Original Research

Published: 28 July 2020

A Low-Investment Option for the Integrated Semi-mechanized Harvesting of Small-Scale, Short-Rotation Poplar Plantations

Raffaele Spinelli, Natascia Magagnotti, Carolina Lombardini & Matevž Mihelič

Small-scale Forestry (2020)Cite this article

Abstract

In recent years, industrial roundwood production has enjoyed a steady success due to the development of a new bioeconomy and the rapid structural changes of the wood market. A very promising new solution for industrial fiber crops is the integrated production of logs and biomass in short rotation poplar plantations. In Europe, the expansion of these crops is concentrated in the Eastern regions, where contractors face strict limitations in their capital availability: hence the interest in developing semi-mechanized, low-investment harvesting systems based on general-purpose equipment that may serve as a stop-gap solution to assist the transition to fully mechanized systems. This study focused on designing and testing such a system, based on two low-cost machines (an excavator with a grapple saw and a second-hand forwarder) and requiring a minimum workforce (two operators only). The system was tested for productivity, cost and work quality, under two variants: production of 2 or 4 m logs. This system can produce approximately 3 loads (90 t) per day, at a cost between 14.5 and 16 € t⁻¹, from stump to roadside landing, ready for loading and transportation. The 4 m log variant was more efficient, resulting in a 10% cost reduction around 1.5 € t⁻¹. However, log yield was relatively low: between 1/3 and 1/4 of the total harvest, the balance consisting of lower-value biomass. The 2 m log treatment offered a higher log yield. The introduction of simple technology may allow increasing log yield and should be the subject of future research.

Introduction

Hybrid poplar (*Populus* × *Canadensis*) plantations cover an area of over 31 million hectares and play an important role in the industrial growth of such countries as China and Turkey (IPC 2016). In fact, planted poplar is a traditional feature of the European countryside, where it is used as a supplementary crop on marginal land. Countries like France, Italy and Spain each grow at least 100,000 ha of poplar, which represents a strategic source of high-quality fibre. Poplar wood is appreciated for its intrinsic qualities and general versatility, and rotations are short

compared with those of most other wood crops, which favours the integration of poplar within common agricultural systems (Britt [2000](#)). Genetic selection allowed developing a wide range of varieties suitable for most field conditions, and if the two are properly matched and good care is taken of the plantation, growers can count on sustained yield and good product quality (Cardias-Williams and Thomas [2006](#)). What is more, these crops do not compete with conventional food crops because they are established on marginal land, where they grow a valuable product while enhancing environment quality at the same time (Sedjo [1999](#)).

The best poplar clones are selected for the production of high-value, veneer-grade logs, which represent the traditional product grown by the French (CNP [2020](#)), Italian (Hongyuan [1992](#)) and Chinese (Ye and Wang [2003](#)) farmers. However, recent years have seen the development of alternative poplar cropping systems, aimed at the production of energy and industrial fibre. These new systems offer the benefit of extremely short rotations and were designed to meet farmers' needs in terms of short return times and extended use of internal resources, such as already available planting and harvesting machinery (Lindegaard et al. [2016](#); Posavec et al. [2016](#)).

While stagnant oil prices have led to the generalized decline of energy plantations (Helby et al. [2006](#)), crops designed for the production of industrial roundwood have enjoyed a slow but steady success because they match the strategic demands of a wood industry that is concentrating production in very large processing plants, with challenging fibre demands. Such plants often struggle to obtain a large and steady raw material supply, especially now that the wood market is experiencing large structural changes (Hetemäki and Hurmekoski [2016](#)). For that reason, the wood industry has become a major promoter of afforestation projects, with the goal of building a strategic fiber reserve it can use to buffer the recurring fluctuations in supply volume and price (Stanton et al. [2002](#)).

In Europe, the majority of the new poplar plantations are being established in the eastern part of the continent, in countries such as Poland, Romania and Slovakia, characterized by an ideal combination of good soil, moderate land prices and a rapidly developing economy (Werner et al. [2012](#); IPP [2019](#)). In these countries, the availability of low-cost rural labor has justified the use of manual or semi-mechanized work techniques for establishing, tending and harvesting the new plantations (Liepinš et al. [2015](#); Talagai et al. [2017](#)). However, the rapid development of these countries is reducing labour availability while driving up costs, and the shift to mechanized work is perceived as the inevitable solution to offset future labour shortages. What is more, mechanization offers great benefits in terms of operator comfort and worker safety, which are ethical imperatives in any modern society (Bell [2002](#)).

Yet, the transition from manual or semi-mechanized work to fully mechanized operations is especially challenging, because it requires specific skills and large capital. Both skill levels and capital availability are increasing along with economic development, but growth proceeds gradually and so should the transition towards fully mechanized work. Hence there is an interest in low-investment, interim solutions that can accelerate a gradual modernization of forestry operations. Such solutions can be based on two main pillars: first, a dramatic reduction of manual inputs, but not a complete exclusion—especially if a minimal proportion of manual work is key to removing the need for heavy investments; second, the use of second-hand forestry machines or general-purpose machines adapted for forest work, rather than more expensive new, dedicated forestry equipment. The latter offers better overall performance, but its superior all-terrain mobility is not a vital requirement when negotiating ex-agricultural fields, where terrain conditions are not as challenging as in natural forests. Furthermore, a low-investment system based on general-purpose equipment offers better flexibility and can be deployed on a larger number of alternative jobs outside of forestry: forestry-fitted farm tractors can be used in agriculture and adapted excavators can be reverted to construction and earthmoving jobs. Task versatility is especially desirable when the new system is designed for plantations that are managed as coppice and can only be harvested during winter (Manzone et al. [2013](#)). In that case, full investment depreciation is best achieved by mitigating capital commitment and maximizing versatility.

Therefore, the goal of this study was to design and test a low-investment semi-mechanized system for harvesting short-rotation poplar plantations in Eastern Europe. System design had to be based on mass handling (i.e. handling more than one tree at a time) and give preference to general-purpose, low-investment machinery that could be easily commissioned by local, small-scale companies. At the same time, the new system had to be capable of producing the largest possible share of 2 or 4 m long logs (small end diameter = 7 cm), as required by the local industries for manufacturing high-quality wood boards. Once designed, the system was to be tested for productivity, cost and work quality—the latter expressed as the capacity to match product specifications and maximize the proportion of higher-quality logs over bulk biomass. The system was to be conceived as a temporary solution, not designed to substitute for more productive, purpose-built machine systems, but to serve as a stop-gap measure to assist with the transition.

Materials

The system designed was a modification of the method already used by some logging contractors operating in northern Italy, and recently described by Vanbeveren et al. ([2017](#)). The key equipment in this system is an excavator-based grapple-saw that is used to fell the trees and cut logs from the bottom part of felled stems. The same machine then stacks logs and tops in separate piles, for later

extraction to the roadside with tractors or forwarders. Tops can be chipped at the roadside, or directly in the stand, in which case chips rather than unprocessed tops are extracted to the roadside. For the purpose of this study, the system just described was subject to specific modifications aimed at accruing the benefit of mass-handling early on along the supply chain. In fact, short-rotation poplar trees are too small for the efficient processing of individual trees, because the cost of handling a single tree often exceeds its value. Hence the need for mass handling, whereby more trees are harvested in one cycle in order to compensate for their smaller size (Dahlin [1991](#)). Therefore, the new modified system was organized as follows:

1. 1

a medium-size (14 t) short tail CAT 314C LCR steel tracked excavator (built in 2009) equipped with a tilting grapple-saw felled the trees and laid them in bunches of 10–15 stems (Fig. [1a](#));

2. 2

an operator equipped with a light chainsaw performed a rough delimbing of the bunches, removing large branches only, since lighter ones had already been broken during felling and bunching (Fig. [1b](#));

3. 3

the same excavator that had previously performed felling and bunching crosscut the base of each bunch in order to obtain logs with a minimum small end diameter (SED) of 7 cm. For the purpose of the study, two log-length treatments were applied: 2-m and 4-m logs. The shorter length was the general specification for conventional pulpwood, whereas the longer one was the new specification for innovative high-quality boards. If 2-m logs were produced, the operator would perform more cuts, since the goal was to maximize the production of logs, not tops (Fig. [1c](#)). When crosscutting, the operator eyeballed size specifications and used the excavator's own width (2 m within tracks) as a reference when assessing log length. Similarly, small-end diameter was eyeballed by the operator;

4. 4

a 10-t capacity forwarder would move logs and tops to the roadside, ready for loading on trucks (Fig. [1d](#)). This machine was built in 2000 and was bought second-hand with 9000 h on its clock, at a fraction of the new price.

Fig. 1

Different steps in the harvesting system being tested: felling and bunching trees with the excavator-based grapple saw (a); delimbing the bunches (b); crosscutting stems into logs with the excavator-based grapple saw (c); forwarding logs (d)

The whole system was managed by two operators: the owner of the firm and of the machines, who operated the excavator and the forwarder, and his employee who worked with the chainsaw. Both were qualified professionals with long experience with their respective machines. Both operators were informed about the purpose of the test and the methods adopted, and all made their best efforts to cooperate towards the best success of the trial.

This system was tested in Sezzadio (AL)—north-western Italy—from February 12 to February 14, 2019. The test was conducted on a 5-year-old poplar plantations established by Biopoplar Srl (www.biopoplar.com) at a 3.5 m × 2.5 m spacing with the *Populus* × *Canadensis* hybrid clone Orion. Tree survival rate was 95% for a total tree density of 1086 trees ha⁻¹. Stocking at the time of cut was 111 green t ha⁻¹ or 131 m³ ha⁻¹. The mean diameter at breast height (DBH) was 12.5 cm and the mean height was 15.4 m. Mean tree mass was 103 kg fresh weight (water mass fraction = 54%). The total surface of the plantation amounted to 4 ha, but the study was conducted on subplots scattered randomly within the stand.

Methods

For the purpose of the test, researchers installed 16 rectangular plots with an area of approximately 400 m² each. Block width was 14 m or 4 rows, which was the optimum work frontage for the excavator. Block length was approximately 30 m, so that each block would contain 40–45 trees. Blocks were distributed randomly within the stand and assigned randomly to the two log-length treatments (i.e. 2 and 4 m). All wood was taken to the same landing and extraction distance ranged from 550 to 700 m depending on the exact location of the specific block.

Researchers recorded the time taken to fell, delimb and crosscut all the trees on each block (Magagnotti et al. [2011](#)). 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 only conducted at the cycle level—still separating the two log length treatments. Productive time was separated from delay time (Björheden et al. [1995](#)). Delays caused by the study itself were excluded from further data processing. Time data was collected at the cycle level, so that the number of cycles and the mass per cycle could also be calculated. Delay time is typically erratic and a short-term study conducted on small blocks may misrepresent the actual incidence of delay time in the long term. Therefore, delay time was added to work time using the delay factors obtained from long-term studies (Spinelli and Visser [2008](#)). In particular, a 20% delay factor was adopted for machine work, considering the favourable conditions offered by rational modern plantations growing on solid flat terrain, within easy reach of all maintenance and repair facilities. A 40% delay factor was adopted for motor-manual work (i.e. the chainsaw operator) in order to reflect the recuperation needs imposed by the heavy physiological workload (Spinelli and Magagnotti [2010](#)).

Harvested volumes were estimated by measuring the diameter at breast height (DBH) of each tree in each block. Height was obtained from a DBH-height curve produced on the basis of 45 sample trees. DBH and height data were introduced into proprietary tables developed by Biopoplar Srl in order to obtain total tree volume. The log volume harvested from each block was determined by taking the mid-length diameter of all logs produced during the test and 100 lengths per treatment. One 200-g wood disc was collected from each block, for wood density and water content determination. Right after collection the discs were weighed fresh in the field with a portable precision scale, then the volume of each disc was determined with multiple measures of their diameter (2 measures) and thickness (5 measures). At the end of the trial, discs were taken to the laboratory for drying in a ventilated oven set at 103 °C and weighed again 48-h later.

Work quality was determined by measuring the lengths of 100 logs per treatment in order to check how many logs met the 15 cm length tolerance, and by measuring the small end diameter of 100 logs to determine how many were within the 7 cm minimum specification.

Machine costs were estimated using the European harmonized machine costing worksheet developed within COST Action FP0902 (Ackerman et al. [2014](#)). Costing assumptions were provided by the contractors, who were interviewed concerning machine price, fuel consumption and price, labour costs etc. Expected service life and resale value were estimated based on Spinelli et al. ([2011](#)). Calculated rates were: 23 € per scheduled machine hour (SMH) for the chainsaw, 59 € SMH⁻¹ for the excavator-based grapple saw and 74 € SMH⁻¹ for the pre-owned forwarder (Table [1](#)). Further analysis of cost item distribution shows that all chosen equipment was low-investment, as capital expenses did not exceed 20% of total cost (Fig. [2](#)).

Fig. 2

Machine cost breakdown for the main equipment on test.

Table 1 Machine costs

Machine	Units	Chainsaw	Grapple saw	Forwarder
Investment price	€	1500	115,000	120,000
Salvage value	€	0	23,000	50,000
Service life	Years	2	8	5

Machine	Units	Chainsaw	Grapple saw	Forwarder
Annual use	SMH	1200	1200	1200
Operator wage	€ SMH ⁻¹	16	16	16
Interest	%	4%	4%	4%
Depreciation	€ year ⁻¹	750	11,500	14,000
Interest	€ year ⁻¹	45	2990	3680
Insurance	€ year ⁻¹	250	2500	2500
Maintenance	€ year ⁻¹	750	5750	14,000
Fuel and lubricant	€ year ⁻¹	1840	17,160	20,590
Personnel	€ year ⁻¹	19,200	19,200	19,200
Overhead and profit	%	20	20	20
Overhead and profit	€ year ⁻¹	4570	11,820	14,790
Total	€ year ⁻¹	27,406	70,920	88,770
Total	€ SMH ⁻¹	22.8	59.1	74.0

Data were analyzed 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 analysis was used to determine the statistical significance of the eventual productivity and cost differences for the two different log-length treatments (2 or 4 m). For all tests, the statistical significance threshold was $\alpha < 0.05$.

Results

Mean productivity was 113 trees or 14 t per scheduled machine hour (SMH) for felling, 26 t SMH⁻¹ for delimbing, and 19–20 t SMH⁻¹ for crosscutting - the difference depending on log length strategy, i.e. 2 or 4 m (Table [2](#)).

	2 m logs			4 m logs			4 m/2 m	U test	
	Mean	SD	Median	Mean	SD	Median	%	<i>p</i> value	
Stocking	t ha ⁻¹	123.5	12.2	120.1	125.6	17.1	124.4	1.7	0.9164

	2 m logs			4 m logs			4 m/2 m	U test	
	Mean	SD	Median	Mean	SD	Median	%	<i>p</i> value	
Tree size	Kg	119	12	115	124	16	123	4.2	0.6744
Felling	trees SMH ⁻¹	113	7	113	114	11	113	0.9	0.8336
	t SMH ⁻¹	13.5	1.7	13.1	14.0	1.0	14.0	3.7	0.2936
	€ t ⁻¹	4.4	0.5	4.5	4.2	0.3	4.2	- 4.5	0.2936
Delimbing	t SMH ⁻¹	25.9	4.2	26.6	26.3	5.6	26.7	1.5	0.9164
	€ t ⁻¹	0.9	0.2	0.9	0.9	0.2	0.9	0.0	0.9164
Crosscutting	Logs tree ⁻¹	2.9	0.9	2.9	1.6	0.4	1.6	- 44.8	0.0033
	t SMH ⁻¹	18.6	2.1	18.3	20.3	2.2	20.4	9.1	0.0929
	€ t ⁻¹	3.2	0.3	3.2	2.9	0.3	2.8	- 9.4	0.0929
Forwarding	Distance m	561	84	590	588	91	578	4.8	0.8875
	t SMH ⁻¹	9.4	0.2	9.4	11.1	0.1	11.1	18.1	0.0008
	€ t ⁻¹	7.8	0.1	7.9	6.7	0.1	6.7	- 14.1	0.0008
Total cost	€ t ⁻¹	16.4	0.9	16.7	14.7	0.4	14.6	- 10.4	0.0016
Log yield	% weight	40.7	5.3	42.4	40.9	4.9	41.4	0.5	0.9215
Rejects	% n	15.8	13.3	10	36.4	20.9	46.7	130.4	0.0460
Net yield	% weight	34.3	-	-	26.0	-	-	- 24.1	-

Forwarding productivity depended of the product being forwarded: 2-m logs, 4-m logs and biomass (Table 3). While payload was approximately the same for all three products, the time to extract one load of 2-m logs was significantly longer, resulting in a lower productivity (7.8 t SMH⁻¹ vs. ca. 11 t SMH⁻¹ for the others). The actual forwarding productivity for each of the two treatments was a combination of the respective log forwarding and biomass forwarding productivities, prorated to the proportion of logs and biomass obtained from each block. The result was an overall forwarding productivity (logs + biomass) of 9.4 and 11.1 t SMH⁻¹ for the 2-m and 4-m treatment, respectively.

	2 m logs			4 m logs			Tops (biomass)			U-test	
	Mean	SD	Median	Mean	SD	Median	Mean	SD	Median	<i>p</i> value	
Cycle time	min	45 ^a	5	45	31 ^b	2	32	28 ^b	3	28	0.0230
Load size	t	5.8 ^a	1.3	6.5	5.7 ^a	0.6	6.0	5.2 ^a	0.7	5.0	0.6160
Productivity	t SMH ⁻¹	7.8 ^a	1.2	7.9	11.2 ^b	0.5	11.3	11.1 ^b	1.8	10.8	0.0266

	2 m logs				4 m logs			Tops (biomass)		U-test	
	Mean	SD	Median	Mean	SD	Median	Mean	SD	Median	<i>p</i> value	
Cost	€ t ⁻¹	9.7 ^a	1.5	9.3	6.6 ^b	0.3	6.5	6.8 ^b	0.9	6.9	0.0266

Before examining the effect of log length specifications, the stand characteristics (stocking, tree size and extraction distance) recorded in the blocks belonging to the two treatments were tested to detect the presence of eventual differences that could have affected the outcome of the comparison: no significant differences were found, and the comparison was considered valid (Table 2). This showed that cutting longer log lengths determined a sizable increase (9%) of crosscutting productivity, but such increase was statistically significant at the 10% level only, not at the 5% level: therefore, this result could not be taken as conclusive, although logical and highly suggestive. On the other hand, the impact of log length on forwarding productivity and cost was both substantial and significant. Overall, cutting longer logs allowed a significant saving on harvesting cost, estimated at 10% (from 16.4 to 14.7 € t⁻¹).

However, the doubled log length also resulted in a doubled log rejection rate, which went from an already high 15% of logs to a whopping 36%. Under the 4-m log length treatment, cutting length errors were not only more frequent but also larger, with a tendency to undercutting (Fig. 3). Once corrected for the respective rejection rates, log yield was 34% and 26% of total weight for the 2-m and the 4-m log treatments, respectively. All differences were statistically significant, except for the uncorrected log yield, which was 41% for both treatments.

Fig. 3

Log length measurement accuracy: 2-m logs and 4-m logs. *Notes:* Data obtained from 100 logs per treatment. Logs within the tolerance limit are in green (= accepts), exceeding the tolerance limit in red (rejects)

Discussion and Conclusions

The integrated production of logs and biomass is relatively new, because until now these plantations have generally been harvested with the main goal of producing whole-tree chips for the pulp and particle-board industries (Spinelli and Hartsough 2006; Spinelli et al. 2012). Only recently, the development of high-quality boards (oriented strand boards and wood flake boards) have generated a demand for board material in roundwood form, because the logs need to be flaked—not chipped—and no mobile flaking machines yet exist. That explains why there are few studies on the integrated production of logs and biomass from short-rotation poplar plantations. The only study conducted on a similar system also used an excavator-based, tilting grapple saw, but it was geared to produce 2-m long logs and performed felling and crosscutting in a direct sequence, without motor-manual delimbing in between (Vanbeveren et al. 2017). That study reports a slightly higher felling productivity (9 t SMH⁻¹ vs. 8 t SMH⁻¹) and a quite similar log yield (29%), thus offering general corroboration. Further confirmation comes from Yu et al. (2017), who studied a similar small-scale felling machine at work in small trees and reported a productivity of 10.5 t per productive machine hour: if a

20% delay factor is applied to that figure, then scheduled productivity becomes 8.7 t SMH⁻¹, which is very close to our estimates. More references and further corroboration is available about forwarding under small-scale forestry conditions, since our figures (9–11 t SMH⁻¹) fall almost exactly between those reported for the same operation as performed with modified farm tractors (3.5 m³ SMH⁻¹, Mousavi-Mirkala and Nikooy [2016](#)) and with a newer and larger forwarder model (15 m³ SMH⁻¹, Proto et al. [2018](#)).

General corroboration mitigates concern about the primary limitation of this study, which is that of being based on one stand and one operation only. As a consequence, the conclusions of this study cannot be generalized without much caution, despite all efforts to select a representative stand and operators. That is also why the study protocol was relatively simple: it was not deemed rational to work out the fine details if they would be meaningless when trying to make a general prediction. The data collection routine was indeed based on detailed elemental time studies, but the fine detail was eventually lumped together because it would have only generated false reliance on an inevitably approximate estimate. Conversely, coarser plot-based estimates were considered more robust, especially if paired with a good assessment of variability. Compared with the 2017 study, the present one offers a more comprehensive evaluation that includes extraction to roadside and is based on a much extended observation time. Besides, this study offers additional information on work quality (log length measurement error) and compares two alternative log-length strategies, providing crucial information for tactical planning.

The system tested here seems to have a moderate advantage over that tested in 2017 in terms of harvesting cost, since the cost for felling and processing (the only two work steps that can be compared directly) is about 10% (1 € t⁻¹) lower, despite the inclusion of delimbing, which was not included in the 2017 operation. The current system also results in a lower harvesting cost compared with the system described by Spinelli et al. ([2012](#)): 14–16 € t⁻¹ versus 16–23 € t⁻¹. However, the system used in 2012 was not designed for the production of logs and was based on whole-tree chipping, so it did not include delimbing and crosscutting, but it included chipping, resulting in a different work sequence and a different end product. Therefore, any comparison between these two systems cannot offer much information about the higher or lower desirability of one or the other technical options, but rather an indication of the cost involved with different product strategies. In that regard, it is worth mentioning that separate marketing of the log component allows accruing a better price, since—under 2019 Italian market conditions—small-diameter poplar logs receive 75 € t⁻¹, while poplar chips only obtain 55 € t⁻¹ (Biopoplar Srl). Besides, tops must be chipped before transportation, which incurs an additional cost of approximately 12 € t⁻¹ (Mihelič et al. [2015](#)). In essence, as they lay stacked at the roadside landing, poplar logs are worth twice as much as poplar tops, which justifies the effort made to maximize log yield.

Indeed, that is the weak spot of the tested system, which proved poorly capable of matching log length specifications. This was especially critical when manufacturing 4 m long logs, since over one third of these logs failed to meet the 15 cm tolerance constraint. Results were much better with 2 m logs, possibly because the operator was accustomed to producing 2 m logs while the production of 4 m logs was an innovation introduced by the recent appearance of new customers with different demands. Therefore, it is likely that rejection rate on the 4 m logs may decrease with experience. In any case, it is very difficult to make accurate cuts of whole bunches without a suitable measuring device and a way to index the tree butts before cutting. Machines designed for crosscutting entire bunches (i.e. slashers) always have a butt plate for indexing the trees before cutting (Klinhoff [1970](#)). However, slashers are stationary machines installed at the landing, and are part of whole-tree harvesting operations (Kammenga [1983](#)), so it would be difficult to include them as part of the system tested without radically changing it and incurring substantial additional costs. On the other hand, a mobile bunch-cutting machine has recently appeared in the South American eucalypt plantations, and perhaps a scaled-down version of the same device might be developed for harvesting European poplar (Miyajima et al. [2020](#)). Of course, the best accuracy is obtained when applying a professionally implemented cut-to-length harvester: however, this machine is more expensive than the tilting grapple saw used for the test (Di Fulvio et al. [2017](#)) and is not designed for managing whole bunches, so that its use would imply forfeiting the efficiency benefits of mass handling. Furthermore, even modern harvesters struggle to produce accurate cuts on trees with a diameter smaller than 14 cm (Bembenek et al. [2015](#)) and therefore the introduction of a harvester might only offer a small quality improvement over mass handling, at a relatively large cost increase.

The study also highlights the substantial imbalance of the operation, where felling proceeds at 14 t SMH⁻¹, crosscutting at 26 t SMH⁻¹, delimbing at 19–20 t SMH⁻¹ and forwarding at 9–11 t SMH⁻¹. This implies an intermittent work sequence, where different tasks are interrupted when no more wood is available for them to process (starvation), and others are resumed when too much wood is accumulating and the buffers are reaching capacity (constipation). However, this limitation can be easily overcome through flexible use of the available resources. Essentially, the chainsaw operator should double as the forwarder driver, since the combined productivity of delimbing and forwarding is about the same as the combined productivity of felling and crosscutting (ca. 8 t SMH⁻¹). This match is almost exact when manufacturing 4 m long logs, which represents one more good reason for developing a satisfactory routine for this treatment.

Some doubt remains for the motor-manual component represented by delimbing, when the operator works outside a protective cab, exposed to danger and weather. Chainsaws are dangerous machines (Robb and Cocking [2014](#)) and although electrical chainsaws offer some improvement (Poje et al. [2018](#)), the most frequent

and severe accidents still occur during tree felling (Albizu et al. [2013](#)), which is fully mechanized in the system proposed here. Of course, a fully mechanized operation would be even more desirable, but it would be difficult to obtain for an investment as low as < 250,000 €, as in this case. Besides, the operation described here must be considered as little more than a stepping stone on the way to full mechanization, that will develop as the market for harvesting services will grow with the new plantations. Further improvements have been recently suggested, which could allow full mechanization and a further reduction of harvesting costs (Spinelli et al. [2020](#)). However, these advantages come with a larger capital investment, in the vicinity of 400,000 €, which is still half the investment required for a purpose-built machine operation, but substantially more than one may need for deploying the simple system described in this paper.

References

1. Ackerman P, Belbo H, Eliasson L, de Jong A, Lazdins A, Lyons J (2014) The COST model for calculation of forest operations costs. *Int J For Eng* 25(1):75–81
2. Albizu PM, Tolosana-Esteban E, Roman-Jordan E (2013) Safety and health in forest harvesting operations. Diagnosis and preventive actions. A review. *For Syst* 22:392–400
3. Bell J (2002) Changes in logging injury rates associated with use of feller-bunchers in West Virginia. *J Saf Res* 33:436–471
4. Bembenek M, Mederski P, Karaszewski Z, Łacka A, Grzywiński W, Węgiel A, Gieffing D, Erler J (2015) Length accuracy of logs from birch and aspen harvested in thinning operations. *Turk J Agric For* 39:845–850
5. Biopoplar Srl (2019) Personal communication
6. Björheden R, Apel K, Shiba M, Thompson MA (1995) IUFRO forest work study nomenclature. Swedish University of Agricultural Science, Garpenberg, p 16
7. Britt C (2000) Poplars: a multiple-use crop for European arable farmers. In: *Poplar and willow culture: meeting the needs of society and the environment*. GTR-NC-215, USDA Forest Service, St. Paul, Minnesota, p 24
8. Cardias-Williams F, Thomas T (2006) Some key issues concerning current poplar production and future marketing in the United Kingdom. *New For* 31:343–359
9. CNP (2020) *Peupliers de France—Le Portail de la Filière Peuplier (Poplars of France - the Portal of the Poplar Supply Chain)*. <https://www.peupliersdefrance.org/n/le-peuplier-en-chiffres/n:1146>. Accessed on 15 July 2020
10. Dahlin B (1991) Cradle type multi-stem delimber. In: Monograph no. 185 in series *Studia Forestalia Suecica*. Swedish University of Agricultural Sciences, Uppsala

11. Di Fulvio F, Abbas D, Spinelli R, Acuna M, Ackerman P, Lindroos O (2017) Benchmarking technical and cost factors in forest felling and processing operations in different global regions during the period 2013–2014. *Int J For Eng* 28(2):94–105
12. Helby P, Rosenqvist H, Roos A (2006) Retreat from *Salix*—Swedish experience with energy crops in the 1990s. *Biomass Bioenergy* 30:422–427
13. Hetemäki L, Hurmekoski E (2016) Forest products markets under change: review and research implications. *Curr For Rep* 2:177–188
14. Hongyuan X (1992) The culture history and breeding strategy of poplar in Italy. *J For Res* 3:95–100
15. IPC (2016) International Poplar Commission—25th Session Berlin, Germany, 13–16 September 2016. *Poplars and Other Fast-Growing Trees - Renewable Resources for Future Green Economies Synthesis: Synthesis of Country Progress Reports*. Forestry Policy and Resources Division - Forestry Department - Working Paper IPC/15. FAO, Rome, Italy, p 120
16. IPP (2019) Biomass plantations in Poland. Consulted on 03/03/2020. <http://www.internationalpaper.com/company/regions/europe-middle-east-africa/sustainability/highlights/biomass-plantations-in-poland>
17. Kammenga J (1983) Whole-tree utilization system for thinning young Douglas-fir. *J For* 4:220–224
18. Klinhoff R (1970) S & L portable timber slasher. Technical release. American Pulpwood Association 1970 No. 70R-23, p 2
19. Liepinš K, Lazdinš A, Liepinš J, Prindulis U (2015) Productivity and cost-effectiveness of mechanized and motor-manual harvesting of grey alder (*Alnus incana* (L.) Moench.): a case study in Latvia. *Small Scale For* 14:493–506
20. Lindegaard K, Adams P, Holley M, Lamley A, Henriksson A, Larsson S, Engelbrechten H, Lopez G, Pisarek M (2016) Short rotation plantations policy history in Europe: lessons from the past and recommendations for the future. *Food Energy Secur* 5(3):125–152
21. Magagnotti N, Kanzian C, Schulmeyer F, Spinelli R (2011) A new guide for work studies in forestry. *Int J For Eng* 24:249–253
22. Manzone M, Balsari P, Spinelli R (2013) Small-scale storage techniques for fuel chips from short rotation forestry. *Fuel* 109:687–692
23. Mihelič M, Spinelli R, Magagnotti N, Poje A (2015) Performance of a new industrial chipper for rural contractors. *Biomass Bioenergy* 83:152–158
24. Miyajima R, Fenner P, Batistela G, Simões D (2020) Technical-economic analysis of grapple saw: a stochastic approach. *Croat J For Eng*. <https://doi.org/10.5552/crojfe.2020.681>
25. Mousavi-Mirkala SR, Nikooy M (2016) Evaluation of tree forwarding by farm tractor in patch cutting of poplar plantations in Northern Iran. *Small Scale For* 13:527–540
26. Poje A, Potočnik I, Mihelič M (2018) Comparison of electric and petrol chainsaws in terms of efficiency and safety when used in young spruce stands in small-scale private forests. *Small Scale For* 17(3):411–422. <https://doi.org/10.1007/s11842-018-9395-4>

27. Posavec S, Bećirović D, Petrović N, Pezdevšek Malovrh Š (2016) Possibilities to produce additional quantities of woody biomass from small-scale private forests in Croatia, Bosnia and Herzegovina and Serbia. *Croat J For Eng* 40(1):175–189
28. Proto AR, Macri G, Visser R, Harrill H, Russo D, Zimbalatti G (2018) A case study on the productivity of forwarder extraction in small-scale Southern Italian forests. *Small Scale For* 17:71–87
29. Robb W, Cocking J (2014) Review of European chainsaw fatalities, accidents and trends. *Arboricult J* 36(2):103–126
30. SAS Institute Inc (1999) StatView reference. SAS Publishing, Cary, NC. ISBN-1-58025-162-5, pp 84–93
31. Spinelli R, Hartsough B (2006) Harvesting SRF poplar for pulpwood: experience in the Pacific Northwest. *Biomass Bioenergy* 30:439–445
32. Spinelli R, Visser R (2008) Analyzing and estimating delays in harvester operations. *Int J For Eng* 19:35–40
33. Spinelli R, Magagnotti N (2010) Comparison of two harvesting systems for the production of forest biomass from the thinning of *Picea abies* plantations. *Scand J For Res* 25(1):69–77
34. Spinelli R, Schweier J, De Francesco F (2012) Harvesting techniques for non-industrial biomass plantations. *Biosyst Eng* 113:319–324
35. Spinelli R, Magagnotti N, Picchi G (2011) Annual use, economic life and residual value of cut-to-length harvesting machines. *J For Econ* 17(4):378–387
36. Spinelli R, Magagnotti N, Lombardini C (2020) Low-investment fully-mechanized harvesting of short-rotation poplar (*Populus* spp.) plantations. *Forests* 11:502. <https://doi.org/10.3390/f11050502>
37. Stanton B, Eaton J, Johnson J, Rice D, Schuette B, Moser B (2002) Hybrid poplar in the Pacific Northwest: the effects of market-driven management. *J For* 100(6):28–33
38. Talagai N, Borz SA, Ignea G (2017) Performance of brush cutters in felling operations of willow short rotation coppice. *BioResources* 12(2):3560–3569
39. Vanbeveren SP, Magagnotti N, Spinelli R (2017) Increasing the value recovery from short-rotation coppice harvesting. *BioResources* 12(1):696–703
40. Werner C, Haas E, Grote R, Gauder M, Graeff-Honninger S, Claupein W, Butterbach-Bahl K (2012) Biomass production potential from populus short rotation systems in Romania. *GCB Bioenergy* 4:642–653
41. Ye K, Wang J (2003) Processing and utilization of poplar wood from plantations. *China Wood Ind* 17:5–7 (Chinese, Engl. Summary)
42. Yu A, Gallagher T, Mitchell D, O’Neal B (2017) Application of a small-scale equipment system for biomass harvesting. *Small Scale For* 16:133–146

Funding

This study was funded by the Bio Based Industries Joint Undertaking under the European Union's Horizon 2020 research and innovation program under Grant Agreement No. 745874 «Dendromass for Europe» (D4EU).

Author information

Affiliations

1. **CNR IVALSA, Via Madonna del Piano 10, 50019, Sesto Fiorentino, Italy**
Raffaele Spinelli, Natascia Magagnotti, Carolina Lombardini & Matevž Mihelič
2. **AFORA - University of the Sunshine Coast, Locked Bag 4, Maroochydore, QLD, Australia**
Raffaele Spinelli & Natascia Magagnotti
3. **Department of Forestry and Renewable Forest Resources, Biotechnical Faculty, University of Ljubljana, Večna Pot 83, 1000, Ljubljana, Slovenia**
Matevž Mihelič
4. **Skogforsk, Dag Hammarskjölds väg 36 A, Uppsala Science Park, 75183, Uppsala, Sweden**
Raffaele Spinelli & Natascia Magagnotti

Contributions

R.S. study conception and design, experimental planning, data collection, data analysis, paper writing; N.M. study conception and design, data collection, data analysis, paper writing; C.L. experimental planning, data collection, data analysis; M.M. data collection, data analysis, paper writing.

Corresponding author

Correspondence to [Raffaele Spinelli](#).

Ethics declarations

Conflict of interest

The authors declare no conflict of interests.

Availability of data and materials

Data and materials can be requested from the corresponding Author at the address indicated.

Code availability

Not applicable.