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Integrated Harvesting of Medium Rotation Hybrid Poplar Plantations: Systems Compared

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Abstract: In this study, the authors provide a direct comparison made between whole tree-harvesting (WTH) and cut-to length (CTL) methods, which was conducted in two sites in the Slovak Republic and applied to poplar plantations. Both systems, WTH and CTL, have been employed at the highest mechanization level in two sites: "Nivky" and "Skalica". Two different strategies, namely, "mass handling" and "small-scale mechanization", have been used for WTH and CTL, respectively. The study results showed that the level of productivity (ODT SMH^{-1}) in the felling operation was almost double for WTH than for the CTL method in Nivky (+84%) and more than double in Skalica (+113%). The extraction operation under WTH showed a productivity increase from one fifth (+20%) to more than double (104%) that of the CTL method in the Nivky and Skalica sites, respectively. Regarding cost-efficiency (EUR ODT^{-1}), the WTH system offers a similar trend except with respect to extraction in Nivky (higher productivity site), in which the CTL extraction was 4.5% less expensive than the WTH extraction. The study results show that the mass-handling technique deployed in the WTH system offers very good performance in poorer plantations since the very small tree size and low-growing stock challenge the CTL system more than the WTH system. The total operation (felling, bucking, and extraction) costs (EUR ODT^{-1}) recorded by the study in commercial conditions (as contractors perform for revenue purposes) were 32.50 and 45.80 EUR ODT^{-1} for CTL and 43.30 and 53.60 EUR ODT^{-1} for WTH for the higher-yield site (Nivky) and lower-yield site (Skalica), respectively. Regarding the WTH System, the researchers found that the drop in efficiency (and the consequent rise in the costs-per-ton of product) depends largely on the bucking phase conducted using the harvester at the landing of the stacked piles of interlocked trees. The main results of this study demonstrate the promising strategy of mass handling associated with the WTH system in medium rotation coppice (MRC) harvesting and shows that bucking is the weaker phase. Future efforts must be made to ensure feasibility of the "mass handling" strategy alongside the entire workflow by means of finding suitable mobile machinery that can delimb, debark, and crosscut tree bunches instead of single trees.

Keywords: mass handling; WTH; CTL; Integrated Harvesting; MRC; ex-arable land

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1. Introduction

As reported by many authors, tree size is a key parameter that affects productivity and costs in forestry operations [1]. In terms of productivity, a declining trend, especially when an industrial operation is deployed (thus using the highest possible mechanization level), is expected when tree size is smaller than optimum [2].

Mass Handling, MH (or Multi-Tree Handling—MTH), is a strategy for small tree dimension diseconomy mitigation in harvesting, consisting of felling, bucking, and extracting many trees per shift [3–5]. MH and MTH are adaptable for both WTH and CTL systems.

Ground-based-harvesting operations can be conducted according to two main systems, namely, a whole tree-harvesting system (WTH) and a cut-to-length system (CTL) [6]. The WTH system consists of extracting trees to a landing as a whole tree (WT) or tree length (TL) and, once there, processing them into logs. When the CTL system is used, the trees are processed into commercial lengths at the stump and are thus extracted as logs directly from the field to the landing.

WTH and its basic setup has proven so effective that it has remained virtually unchanged since the first available documentation [7], and it is especially appreciated in the USA.

CTL system harvesters and forwarders are experiencing a global increase among forest companies worldwide; on the contrary, it seems that WT and TL systems (skidders especially) are often used in poorer countries because their equipment is less sophisticated, but in reality WT systems offer very good performances [8].

The WTH system popularity has been undergoing a worldwide declining trend since the CTL system has been increasing, as shown by the equipment sales trends in European countries [9].

It was also found by [10] that Eastern European countries (with the exception of Baltic countries) have a lower average machine refresh rate (and thus a longer machine economic life) than other European countries. In consequence, the market trend is only a factor of a more complex phenomenon and does not provide a full understanding of it [11].

In terms of forest ownership and management, the amount of state-managed forest decreased from 82% to 50% in the last 30 years, due to important political and socio-economic changes that have been occurring from the dissolution of the Soviet Union (1992) until the present time [12].

The most representative form of mechanization in the Slovak Republic is the intermediate-level, ground-based operation of a WT system, consisting of three steps: motor-manual felling, skidder forwarding from the stump, and motor-manual bucking at the landing site [10].

Motor-manual operations (felling, delimbing, and crosscutting) present the highest marginal risk for injuries [13]; furthermore, the stump site is very often cluttered with branches, which makes the progression of the natural ground more risky and ergonomically disadvantageous.

Considering risk management and ergonomics, conducting bucking operations at the landing site improves safety and ergonomics more than when conducted at the stump site [14,15] by means of the admittance of reduced-mobility machines in delimbing and cross-cutting (excavator-based processors) operations.

So, the socio-economic aspects, mechanization level (country average), the need for greater flexibility (less-specialized machinery), operator training, safety, and ergonomic aspects make TL and WT the best choice to harvest upcoming and expanding marginal land (ex-arable land) poplar plantations in Eastern European countries [16].

Eastern European countries' forestry firms may have skidders and excavators already used for other tasks available for occasional harvesting. MRC plantations see steady success on marginal land (ex-arable lands) [17] and the WTH system is presumed to be flexible and reliable enough to cope with the safety and efficiency standards of contemporary industrial harvesting [14].

Furthermore, it must be considered that the awkward maneuvering of the skidder operator to avoid stand damage does not apply in MRC since clear cuts considerably ease the operations and felling can be performed at the field edge.

A medium rotation coppice (58-year turnover) involving fast-growing trees (such as poplars) that presents a total tree volume below 0.2 cubic meters is sub-optimal for forestry-fitted machines. However, MRC dimensions exceed single-pass machines' working capacity in terms of stem diameter and stem total height.

Motor-manual felling is not an option, considering its safety and ergonomics; thus, MRC harvesting conducted with forestry-fitted machines seems to be the only viable option at the moment [18–20].

To complicate the already challenging harvesting phase, the logs extracted must be 4 m long and the smallest end diameter must reach 8 cm in order to fulfill the industry supply requirements regarding lightweight board production from wood flakes. The production of flakes instead of woodchips requires the integrated production of a higher added value product (logs for flake production) and biomass (from rejected logs or tops)—this is so-called Integrated Harvesting or IH [4,21–23].

This study has been conducted to test different combinations of technologies with the purpose of increasing the information available for harvesting operations under the small individual tree limitations and technical constraints. The goal of this study was to compare the technical and economic performance of WTH compared to the conventional CTL system, applied to short-rotation poplar plantations.

The null hypothesis was that there was no significant difference in the performance of the two work systems when applied to short-rotation poplar plantations.

2. Materials and Methods

Two sites were chosen for the purpose of the study, namely, "Nivky", near Vel'ké Leváre (48°31′25.11″ N; 17°03′25.21″ E in WGS84), and "Skalica", which bears the name of the nearest town (8°50′31.55″ N; 17°11′21.73″ E in WGS84). Both sites are in Slovak Republic near the IKEA Industry plant in Malacky.

The plantation schemes were 3.0 m × 2.0 m and 3.0 m × 1.8 m for Nivky and Skalica, respectively. Skalica plantation was established one year earlier (2016) than Nivky plantation (2017). Both sites were planted with the hybrid poplar (*Populus x euramericana* Dode (Guinier)) clones AF16 (Nivky) and AF2 (Skalica).

The Diameter at Breast Height (DBH) of all trees in all plots was measured manually with measuring tape. Furthermore, 6 trees—representing the whole DBH collection—were destructively sampled in order to retrieve their total height and the weight of the logs and biomass potentially obtained from them [24,25]. This process enabled the construction of a DBH–height curve and an allometric equation to determine the mean height and the standing mass on each individual plot [26].

The homogeneity of even-aged clonal poplars makes it possible to build trustworthy allometric functions with small samples [27]. In any case, mass estimates were later adjusted using ad hoc correction factors obtained by matching the total log and chips' biomass estimates with the actual amounts taken to the weighbridge available at the downstream factory gates.

The growing stock inventory data were corrected with one single correction factor for both systems, resulting in a log mass correction factor for Nivky and one for Skalica, and one chip correction factor for Nivky and one for Skalica. Within the same field (Nivky or Skalica) and biomass type (Logs of Chips), the correction factor was the same regardless of the system.

Moisture content (i.e., water mass fraction) was determined both at the time of destructive sampling by gravimetric methods (according to the standard UNI EN 14774-1-2009) and at delivery to the factory so as to match dry mass with dry mass. Moisture content at delivery was 57% with respect to humidity. The ratio between factory mass and inventory mass was 0.99 for logs and 0.72 for chips (tops and branches), and these ratios were applied to the plot inventory in order to correct and transform estimated mass into actual mass at the factory.

The systems under investigation consisted of the classic CTL combination of a harvester and a forwarder and an equally classic WTH chain comprising a feller-buncher, a clambunk skidder, and a roadside processor. Both systems yielded 4 m long logs, with a length tolerance ±0.15 m and a minimum small-end diameter of 8 cm over bark. Tops were piled separately at the roadside.

The machine makes and models used for the study are listed in Table 1.

Table 1. List of all machinery used for the harvesting and extraction per System.

System	Machine 1	Machine 2
CTL	Sampo HR46 harvester (124 kW, 9.5 t);	Sampo FR28 forwarder (124 kW, 10 t payload capacity);
WTH	Silvaro 250 shears; Kobelco 200 tracked excavator (20 t);	LKT 82 clambunk skidder (93 kW) [1]

[1] Sampo HR46 harvester was used as landing processor in the WTH harvesting system as well.

Each machine had its own operator, who was a qualified forestry professional with significant experience (at least 5 years) for the specific task [28]. In this study, "significant experience" means that the operator has already reached the steady state as reported in Purfürst (2010) for harvester operators and in Spinelli et al. (2011) for the introduction of new machines [29,30].

All operators were informed about the purpose of the test and the methods adopted, and all made their best efforts to cooperate towards the success of the trial. They were all given at least one full day of practice outside the marked experimental plots in order to familiarize them with their specific tasks and settings before engaging in the experiment. The harvester head-measuring system was checked and calibrated before starting the trial.

Four alternative treatments were obtained from a simple and robust factorial design comprising CTL and WTH systems tested in both sites, i.e., Nivky and Skalica. Each treatment was assigned 8 plots per site (except for the combination "CTL*Nivky", which was replicated 9 times), each covering an area between 0.08 and 0.10 ha, equal to 114 and 190 trees per plot (Figure 1).

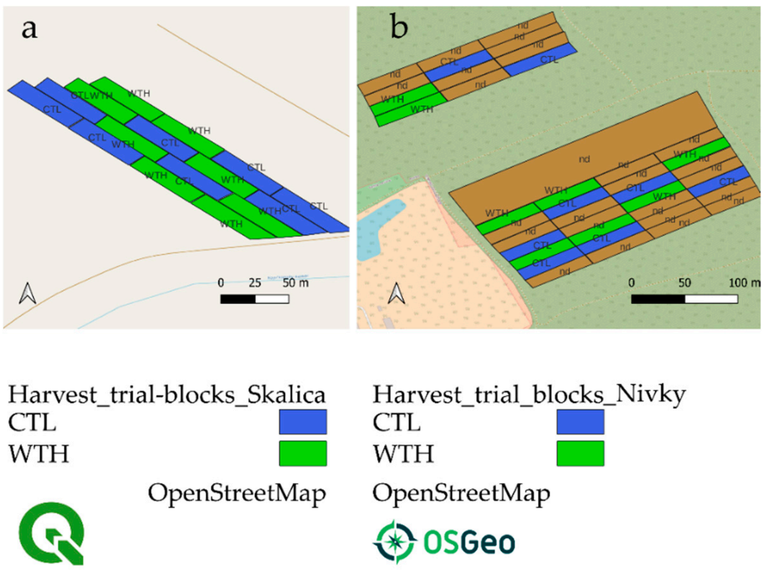

Figure 1. (**a**) Harvest plots in Skalica; (**b**) Harvest plots in Nivky.

The base requirement was that each plot should take at least one working hour to fell and process and the amount of wood on each plot should be enough for at least two full forwarder loads—one for the logs and the other for the top material.

Plots were designed as five-row work-frontage in order to replicate the standard procedure observed during the training sessions. Plot boundaries were marked with high-visibility paint and randomly assigned to the two work system treatments to avoid biases in the datasets caused by local spatial gradients (local soil fertility gradients, plantation failures, etc.).

At the time of harvesting, the researchers determined the following specifications for each plot: productive time consumption; delay time; number of trips (for forwarders only); payload fill rate (actual load as a % of maximum available payload volume—forwarders only); extraction distance (forwarders only—estimated from Google Earth pictures, from the center of the plot to the center of the landing).

Since CTL and WTH felling operations were conducted by different machines, the label "felling" includes felling and processing for CTL system and only felling for WTH system. Processing operations ("processing" = "bucking") constitute the crosscutting and delimbing procedures. Processing transformed each full tree to the final assortments: logs (4 m long logs with smallest diameter above 8 cm) and biomass (tree tops and limbs to be chipped). Finally, "extraction" denotes the hauling operation (for both CTL and WTH) from the stump to the landing of logs and biomass of full trees with regard to the system adopted.

As a safety measure, plot-level time consumption was determined concurrently by the researchers on-site using stopwatches and by the operators on the machines using their own wristwatches (obviously at a lower definition). Furthermore, action cameras were attached to all machines in order to acquire a permanent record of operation in case of any doubts or mistakes. All data used in the final plot study were derived from the time study conducted by the researchers' field crew, which were composed of experienced and motivated specialists in time studies, in order to obtain accurate time data and to achieve the separation of work time from delays in a manner reliable for the purpose of the present study [31].

As an additional safeguard, researcher records and operator records were compared, and they all presented a reasonably good match, which excluded any gross errors in time data collection.

Occasionally, the mass of wood on one plot would exceed the capacity of the forwarder assigned to that plot. When that occurred, partial loads were hauled in order to avoid mixing the times and materials belonging to each plot. Therefore, the vehicle travel time was multiplied by the payload fill rate of that load in order to account for the fact that a full load would have been extracted in real operational conditions and, therefore, that same travel time would have been distributed over a larger payload.

Since the study was not long enough to accurately estimate downtime, all estimates were made based on net timework per plot, which was enlarged by 20% in order to consider preparation- and delay-related downtimes. This 20% inflation was consistent with the results of previously published studies, especially considering the harvesting of plantation forestry [32].

Machine cost was assumed to be the rates charged at the time of the study by the service providers. These were 40 EUR per scheduled machine hour (EUR SMH^{-1}) for the forwarder, 60 EUR SMH^{-1} for the harvester, 35 EUR SMH^{-1} for the feller-buncher, and 50 EUR SMH^{-1} for the clambunk skidder.

Data were used to quantify machine productivity and harvesting cost as mean values, and the differences between alternative treatments was checked using a linear model (LM), which is considered both simple for addressing and powerful against violations of the main statistical assumptions. Furthermore, regression analysis was used to test the effect of sites (Nivky or Skalica) and systems (CTL or WTH) [33]. For all analyses, the significance level was set at $Pr(>F) < 0.05$.

After a check of the normal distribution, the linear model that was built for independent variables of growing stock data, total tree height (H), DBH, oven-dried tons per hectare (ODT ha^{-1}), shares of logs (% Logs), and productivity/cost of operations ODT per Scheduled Machine Hours (ODT SMH^{-1}) and EUR per ODT (EUR ODT^{-1}) under the resulting 4 treatments ("CTL Nivky", "CTL Skalica", "WTH Nivky" and "WTH Skalica") was used to conducted the Analysis of Variance (ANOVA).

R software "Base" package [34] was embedded into R Studio [35], integrated with "Tidyverse" [36], "GGPLOT", and "Markdown" (and relative dependencies) packages.

No endeavor was made to normalize individual staging by means of productivity ratings [37], as all sorts of normalization or corrections can introduce new sources of errors and uncontrolled variation in the data figures [38].

The authors acknowledge that regional rates can hardly offer a general benchmark and encourage readers operating under different economic environments to recalculate harvesting costa using their own rates and the productivity data presented in this paper.

3. Results

The field-stocking data presented in Table 2 show the total tree height (H), diameter at breast height (DBH), growing stock (ODT ha^{-1}), and shares of logs' (% Logs) descriptive statistics (mean standard deviation, etc.). With regard to the mean values, Nivky had higher growing stock values (52.6 ODT ha^{-1} for CTL and 44.2 ODT ha^{-1} for WTH) than Skalica (42.5 ODT ha^{-1} for CTL and 41.5 ODT ha^{-1} for WTH).

Table 2. Descriptive statistics for the 4 treatments comparison—growing stock data (H, DBH, ODT ha^{-1}, and % Logs).

Variable	Site	System	Mean	Std_Dev	Count	Std_Error	Minimum	Maximum	Median
H (m)	Nivky	CTL	15.072	0.098	9 *	0.033	14.931	15.218	15.070
	Nivky	WTH	14.935	0.143	8	0.051	14.716	15.141	14.917
	Skalica	CTL	12.140	0.789	8	0.279	11.044	13.235	12.124
	Skalica	WTH	12.040	0.780	8	0.276	10.689	12.875	12.129
DBH (cm)	Nivky	CTL	12.218	0.405	9 *	0.135	11.694	12.951	12.201
	Nivky	WTH	11.617	0.553	8	0.196	10.815	12.465	11.532
	Skalica	CTL	13.199	1.063	8	0.376	11.728	14.691	13.248
	Skalica	WTH	13.108	0.976	8	0.345	11.483	14.145	13.328
Growing stock (ODT ha^{-1})	Nivky	CTL	52.638	5.081	9 *	1.694	47.070	62.917	50.850
	Nivky	WTH	44.195	6.758	8	2.389	32.188	54.338	43.735
	Skalica	CTL	42.518	9.009	8	3.185	31.790	56.922	41.432
	Skalica	WTH	41.530	7.748	8	2.739	30.966	50.857	42.311
Shares of Logs (% Logs)	Nivky	CTL	61.119	2.877	9 *	0.959	58.212	66.294	59.290
	Nivky	WTH	54.621	4.712	8	1.666	47.764	62.206	54.266
	Skalica	CTL	45.631	2.307	8	0.816	42.558	48.998	45.398
	Skalica	WTH	45.813	2.228	8	0.788	43.570	49.657	45.215

* Nivky X CTL is the only treatment (Site X System) that had 9 replications instead of 8.

The value recovery, as expressed by "share of log" (% Log), was higher for Nivky than for Skalica. The ANOVA (Table 3) yielded a value of 61% for the logs from Nivky and a decrease on the order of 15% (−15.488) for Skalica (a less developed site). As already found by Spinelli et al., there is a directly proportional relationship between the growing stock value (growing stock in ODT ha^{-1}) and the share of logs parameter [23].

Total tree height (H) was 15.07 m for "Nivky CTL" and 12.14 m for "Skalica CTL". The DBH was higher in the less developed site—Skalica; for instance, the Skalica CTL treatment had mean diameter values of 13.19 cm, while the more developed site had a DBH mean of 12.21 cm for the Nivky*CTL treatment.

The sites' differences among the measured variables (H, DBH, growing stock, and share of logs) shown by ANOVA (Table 3) were statistically significant, although those concerning the system were not (the significance level was set at Pr(>F) < 0.05) for the share of logs (% Logs) variable only; this is reasonable, since the share of logs, which represents the output of the grading capability, was also partially influenced by the system variable.

The standard deviation values (Table 3) were not homogeneous across the treatments: H and DBH show a higher standard deviation in the Skalica site than in Nivky, although the yield and share of logs do not show a precise pattern since the system and site variables affected both standard deviation values.

Table 3. ANOVA table for H, DBH, growing stock, and share of logs parameters. Significance threshold set as Pr(>F) < 0.05.

Parameters	Variables' Interaction	Df	Deviance	Resid. Df	Resid. Dev	F	Pr(>F)
H (m)	NULL	NA	NA	32	79.14	NA	NA
	site	1	70.18	31	8.96	230.22	0.00 ***
	system	1	0.12	30	8.84	0.38	0.54
	site:system	1	0.00	29	8.84	0.01	0.92
DBH (cm)	NULL	NA	NA	32	31.84	NA	NA
	site	1	12.24	31	19.60	19.69	0.00
	system	1	1.03	30	18.57	1.65	0.21
	site:system	1	0.54	29	18.03	0.86	0.36
growing stock ($ODT\ ha^{-1}$)	NULL	NA	NA	32	2183.91	NA	NA
	site	1	363.50	31	1820.41	6.96	0.01
	system	1	191.47	30	1628.94	3.67	0.07
	site:system	1	114.33	29	1514.62	2.19	0.15
Share of Logs (% Logs)	NULL	NA	NA	32	1727.56	NA	NA
	site	1	1254.91	31	472.65	123.92	0.00
	system	1	87.17	30	385.48	8.61	0.01
	site:system	1	91.79	29	293.68	9.06	0.01

Significance codes: '***' [0.0001, 0.001].

It is remarkable that the feller-buncher reached a very high productivity in felling operations and considerably low costs per product units in both sites (Table 4).

Table 4. Descriptive statistics for the 4 treatments' comparison—productivity and costs.

Variable	Site	System	Mean	Std_Dev	Count	Std_Error	Minimum	Maximum	Median
Felling productivity ($ODT\ SMH^{-1}$)	Nivky	CTL	3.029	0.289	9 *	0.096	2.672	3.530	2.916
	Nivky	WTH	5.580	0.474	8	0.168	4.770	6.120	5.744
	Skalica	CTL	2.176	0.336	8	0.119	1.827	2.877	2.086
	Skalica	WTH	4.624	0.711	8	0.251	3.548	5.581	4.641
Felling cost ($EUR\ ODT^{-1}$)	Nivky	CTL	19.961	1.818	9 *	0.606	16.999	22.456	20.573
	Nivky	WTH	6.315	0.578	8	0.204	5.719	7.338	6.093
	Skalica	CTL	28.087	3.837	8	1.357	20.856	32.847	28.770
	Skalica	WTH	7.736	1.248	8	0.441	6.272	9.864	7.549
Extraction Productivity ($ODT\ SMH^{-1}$)	Nivky	CTL	3.257	0.426	9 *	0.142	2.469	3.824	3.429
	Nivky	WTH	3.908	0.607	8	0.215	3.157	5.046	3.829
	Skalica	CTL	2.276	0.227	8	0.080	1.941	2.530	2.298
	Skalica	WTH	4.648	0.333	8	0.118	4.290	5.238	4.584
Extraction cost ($EUR\ ODT^{-1}$)	Nivky	CTL	12.490	1.803	9 *	0.601	10.460	16.199	11.665
	Nivky	WTH	13.053	1.927	8	0.681	9.909	15.838	13.066
	Skalica	CTL	17.730	1.811	8	0.640	15.807	20.611	17.439
	Skalica	WTH	10.805	0.745	8	0.263	9.546	11.654	10.908
Total cost ($EUR\ ODT^{-1}$)	Nivky	CTL	32.451	2.512	9 *	0.837	28.145	37.065	32.348
	Nivky	WTH	43.252	5.319	8	1.881	35.926	50.082	43.594
	Skalica	CTL	45.816	4.890	8	1.729	37.173	52.181	46.608
	Skalica	WTH	53.565	2.653	8	0.938	51.168	59.159	53.207

* Nivky X CTL is the only treatment (Site × System) that had 9 replications instead of 8.

As shown in Table 5, depending on the site, the feller-buncher (felling productivity in the WTH system) was about twice as productive as the harvester (felling productivity in the CTL system). Clambunk (extraction productivity in the WTH system) was 5% (Nivky) and twice as productive (Skalica) as the forwarder (extraction productivity in the CTL System). The WTH felling cost (EUR ODT) was between 1/3 (one third) and 1/2 (half) the cost required for the same stage under the CTL system (though the CTL machine executed the additional tasks involved in processing). The extraction cost ($EUR\ ODT^{-1}$) under the

WTH system was comparable to the extraction cost under the CTL system in Nivky, while for Skalica WTH was much more competitive (40% less expensive).

Table 5. Summary of the productivity and cost differences between the two systems and sites.

System	Site	CTL	WTH	Diff	Diff %
Felling productivity (ODT SMH^{-1})	Nivky	3.03	5.58	2.55	84.22
	Skalica	2.18	4.62	2.45	112.50
Felling cost (EUR ODT^{-1})	Nivky	19.96	6.31	−13.65	−68.36
	Skalica	28.09	7.74	−20.35	−72.46
Extraction Productivity (ODT SMH^{-1})	Nivky	3.26	3.91	0.65	20.00
	Skalica	2.28	4.65	2.37	104.17
Extraction cost (EUR ODT^{-1})	Nivky	12.49	13.05	0.56	4.50
	Skalica	17.73	10.80	−6.92	−39.06
Processing Productivity (ODT SMH^{-1})	Nivky	0.00 *	2.66	2.66	NA
	Skalica	0.00 *	1.72	1.72	NA
Processing cost (EUR ODT^{-1})	Nivky	0.00 *	23.88	23.88	NA
	Skalica	0.00 *	35.02	35.02	NA
Total cost (EUR ODT^{-1})	Nivky	32.45	43.25	10.80	33.28
	Skalica	45.82	53.57	7.75	16.91

* Operation "Felling" differs from CTL to WTH: in CTL, felling operation also comprises processing.

As shown, the very low productivity, 2.7 and 1.7 ODT SMH^{-1} (for Nivky and Skalica, respectively), and the resulting high cost (24 and 35 EUR ODT^{-1}, in the same order) encountered in the whole tree-processing operation within the WTH system offsets all the profits accrued in the felling operations under WTH.

The total costs of the operation are EUR 32.45 ODT^{-1} and EUR 43.25 ODT^{-1} for CTL and WTH, respectively, in Nivky, and EUR 45.82 ODT^{-1} and EUR 53.57 ODT^{-1} for CTL and WTH, respectively, in Skalica.

The effect of the system is dominant versus that of the site when it comes to felling productivity and cost, while the reverse is true for the total cost, where the site effect is stronger than the system effect (see Table 6). Site and system effect in the ANOVA (Table 6) was statistically significant since Pr(>F) values fits the significance condition (Pr(>F) < 0.05). Site had statistically non-significant effect on extraction productivity.

Table 6. ANOVA for the 4 treatments' comparison—productivity and cost. Significance threshold set as Pr(>F) < 0.05.

		Df	Deviance	Resid. Df	Resid. Dev	F	Pr(>F)
Felling productivity (ODT SMH^{-1})	NULL	NA	NA	32	63.78	NA	NA
	site	1	5.68	31	58.10	25.07	0.00 ***
	system	1	51.51	30	6.58	227.53	0.00 ***
	site:system	1	0.02	29	6.57	0.10	0.76
Felling cost (EUR ODT^{-1})	NULL	NA	NA	32	2745.59	NA	NA
	site	1	157.54	31	2588.04	32.00	0.00 ***
	system	1	2352.83	30	235.22	477.95	0.00 ***
	site:system	1	92.46	29	142.76	18.78	0.00 ***
Extraction Productivity (ODT SMH^{-1})	NULL	NA	NA	32	29.55	NA	NA
	site	1	0.85	31	29.46	0.47	0.50
	system	1	18.20	30	11.26	102.12	0.00 ***
	site:system	1	6.09	29	5.17	34.14	0.00 ***

Table 6. *Cont.*

		Df	Deviance	Resid. Df	Resid. Dev	F	Pr(>F)
Extraction cost (EUR ODT^{-1})	NULL	NA	NA	32	290.86	NA	NA
	site	1	18.85	31	272.01	6.93	0.01 *
	system	1	77.83	30	194.18	28.62	0.00 ***
	site:system	1	115.33	29	78.85	42.42	0.00 ***
Total cost (EUR ODT^{-1})	NULL	NA	NA	32	2417.56	NA	NA
	site	1	1218.05	31	1199.51	75.93	0.00 ***
	system	1	715.11	30	484.40	44.58	0.00 ***
	site:system	1	19.16	29	465.24	1.19	0.28

Significance codes: '***' [0.0001, 0.001]; '*' [0.01, 0.05].

The total harvesting cost for the WTH treatment was between 0.3 (Nivky) and 0.15 (Skalica) times higher than that for the CTL system (Figure 2). Therefore, the null hypothesis (H0), "systems are equal under the cost and performance descriptors (parameters) in both sites" was rejected.

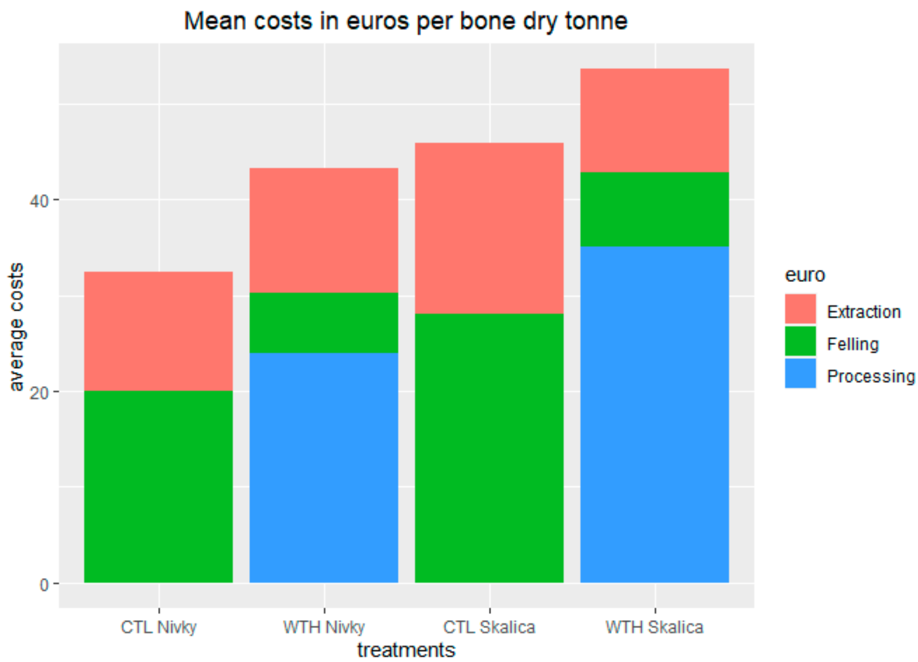

Figure 2. Summary of productivity and costs.

4. Discussion

The opportunity to test the CTL and WTH systems in a clonal poplar plantation (two sites) provided the opportunity to conduct a direct comparison between harvesting systems in a reduced noise variables experimental environment (concerning tree dimension, canopy density, fertility, and ground surface).

With regard to mobile harvesting machines, physical ground conditions, may act as noise variable in performance studied, thus poplar plantations on flat and homogeneous terrain, represent an opportunity especially in a direct comparison between two working methodologies (systems).

Since it was not possible to separate the logs and the biomass produced with the CTL system from those produced from the WTH system, the correction factor acquired from the inventory data (yield) obtained by matching actual scale weights with allometric inventory figures would not account for the possible biomass recovery differences between the two harvesting systems. It is reasonable to assume that under the CTL system, more branches and tree-tops biomass is left in the field compared with the WTH system. This would correspond to the visual observations. This approach ignored the eventual harvesting system effects and most likely overestimated the biomass recovery under the CTL system and underestimated it under the WTH system, thus producing a more conservative estimate of the productivity advantage enjoyed by WTH harvesting.

Human interaction comes with multiple effects [39], and blocking could not resolve the issue from a statistical point of view [40]. However some studies conducted under similar conditions (with respect to methodology, purposes, sites, and harvesting systems) suggest that the operator effect can actually blur the present paper's findings since its contribution to productivity is around 20% [41]. Nevertheless, the results of this study strongly suggest that the WTH system, under the integrated harvesting mode (IH mode—see introductory section) shows interesting improvement margins due to its flexibility. The flexibility of WTH allows for the application of many strategies for performance improvements, for instance, pre-sorting may dampen WTH processing by 100% in terms of productivity [42], and low-investment machines could fit small forestry firms' expectations for reducing machines' hourly costs and increasing the annual machine usage rates by purchasing less-sophisticated machines [5]. So, the results are considered by the authors as a good estimation under commercial conditions concerning the productivity and costs for the operations described, since other studies conducted under similar conditions (in poplar clone plantations, with the same output, etc.) yielded similar results (Table 7).

Table 7. Bibliography of similar studies and respective results in average costs per product unit.

Authors	Year	Reference	Values Range (EUR ODT^{-1})
Spinelli et al. [1]	2022	[22]	33.8–46.1
Spinelli et al. [2]	2022	[41]	29.9–35.4
Spinelli et al. [3]	2022	[42]	46.1–42.2
Spinelli et al. [4]	2022	[23]	28.3–32.0

[1] min and max values total costs. Machine costs were: EUR 69.00 SMH^{-1} for the harvester and EUR 53.00 SMH^{-1} for the forwarder. [2] CTL min and max values. Machine costs were: EUR 65.00 SMH^{-1} for the harvester and EUR 40.00 SMH^{-1} for the forwarder. [3] Costs actually charged for CTL and WTH. Machine costs were EUR 69.00 SMH^{-1} for the feller-buncher, EUR 75.00 SMH^{-1} for the forwarder, and EUR 47.00 SMH^{-1} for the processor. [4] CTL system, Agama and Vimek harvesters, and Vimek and Sampo forwarders. Machine costs were EUR 40.00 SMH^{-1} for the Vimek harvester, EUR 45.00 SMH^{-1} for the Agama harvester, and EUR 40.00 for the Vimek or Sampo forwarder.

The study results showed that under small tree dimensions, high added value outputs (4 m long logs) of more than 61% could be achieved compared to similar studies regarding the log yield (50% rejects) [5].

Processing operations take place at the landing rather than at the stump (cutover) only in the WTH system. This means that the WTH system allows non off-road negotiating machines (or less deployable devices, e.g., stem-slasher devices [5,43,44]), to be used for processing operations.

In felling operations, WTH performed significantly better in the low-yield site (Skalica) compared to the CTL technique and it was competitive with the CTL technique in the best-performing growing-stock site (Nivky) with respect to extraction operations. Since the CTL system carried out felling and processing (Sampo harvester) and WTH performed only felling (Kobelco accumulating shears) rather than processing at the landing of stacked piles, WTH's total costs rose significantly and productivity dropped.

The CTL technique's productivity margins dropped as the single tree dimension fell below a certain threshold, depending on the machine productivity and hourly costs, for example, below 0.05 m^3. The mass-handling concept developed in the WTH system could be helpful for significantly reducing felling and extraction time consumption and monetary expenses.

Unfortunately, in the present study, we were not able to present a WTH system with a fully implemented mass-handling strategy due to the unavailability of a mass-handling device in the processing phase. Such a "device" would maintain high productivity and low costs by using a slasher to perform crosscutting—as experienced in less mechanized settings—and a chain flail de-limber/de-barkers capable of processing multiple trees per shift.

The additional value of the presented WTH mass-handling strategy resides in the fact that, especially in Eastern European countries, the WTH equipment is available and represents a better solution due to its higher economic life and lower purchase price than CTL equipment, fulfilling the socio-economic nature of the local firms in the territory [45].

The attempt to show objective results may also progress toward the direction of promoting a rational perspective and demonstrating the validity of WTH in MRC poplar plantation harvesting as well, removing any prejudice regarding the deployment of larger heavy machines for small trees.

With regard to the extraction productivity under the WTH and CTL systems (ODT SMH), the margin of the WTH system was larger in Skalica partly because the smaller tree size further handicapped the already challenged CTL harvester and partly because the clambunk skidder worked on a longer distance than the forwarder when in Nivky, while in Skalica the distance was about the same and, what is more, the clambunk had optimized its routine by accumulating larger loads than in Nivky.

5. Conclusions

The findings clearly show that under small tree dimension limitations, mass handling represents a valid strategy to improve performance in felling and extraction operations.

The CTL system in general has a better potential for valorization because of the possibility of grading directly at the landing before extraction, thereby reducing the contamination of logs and providing an improved grading strategy (single tree).

- WTH performed better than the CTL system in felling and extraction operations;
- The overall WTH performances were blunted by the lack of the availability of proper "mass handling" processing machines to be deployed at the landing;
- WTH shows significant margins for improvement through the implementation of full "mass handling" techniques from the stump to the industry gate.

This study stressed the excellent performance of the WTH system over the CTL system during felling and extraction operations.

Future studies will address the testing of the complete mass-handling work chain in order to demonstrate the present study's hypothesis suggesting that under small tree dimension constraints, simplified forest handling is more important than single tree valorization.

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