric *U* test

significant random variation was found in the harvester productivity measurements, likely due to the inevitable fluctuations of operator concentration and to the changing environment during the working day (especially lighting, due to the shifting sun position). For that reason, most indications are suggestive rather than conclusive. The only one statistically significant result was the 8% higher productivity achieved under the multi-stem handling mode, when productivity is measured in terms of trees per scheduled machine hour (SMH). However, the margin is rather small, and when other units were used (total tree volume per SMH, log volume per SMH) (Table 3), then the variability in the unit combined with the other sources of variability, blurred the picture until no statistical significance could be demonstrated.
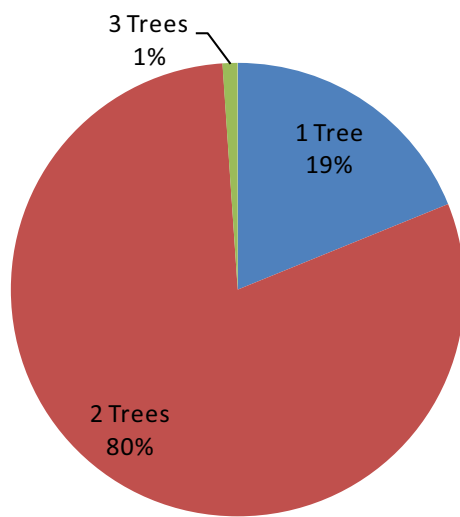
Fig. 2 Distribution of trees cut per cycle when operating in the multi-tree handling mode

Nevertheless, all indicators pointed at a better performance in the multi-stem handling mode.

The effect of handling mode emerged best through regression analysis, which also pointed at the usual increasing relationship between tree size and productivity (Table 4). Once variations in individual tree size were compensated for through regression, then the effect of handling mode became easier to detect and the indicator variable for multi-tree handling became statistically significant. Measured as net log volume, harvester productivity was about 10% higher when in the multi-stem mode rather than in the single-stem mode. As expected, the benefit was larger with smaller trees. The equations in Table 4 explain a large proportion of the total variability in the dataset (50 to 80%), offering a very good fit to the original point cloud (Fig. 3). Depending on tree size and handling mode used, mean productivity ranged from 17.4 to 18.2 m^3 total tree volume SMH^{-1}, or 6.5 to 7.5 m^3 gross log volume SMH^{-1}.

Once a 20% delay factor was applied to the net working time, the 15 forwarder turns accounted for a total of 6.3 SMH, or 25 min per turn. Forwarder productivity was 24.4 m^3 total mass SMH^{-1}, over a mean distance of 250 m. Mean load size was 10.3 m^3 or 6.6 t per turn. Loading accounted for almost half of the total cycle time (Fig. 4). The amount of timber and biomass in each single plot was much smaller than the payload capacity of the forwarder, and therefore, the forwarder operator formed full loads by consolidating the harvest from more than one plot: that would complicate calculating specific functions capable of associating productivity with distance, individual load size or timber assortment type (i.e. logs or biomass). Furthermore, that would make the eventual such functions inherently unreliable, and therefore, they were not estimated.

Table 3 Comparison between the two harvesting modes ($n = 18$)

	Single-stem					Multi-stem					Multi/single	
	Mean	SD	Min	Max	Median	Mean	SD	Min	Max	Median	Increase	P Value
Tree size												
m^3 total	0.087	0.008	0.075	0.103	0.085	0.085	0.006	0.074	0.091	0.087	-2%	0.8253
m^3 gross logs	0.034	0.007	0.024	0.044	0.030	0.035	0.004	0.029	0.040	0.035	3%	0.6911
m^3 net logs	0.031	0.005	0.024	0.038	0.028	0.031	0.004	0.025	0.036	0.030	0%	0.9648
Productivity												
Trees SMH^{-1}	194	16	174	222	191	212	19	190	251	207	8%	0.0469
m^3 total SMH^{-1}	17.4	2.6	14.9	23.5	17.3	18.2	2.5	14.6	22.0	18.2	4%	0.4529
m^3 gross logs SMH^{-1}	6.5	1.5	4.3	9.1	6.7	7.5	1.1	5.8	8.9	7.9	13%	0.0851
m^3 net logs SMH^{-1}	5.9	1.1	4.3	7.9	6.0	6.5	1.2	5.0	8.7	6.2	9%	0.2697

m^3 gross logs = volume of all logs irrespective of them matching set quality specifications; m^3 net logs = volume of all logs matching set quality specifications; SMH = scheduled machine hours, inclusive of delays; SD = standard deviation; *U* test = probability that difference between single- and multi-stem treatment is due to chance, according to Mann–Whitney non-parametric *U* test

Table 4 Regression equations for predicting harvester productivity as a function of tree size and harvesting mode ($n = 18$)

Equation	Adj. R^2	F Value	a	P Value	b	P Value	c	P Value
[1] m^3 total SMH^{-1} = $a + b *$ m^3 total tree^{-1} + $c *$ Multi	0.507	31.1	−7.126	0.2324	282.374	0.0006	1.354	0.1322
[2] m^3 gross logs SMH^{-1} = $a + b *$ m^3 gross logs tree^{-1} + $c *$ Multi	0.801	35.2	−0.167	0.8545	198.547	<0.0001	0.637	0.0468
[3] m^3 net logs SMH^{-1} = $a + b *$ m^3 net logs tree^{-1} + $c *$ Multi	0.757	27.4	−0.602	0.5306	213.100	<0.0001	0.577	0.0487
[4] m^3 net logs SMH^{-1} = $a + b *$ m^3 net logs tree^{-1} + c *Multi * m^3 net logs tree^{-1}	0.765	28.6	−0.399	0.6780	206.078	<0.0001	19.648	0.0364

m^3 total = total tree volume, including whole above-ground biomass, i.e., logs and biomass; m^3 gross logs = volume of all logs irrespective of them matching set quality specifications; m^3 net logs = volume of all logs matching set quality specifications; SMH = scheduled machine hours, inclusive of delays; Multi = indicator variable for multi-stem treatment: 0 if single-stem mode, 1 if multi-stem mode; Adj. R^2 = adjusted R^2
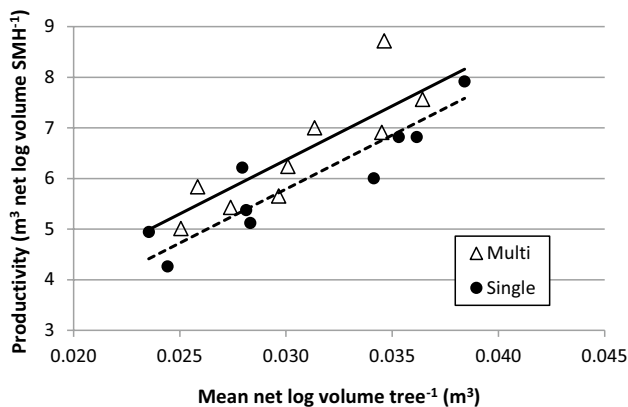
Fig. 3 Relationship between mean tree size and harvester productivity in the two separate handling modes (single and multi-stem) tested in the study
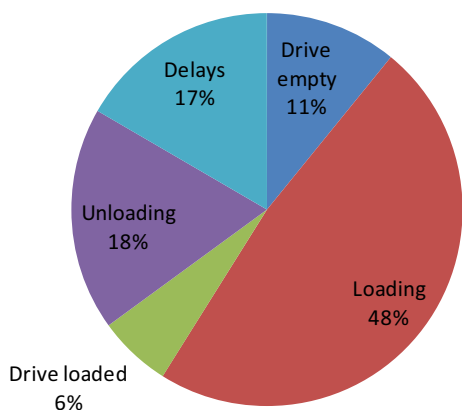
Fig. 4 Distribution of total forwarding time in the study

Overall, the total harvesting cost (turning standing trees into stacked logs and tops at the edge of the field) was estimated at around 9.1 € m^{-3}, or 14.1 € t^{-1} when applying a harvesting chain based on multi-tree handling (Table 5). Correspondingly, when using the harvesting system of single-tree cutting, the total harvesting costs were slightly higher (9.4 € m^{-3}, or 14.5 € t^{-1}) than those of the system based on MTH. These figures are valid for the specific costing assumptions made in Table 1 and may not reflect all individual machine rates: for this reason, readers are encouraged to re-calculate machine rates based on their own cost assumptions.

Discussion

Estimating the benefits of MTH

Concerning productivity, very few studies offer an insight into the performance of cut-to-length harvesting in the clear-cutting of industrial tree farms, since the largest majority of trials have been conducted using whole-tree harvesting equipment (Spinelli and Hartsough 2006). The closest comparison might be made with the clear-cutting of eucalyptus plantations in the temperate regions (e.g., Europe and North America), where CTL harvesting is prevalent and eucalyptus trees are still relatively small at the time of harvest. However, most such studies include the debarking of stems, which is common practice when harvesting eucalyptus (Spinelli et al. 2009). Nevertheless, some studies offer figures for the felling, delimbing and bucking without debarking of stems with a DBH around 12–13 cm: they report a productivity of 7.8 m^3 log volume per productive machine

Table 5 Calculation of total cost (standing tree to wood stacked at the roadside landing)

Treatment	Cutting		Forwarding		Total	
	m^3 SMH^{-1}	€ m^{-3}	m^3 SMH^{-1}	€ m^{-3}	€ m^{-3}	€ t^{-1}
Single-stem	17.4	6.0	24.4	3.3	9.4	14.5
Multi-stem	18.2	5.7	24.4	3.3	9.1	14.1

m^3 = total tree volume, logs and biomass; SMH = Scheduled machine hours, inclusive of delays; t = total mass (logs and biomass) in fresh tons

hour (PMH) (Hartsough and Cooper 1999) and 8.8 m³ log volume PMH⁻¹ (Magagnotti et al. 2011). When the productive machine hour (PMH) productivity is converted into the scheduled machine hour (SMH) productivity applying a 20% delay factor according to Spinelli and Visser (2008), the corresponding productivity figures are 6.5 and 7.3 m³ log volume SMH⁻¹, respectively, which are almost exactly what is reported in this paper. Of course, tree form and machine types are different, and one cannot compare operator skills—although experienced and motivated operators were used in all studies: nevertheless, working conditions were relatively similar and so too were the productivity results, offering at least a principle corroboration of the general plausibility of the figures presented in this paper. Similar corroboration is available for the results of the forwarding study, with figures obtained from forwarding in industrial eucalyptus plantations that range from 17 to 23 m³ log volume SMH⁻¹ on comparably short extraction distances (Spinelli et al. 2004; Strandgard et al. 2019).

Concerning the benefits of CTL multi-stem handling, most previous studies available to an international scientific readership refer to thinning operations—which is consistent with the fact that this technology was developed specifically for thinning operations. Previous trials conducted in thinning work indicate that shifting from single-stem to multi-stem CTL handling accrues significant productivity increases, estimated at 2–7% (Petty and Kärhä 2014), 3–17% (Kärhä et al. 2012), 5% (Erber et al. 2016), 8–16% (Kärhä et al. 2011), 12–14% (Lilleberg 1994), 18% (Bergkvist 2003) and even 20–33% (Gingras 2004). Therefore, the 10% increment found in this test fall within the range previously reported. If at all, one may have expected a larger increment when multi-stemming was applied to clearcuts. It stands to reason that an unobstructed field of work should facilitate stem accumulation, and that is essentially what Lilleberg (1994) and Belbo (2011) demonstrated in their studies when they indicated that the benefits of multi-stem handling increased with cutting intensity (i.e., with fewer residual trees left in the way).

Visual observation of the test in Gardeja suggested that the operator could have used a more effective cutting pattern, and that could have led to richer accumulations and—consequently—more productive cycles. It is a fact that the mean number of trees per accumulation recorded in this study was 1.8, basically the same value reported by Laitila and Vaatainen (2013) for a much smaller machine used in the selective thinning and cutting of substantially larger trees (0.057 m³ vs. 0.035 m³). However, trials with accumulations larger than 2 trees showed that the probability of tree crossing was much higher and log processing less effective or with larger errors in length accuracy than when only working with two trees. At the same time, the harvester operator working at Gardeja had significant experience in the use of multi-stem CTL handling in thinning operations in Finland, but not with clear-cutting, and it is plausible he may have slipped into his habitual thinning mode, making little profit of the new opportunities offered by a clearcut. It is not, perhaps, taking the evidence too far to suggest that this study offers quite a conservative estimate of the potential benefits obtained from the application of multi-stem CTL harvesting to industrial plantations, and that even better results could be achieved with the operator having slightly more experience with the specific conditions. Further gains could possibly result from adding hardware solutions (e.g., accumulating arms) to the software upgrade tested in this experiment—a combination of both was tested by Gingras (2004), who recorded productivity increments up to 33%.

A note should also be made on the functions in Table 4, and in particular on the two competing equations (3) and (4). The difference between the two methods is small and subtle, but not meaningless. While equation (3) represents the effect of the multi-stem handling mode as a fixed increment, equation (4) makes this increment proportional to tree size. The change in the final estimate is minimal for the range of tree sizes explored in the study, nor does one suggest here the extrapolation of the results of the experiment far beyond that range. However, a fixed increment would result in the benefit of multi-stem handling becoming proportionally smaller as tree size increases, which would contradict the results obtained by Kärhä et al. (2012) which indicate bigger machine models offering better productivity gains under the multi-stem mode as tree size increases. Now, the machine used for the test in Gardeja was quite large for the tree size actually harvested, and therefore, one may expect that gains would increase with larger tree size, not the contrary.

Limitations of the study

First of all, it is fair to state what the main limitations of this study are, so that its results are interpreted correctly and with due caution. An obvious characteristic of the experiment is that the test was conducted on one stand type only, one clone and one single operator per machine. Therefore, much caution must be taken when trying to generalise the conclusions of this study, despite the selection of representative stand and operators. This is one more reason why the data collection and analysis technique was kept simple: looking for fine detail made little sense if such a level of detail could not be relied upon when trying to make general predictions. The data collection routine did include detailed elemental time studies of both machines, but eventually most of the fine detail was not reported in the study since it might have created a false sense of confidence in a prediction that was inherently approximate. On the other hand, this deliberate strategy leads to very robust estimates. It may be argued that the use of a single operator and stand may weaken the capacity to generalise, but the proposed test design was applied

to enhance the validity of an essentially comparative study, where both treatments—single-stem and multi-stem handling—had to be compared under exactly the same conditions (same stand, machine and operator) (Harstela 1991).

A second limitation of the study is in the method of volume estimation, in the sense that only log volume was actually scaled—and quite accurately, on a log-by-log basis—while total volume was estimated using DBH-to-volume conversion tables. While the tables were specifically developed for the clone and the stand types in question, and were deemed the most accurate available, still they could not be as accurate as the actual scaling of all the harvested product. Since log yield was calculated by matching scaled log volume with the total volume obtained from the table, it is possible that yield estimates may contain a certain degree of approximation that must be considered when interpreting the results. Again, since log yield was estimated the same way for both treatments, any eventual errors would impact both of them equally and the comparison would remain entirely valid. Furthermore, the recovery rate found in this study is very near to that found in a similar study of multi-tree processing conducted on the same stand type, where gross log yield was estimated at 51%, with a reject rate between 8 and 15% leading to a net log yield ranging from 36 to 43% (Spinelli et al. 2020). In that study, all timber and all tops were taken separately to a certified weighbridge and actually weighed, so that the reported figures can be taken as a reference for absolute values.

Machine selection and logistics

A final remark can be made about machine selection. Commissioning the complete machine system presented in this study (harvester and forwarder) requires a significant capital investment, which is almost twice as large as one would need for purchasing similar machinery derived from general-purpose equipment, such as farm tractors and excavators. Obviously, purpose-built machines offer better overall performance than adapted general-purpose machines, but the high investment cost can make them more challenging to deploy for the typical small-scale logging contractor (Penttinen et al. 2010). While it is obviously possible to finance such an investment by a bank loan, then the loan must be repaid from a suitably large work flow. In that regard, it is worth remembering that the machine rates estimated in this study are based on an annual use assumption of 2000 SMH per year, which is unlikely to be achieved if the machines are used in single shifts and if they are used only in poplar plantations, which are normally managed as coppice and can only be harvested during winter (Manzone et al. 2013). Hence, there is a benefit of relatively large machines with reversible small tree adaptations, which can be easily re-deployed in conventional forest operations when the coppice season is over.

Conclusions

A new, software-based, multi-tree handling (MTH) system tested in a short-rotation poplar plantation for logs and biomass harvesting gave a 10% higher productivity in comparison with a single-tree harvesting system. For the tree size of the poplar plantation, harvesting costs below € 15 per green ton can be considered satisfactory, especially taking into account the expensive technology employed. When we have an initial MTH test in poplar plantation, we can assume that the operator was not yet proficient in the working method. Hence, it can be expected that a higher productivity rate and lower costs might be achieved once the harvester operator has gained more experience using the technology and the proposed harvesting pattern. The multi-stem treatment resulted in a higher gross log yield but also in higher log rejection. However, in the end mean net log yield in the multi-stem mode was 6% higher than when single-stem harvesting was used. Using harvester and forwarder technology for timber harvesting in short-rotation poplar plantations is a good way to increase the annual machine utilisation rate. The MTH system based on specially designed software is an attractive alternative to a specially dedicated multi-tree harvester head. By using the new software, a standard harvester head can be used in one mode as a single-tree harvester head in typical forest conditions and in a new mode, as a multi-tree harvester head, for small-sized trees in poplar plantations or in early thinnings in young stands.

Data availability The raw data are proprietary, but can be disclosed by sending a motivated request to the corresponding author.

Compliance with ethical standards

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